Hydrological Sciences Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

How robust is the evidence for beneficial hydrological effects of urban tree planting?

Henry J. Baker, Michael G. Hutchins & James D. Miller

To cite this article: Henry J. Baker, Michael G. Hutchins & James D. Miller (2021): How robust is the evidence for beneficial hydrological effects of urban tree planting?, Hydrological Sciences Journal, DOI: 10.1080/02626667.2021.1922692

To link to this article: https://doi.org/10.1080/02626667.2021.1922692

Publisher: Taylor & Francis & IAHS

Journal: *Hydrological Sciences Journal*

DOI: 10.1080/02626667.2021.1922692

How robust is the evidence for beneficial hydrological effects of urban tree planting?

Henry J. Baker[1]; Michael G. Hutchins[2*], James D. Miller[2]

1) Department of Earth Sciences, Royal Holloway University of London, Egham Hill, Egham TW20 0EX, UK
2) UK Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK

*corresponding author email: mihu@ceh.ac.uk

Abstract

Sustainable urban water management initiatives are increasingly required to combat rapid urbanisation and climate pressures. Initiatives include the role of tree planting for which there is need for strong evidence of benefits and drawbacks to support effective future planning. We report robustness of evidence from an assimilated database of urban hydrological impact studies which often had differing primary purposes. Consistent impacts were found at local level, with trees reducing runoff and infiltration. Despite the consistency of evidence, much is undermined by being somewhat lacking in robustness and scientific rigour. Many studies lack adequate controls, and models are often not strongly tested against observations. Moreover, evidence of impact at larger scales is lacking. Effects of tree characteristics were also investigated; such as maturity and species for which evidence is consistent and detailed, and arrangement for which there is less evidence. Realising the full potential of trees in urban water management decision-making would benefit from more-rigorous evidence.

Keywords

Urbanisation, tree, hydrology, stormwater, green infrastructure, runoff, modelling, nature-based solutions

1 Introduction

1.1 Urban water management

There is growing pressure on urban water management (UWM), exacerbated by population growth, climate change and the deterioration of current urban infrastructure systems. Alongside an increasing population also comes increasing water demand (United Nations Educational, Scientific and Cultural Organisation [UNESCO], 2019), and with 70% of the global population forecast to be living in cities by 2050 (Romano and Akhmouch, 2019) this presents further challenges for UWM. The Urban Water Management Programme (UWMP) was set up by UNESCO to address these stressors, and the promotion of scientific policy guidelines, knowledge of new approaches and sustainable tools provided are hoped to improve UWM as a whole / provide a holistic approach (UNESCO, 2019). Romano and Akhmouch (2019) point out, there is no 'one size fits all' approach to UWM, currently. It is a concept that varies significantly by context, and there is an increasing need for more widely applicable approaches to solving these issues of UWM (Hurlimann *et al*., 2017). Degrading water quality and increased urban flooding are among the concerns for UWM, in conjunction with both population growth and climate change (Miller and Hutchins, 2017).

1.2 Impacts of trees

Sealing of pervious surfaces such as conversion of gardens to driveways serves to reduce the infiltration of rainfall and increase the risk of urban flooding (Warhurst *et al*., 2014). The overall increase in runoff volume, reduction in runoff lag time, greater peak discharges during storm events and increased streamflow flashiness are all symptoms of increased impervious surface cover. One strategy proposed to counteract this sealing has been sustainable urban drainage systems (SUDS). SUDS include interventions such as infiltration trenches, biofiltration swales, and the planting of trees and other vegetation (McGrane, 2016). Street trees have been recognised as an essential part of stormwater management in the urban context. Trees are able to reduce runoff via interception from their canopy, returning some of this water to the atmosphere through evapotranspiration, and allowing greater infiltration of water through the soil surface to be absorbed by their roots or stored in litter (Center for Watershed Protection, 2017). There are also technologies designed for urban areas which implement trees with the aim of reducing stormwater runoff (GreenBlue Urban, 2015). The extent to which trees can provide these services has not been defined, nor has literature been objectively reviewed.

1.3 Aims and objectives

The aim of the present study is to evaluate the impacts of urban tree planting on hydrology. The primary objective to achieve this aim is:

- Critically analyse the evidence assimilated to assess scientific robustness and the quality of the outcomes found

Other secondary objectives include:

- To assess the impact of tree arrangement or planting location on hydrology
- To analyse the extent to which vegetation type affects hydrology
- To identify differences between modelled impacts to actual measured impacts of urban tree planting

To assess these objectives, a rapid evidence assessment (REA) incorporating a systematic evaluation of evidence was undertaken for which primary question and secondary questions were formulated as highlighted below.

Primary question:

i. What are the impacts of urban trees on hydrology?

Secondary questions:

i. Does arrangement of trees or planting location affect the impact on hydrology?
ii. Is there a difference between the monitored and modelled impacts of trees?
iii. Does tree species have a significant effect on the impacts found on hydrology?

2 Methodology

In order to address the primary and secondary questions a database of evidence from online literature resources was assimilated through a systematic methodology. Search queries on Web of Science (https://apps.webofknowledge.com/) were designed using a list of keywords developed from PICO criteria (Population, Intervention, Comparator, Outcome) set up to address the primary and secondary questions (Table 1). With regards to the outcomes, keywords related to the variables being studied, i.e. interception, were used to narrow the search, otherwise results would be too broad.

2.1 Search engines and queries

Search queries were refined iteratively to focus the process whilst ensuring the return of appropriate and relevant evidence. This was achieved by using pieces of control evidence comprising literature known at the outset to be of key significance (e.g. Livesley *et al*. (2016), Frosi *et al*. (2019), Matteo *et al*. (2006)). The search queries were put together in sections using individual elements of the PICO criteria and then combined (Table 1).

The primary searches (Web of Science) were limited to only return evidence published in English due to the language comprehension restrictions. Individual searches yielded around 5,900,000 hits which on combination was reduced to 1,142 (Table 2). There is potential for published literature to be biased, with studies remaining unpublished if their findings are not significant (Gough *et al*., 2013; Collins *et al*., 2015). Therefore, search strings were set up in Google Scholar (https://scholar.google.com/) to ensure other important academic and grey literature was not excluded and a fully representative evidence base assimilated.

Simpler strings were used as the Google Scholar search engine cannot recognise all Boolean operators. Following guidance from Haddaway *et al*. (2015), the first 200 Google Scholar hits were screened at title level, aided by the text preview feature.

2.2 Screening process

The next stages of the database creation involved screening, whereby evidence was included or removed depending on whether criteria were met (Appendix A1). This was carried out in three stages: title, abstract and full-text screening.

2.2.1 First-stage screening

After all evidence was assimilated, it was first screened by title. Evidence was categorised as *relevant (1)*, *irrelevant (0),* or *uncertain (-)*. If terminology related to green infrastructures in urban areas such as bioretention pits or bioswales were mentioned, but trees were not explicitly referenced, evidence was included but scored as *uncertain*.

Web of Science searches were added to the database before going through the first stage of screening, but Google Scholar and Google searches were screened as they were searched for. It must be noted that both Google search engines provided a preview of the text which was used as an aid for deciding relevance.

2.2.2 Second-stage screening

Evidence reaching the second stage of screening was assessed using the abstract or first paragraph. If relevance was still uncertain after this, the full text was briefly searched for terms that made its classification *uncertain*. For example, if the abstract mentioned green infrastructure but not trees explicitly, the text was searched for ‘trees’, and if the population was not certain ‘urban’ was searched for.

2.2.3 Final-stage screening

All evidence reaching the final stage of screening was screened using the full text. An additional inclusion criterion considered at this stage was whether the evidence included primary evidence. Review studies were still included, but then separated from primary literature, as there is greater potential for bias in review papers. In review papers, the robustness of evidence cited cannot be accounted for unless their rationale for study inclusion is stated, or it is made explicitly clear as to the integrity of each study. Evidence which mentions urban tree planting and its impacts, which is not a review study, without reference to primary data will be excluded.

When screening the full text, a note was made if the text was accessible or not. Those that were not accessible were screened out, which had implications for this study due to such evidence being potentially relevant.

After all evidence had passed the final screening stage, the evidence that had been screened out was checked again, comprehensively, to assess whether there were incorrect exclusions at both title and abstract level screenings. The results of doing so found no studies that had been incorrectly screened out and the final number of items of evidence to be used in the assessment after duplicates were also removed, was 55.

2.3 Critical appraisal database

The final set of literature was compiled into a database with categorical fields, as highlighted in Appendix A2, to systematically describe the evidence (in addition to the meta-data: source, title, author, publisher, publication year).

2.4 Critical appraisal (CA) scoring

Relevance was scored as either one or zero depending on whether the evidence meets full inclusion/exclusion requirements for population, intervention, and outcome(s). The critical appraisal of relevance is stricter, however: it had to be explicitly stated and not inferred. For example, the impacts of trees on hydrology had to be direct, and not inferred from impacts on tree health (e.g. Grey *et al.*, 2018a).

Robustness scores were split into sections: general, methodology, and analysis. Each of these sections had a set of criteria that each piece of evidence had to fulfil to achieve a score of one (Appendix A3, Table A3). If less than the majority of criteria for each section were not met, it was scored zero.

Some evidence primarily used modelling to determine the impacts of urban trees. Such evidence had additional criteria to meet for both methodology and analysis sections of robustness scoring. The way in which the model operated had to be well described, and the potential error or confidence values of the modelled impacts must also be stated.

Once both relevance and robustness scores had been finalised, they were multiplied together to give an overall appraisal score. Scores could therefore range between one and nine. Evidence with higher appraisal scores will be given higher weighting in the synthesis of evidence and the formulation of evidence statements. The final appraisal score will also be indicative of those studies which reduce bias the most.

2.5 Monitoring/modelling (MM) scores

Robustness was also assessed by scoring the length of monitoring/modelling controls and interventions and their monitoring/modelling frequencies. Studies that had short or no control/ intervention periods or low frequencies received a score of one; moderate scored two; and high scored three (N/A scored zero). The total score was calculated using the sum of each category; thus, they can range from one to nine. The sum was used instead of multiplying scores like in CA scoring, as it discounted the importance of studies having a control even if it was a poor one.

2.6 Evidence Statement (ES) index

CA and MM scores were combined in the form of an evidence statement (ES) index as a final appraisal of the outcomes in the studies assimilated. The mean CA and MM scores were calculated for each general outcome, e.g. reduced runoff, and then these were averaged to find the ES index value.

We strongly emphasise that whilst potentially giving the suggestion of being definitive, final scores and the components thereof should not be interpreted as being indicative of the entire value of individual research studies, which in many cases had a different or wider purpose.

3 Results

3.1 Type, spatial extent and outcome/population of study

Studies on urban tree planting and the impacts on hydrology have been more common over the last few years. This is a promising trend for this field of research. Of all 55 pieces of evidence (Appendix B1, Table B1), 53 were journal articles and two were books. There was one piece of grey literature found in all 55 studies as opposed to peer-reviewed. The study types of the primary evidence were split relatively evenly, with a much smaller number of review articles (Figure 1). Although reviews were not solely focused on modelling, the secondary evidence used in three of the studies used a combination of both modelled and measured tree impacts.

There were multiple different populations of study across the evidence database. Some evidence covered multiple categories of outcome, but all could be categorised in one of 13 different dominant populations (Figure 2a). The most common populations of study in the evidence base were runoff, stormwater, and interception.

Most studied populations (infiltration, rainfall partitioning, stemflow) are close to the trees themselves (Figure 2a) either adjacent or directly beneath. In some cases, litter leachate impacts were found further downstream and other studies focused on further away surface waters, runoff, or on stormwater at multiple scales.

In terms of geographic focus (Figure 2b) the majority were based in North America. Five of the studies had multiple geographical foci. No evidence was found from Africa or Antarctica; and only one mention of a South American location as part of a 'multiple' study (Revelli and Porporato, 2018). Of the five categorised as 'multiple' four were reviews (secondary evidence), which unsurprisingly considered a wider range of locations.

Only a third of primary studies reported the size of the intervention area or the catchment area, and of these eight only reported intervention size, and two reported just the size of the catchment (Appendix B2, Table B2). There were a vast range of sizes reported, the smallest of which were 0.6m^2 individual plots in Grey *et al*. (2018b) and the largest was in a study by Holder and Gibbes (2017) with an intervention area of 502km^2 within a catchment study area of 2409km^2. Interventions with very low area percentage compared to the catchment they are within (as defined by the location of downstream monitoring or modelling) do not provide robust outcomes. To provide more robust evidence, a higher intervention to catchment area ratio is necessary. In this case, the highest was a study with an intervention to catchment ratio of 21% (Holder and Gibbes, 2017).

3.2 Tree type and configuration

Of the 49 primary studies, 14 focused on more than five individually named species and were classed as 'mixed', and 21 studies reported one to five different species. The remaining 14 studies did not specify.

Some of the studies that focused on the effect of species or tree characteristics compared multiple types of trees, i.e. evergreen and deciduous (Appendix B3, Table B3). However, some only focused on one type, meaning observations had a less extensive comparator.

Many studies did not specify tree arrangement but of those that did the majority were individually spaced (Figure 2c). Trees in bioretention pits, individual stands or open areas were of greater focus as they are more easily analysed than linear or groups arrangements, although some analysed multiple arrangements. Where arranged linearly, these were street trees. When grouped, this often meant trees were part of an urban forest system, a park, or even in parking lots. In 18 of the studies, the arrangement of trees was not specified.

Although not part of the above categories, some studies mentioned the planting of trees within green infrastructure (GI) technologies such as bioretention pits and bioswales. One study by Maniquiz-Redillas and Kim (2016) compared the impacts of Green Infrastructure with and without trees.

3.3 Assessment periods

Only a few studies reported monitoring periods under control conditions (Figure 3a), and of those that did none exceeded two years. Although there are relatively very few reported control periods, there were clear consistencies between length of control and length of intervention.

Only one study scored high for both intervention period and monitoring frequency (Figure 3b). However, it did not report a control period and thus its overall robustness is not as strong. In most cases, if studies reported a high monitoring frequency, the length of the monitoring period was short, which probably reflects limited resources and difficulty in sustaining intensive monitoring for extended periods. It should be noted that various studies categorised with low scores for monitoring frequency were those that did not specify a defined frequency of study. Furthermore, most studies scoring high for intervention monitoring/modelling, also had low monitoring frequency (five studies). Six primary studies scored N/A for their monitoring/modelling lengths, as well as monitoring frequency and monitoring period. It is not expected that quantitative studies would not mention their monitoring/modelling period lengths or their frequencies, and so their overall robustness is not as good. All seven review studies scored N/A in all monitoring length and frequency categories.

Of the 10 studies which reported length of monitoring periods for both controls and intervention, as well as monitoring frequency, three were *ex-situ*; five were *in-situ*; one modelled; and one modelled and measured. Considering there are only four *ex-situ* studies in total, the robustness of monitoring for these studies is better than that of the other study designs.

3.4 Critical appraisal scoring

3.4.1 Relevance scoring (population, intervention, outcome)

Low relevance scores are likely to arise in studies where the primary objective was notably different from the subject of our REA. All primary evidence (quantitative observational and quantitative experimental studies) scored 1 for population relevance. Due to a lack of *explicit* reference to trees being planted or used one study scored low for intervention relevance: Tirpak *et al*. (2019) reported the use of a tree in a suspended pavement study but did not study the impacts of the tree itself. Two primary studies received low scores for outcome relevance. Grey *et al*. (2018a) analysed the impacts of street tree planting technologies based on their improved growth capacity, but focused on the impacts not on stormwater itself, but on its effect on tree health. Tratalos *et al*. (2007) scored low for outcomes as runoff reduction was reported as a result of address (housing) density and not tree density.

3.4.2 Robustness scores

Although all studies passed the general criteria of robustness, 14 and 11 studies respectively scored low for methodology and analysis robustness criteria. Studies that did not fulfil criteria for methodology robustness in primary studies were due to the lack of a control group in combination with another criterion. Perhaps unsurprisingly, five out of six of the review (R) studies also scored low for methodology criteria. In cases where robustness criteria was scored low, minimisation of bias was not evident, and most reviews did not fulfil any of the methodology criteria.

The objectives of most review studies are slightly different to that of this REA. The core of the protocol in this study is to minimise bias. Objectives of published reviews often favour positive outcomes of the intervention they are implementing and reflects the issue of less significant or negative results tending to go unpublished (Collins *et al*., 2015).

Of the primary evidence, only six scored low for analysis, but three of these also scored low for methodology. Whilst analytical methods were always stated by studies, many were scored low due to a lack of precision values in combination with either a lack of defined magnitude of effects, or a lack of explanation behind the results found. Contrastingly, the same five review papers which had low methodology robustness also had low analysis robustness, in all cases due to a lack of bias minimisation in the synthesis of evidence. There is a lack of systematic reviews in this field.

3.4.3 Critical appraisal (CA) scores

Critical appraisal (CA) scores were calculated from the multiplication of total relevance and robustness scores. Encouragingly, primary evidence studies mostly achieved the highest possible score of 9 (Figure 4a). Secondary evidence from review papers is considered separately as appraising the rigour of the primary evidence which they used is not possible or out of scope of the present study. However, the overall rigour of the reviews themselves is much lower than quantitative studies. Only one of the reviews minimised bias effectively (Roy *et al*., 2012)

3.4.4 Monitoring/modelling scores

Only one study scored ≥7, which suggests the overall rigour of methodologies was somewhat unsatisfactory. Thus, although many studies have high critical appraisal scores, all of these apart from one have low to moderate control/intervention periods and frequencies (Figure 4b).

4 Discussion

4.1 Hydrological impacts

From primary evidence collected, there were 27 studies that reported runoff and the presence of trees to be inversely related (Figure 5). Some reported this in terms of an overall value of trees present, and some modelled the impact of reduced/increased urban tree cover. Other related hydrological responses included the increase in interception (17 studies); increased infiltration (six); and evapotranspiration loss (seven).

There were six primary studies and three review studies which reported increased infiltration as a result of urban tree planting. The importance of trees in increasing infiltration rates (IR) was demonstrated by Bartens *et al*. (2008), where extension of tree roots increased IR by 153%, the results of which were 27 times larger than that of the unplanted controls. However, one of these studies, by Nielsen *et al*. (2007), reported that maximising total infiltration could also be done by expanding the underlying pit surface area beyond the crown drip zone. In the same study, it was noted that while evapotranspiration led to water loss in soil (measured at over 10 L day^{-1}), this was not a driving mechanism in the overall hydrology of the tree pit.

The impact of differing meteorological conditions, such as storm intensity, was also identified as an important factor affecting interception and runoff (13 studies); with canopies reaching saturation faster with increased rainfall intensity (Guevera-Escobar et al., 2007). Seven of the primary studies linked reduction in runoff to the increased interception arising from increased tree cover (Figure 5). The urban water balance is controlled by multiple factors involving runoff, interception, infiltration, evapotranspiration, throughfall and stemflow, all of which are reported as part of the outcomes in the evidence found. Eleven primary studies focused on just one of these factors, but their relationship with other processes was not always reported. For instance, Xiao and McPherson (2011) reported an increase in infiltration due to the presence of trees, but did not link this back to runoff, which can be considered the main hydrological issue in urban areas.

Meteorological conditions were found, in 13 primary studies, to be a key factor affecting the success of trees improving hydrological regime. Interception in low intensity storms was much more successful than in larger storms, or in larger storms as rainfall increased past a saturation point (Livesley *et al.*, 2014; Xiao *et al.*, 2000; Zabret *et al.*, 2018; Wang *et al.*, 2008). Interception was controlled by precipitation characteristics for smaller events, but by the maximum canopy storage for larger events (Xiao and McPherson, 2016; Xiao *et al.*, 1998).

The other main variables controlling interception rates and volumes were mostly related to the characteristics of the tree itself, such as leaf area index (LAI), canopy morphology (volume, area, etc.), and bark roughness, as highlighted in 12 of the primary studies. These characteristics reflect species, see Section 4.4.

The diversion of interception to stemflow was an important factor highlighted by two studies, which aided the reduction of throughfall and thus runoff by directing water towards the base of three whereby greater infiltration was encouraged (Huang *et al.*, 2017; Carlyle-Moses and Schooling, 2015).

All secondary evidence reported similar impacts of trees on urban hydrology. Overall, 54 of the 55 primary and secondary studies highlight that trees are beneficial in hydrological terms on a variety of scales. The one study that does not, by Zabret *et al.* (2018) has a neutral conclusion, with impacts instead being controlled by meteorological conditions.

4.1.1 Robustness and consistency of evidence

Although most studies on hydrological impacts achieved maximum critical appraisal (CA) scores, there was only one study with a high monitoring/modelling (MM) score. This suggests that although the study designs were well structured, the frequency and length of monitoring and modelling periods for most studies were not as robust. Yet, of all 27 studies reporting outcomes related to runoff, there was a reduction in runoff despite differences in overall robustness. However, there is still a need to improve the length and frequency of study interventions as well as increase the number of controls used, to make a more reliable comparison on the impacts of trees on urban hydrology. Only ten primary studies had a control period (Figure 3a); 39% of primary studies had an intervention period of less than a year; and just 8% of primary studies had an intervention period longer than 2 years. In order to improve confidence in urban tree planting as a means to reduce runoff longer periods of monitoring under intervention and control periods would be beneficial.

4.2 The effects of tree arrangement

Ten studies reported differentiation in the outcomes they recorded based on tree planting arrangement, location, and techniques. One study by Scharenbroch *et al.* 2015 noted that when a tree's growth is impaired, so is its health, and thus has a lower potential to reduce runoff.

Five studies that compared tree arrangement focused on tree density. Studies such as those by Asadian and Weiler (2009) showed that isolated, individually spaced trees with open canopies performed better in terms of increasing interception losses. In addition to tree density, Song *et al*. (2020) showed through modelling of different types of urban green space (Figure 6) that replacing existing trees with ones that had a higher leaf area index (LAI) would also have a significant effect on runoff reduction. On a neighbourhood scale, Inkiläinen *et al*. (2013) highlighted differences in measured total throughfall between trees in front and back yards. The higher total throughfall was found in front yards, but this was mostly attributed to the density and type of vegetation in front yards. It was suggested the arrangement of trees and thus the reduction of runoff at this scale could be controlled by the residents themselves.

Four studies had a defined linear arrangement of trees, all of which were planted in streets. Grey *et al*. (2018b) found that with regards to street tree pits, runoff retention was also linked to the connectedness of impervious cover. Thus, an increase in tree density as well as cover enhances the benefits for urban hydrology. This is congruent with a study (Baró *et al*., 2019) on street trees in Barcelona, where the total ecosystem benefits of urban street trees within each district were closely related to their density.

To explore how best urban runoff might be best mitigated, Matteo *et al*. (2006) modelled the impacts of 10ft street trees and 200ft riparian buffers. It was found street trees performed better at reducing runoff than the riparian buffer zones in urban areas. On the other hand, riparian buffers were more efficient at reducing runoff in suburban watersheds.

Five studies focused on the impact of grouped trees, although, Song *et al*. (2020) also showed that the increased density of groups of trees in different urban settings could increase potential runoff reductions further. The study has a larger intervention area focus than most others at 33km^2 However, in terms of specific CA scoring criteria for analytical robustness, the study scored lower than 80% of other studies focused on tree arrangement. Thus, although reported outcomes have been recorded positively on a larger scale, the relatively low robustness of these findings makes for tentative evidence.

4.2.1 Robustness and consistency of evidence

The robustness (CA) of evidence found regarding the importance of tree arrangement comparisons is high (9) apart from two of the studies (6). There is some inconsistency of evidence between studies. Song *et al*. (2020) suggest that an increase in tree density will lead to further reductions in runoff, alike other studies (Inkiläinen *et al*., 2013; Baró *et al*., 2019; Grey *et al*., 2018b). However, Asadian and Weiler (2009) challenge this, suggesting that more isolated trees with open canopies and in good health will perform better.

There is a need for more in-depth qualitative studies comparing the influence of different tree arrangements on urban hydrologic regimes. There are different reported arrangements of trees within studies, but not many comparisons between different arrangements. This is important for urban planners to maximise the efficiency of tree planting and increase the overall cost-effectiveness of such schemes. Song *et al*. (2020) presented outcomes that would be beneficial for urban planners when deciding the location and arrangement of urban trees.

4.3 Corroboration of modelled effects by observations

Although there are eight urban model study designs and 18 combined studies (modelled and measured), only four analyse differences between modelled impacts with observations. No secondary studies cover modelling. Compared to other study designs, those that employed modelling were mostly focused on runoff reduction (seven studies)

Guo *et al*. (2017) reported an error rate of <5% for 12 of the models applied. Deutscher *et al*. (2019), however, reported accuracies of 66% for tree stand land cover when measuring soil moisture on a monthly scale over two years (potential error of 34%). These two studies highlight the range in accuracy (difference between modelled and measured values) of different models.

Inkiläinen *et al*. (2013) carried out sensitivity analysis to show the impact of initial canopy dryness on their model. However, their model was able to explain 94% of the variation in measured throughfall. The increase in storm magnitude also increased residuals, reflecting a decline in model performance as rainfall increased.

4.3.1 Robustness and consistency of evidence

Overall, the robustness of research into modelling the impacts of different tree species is limited. The contrasting evidence and lack of model comparison or calibration against measured impacts hinders the overall robustness of the studies. Four of the six identified studies had moderate monitoring scores, whilst two had low scores. The relatively short modelling periods hinder the overall robustness of the studies. For most of the monitoring studies there are no control periods (25 of 27 modelled and combined study designs). Also, intervention periods did not tend to last longer than two years, other than one study, whilst modelling frequencies only occurred on greater than a fortnightly temporal resolution in five out of 27 studies.

4.4 Tree species variation

Twenty-two primary studies focused on the different impacts caused by tree species. However, seven of these did not have baseline comparators to judge the overall impact of tree planting, as opposed to the benefit of one species over another. Evergreen and coniferous trees have advantages over deciduous trees in terms of runoff reduction and increased interception (Zabret and Šraj, 2015, 2019). Guo *et al*. (2017) studied the water storage ability per unit leaf area of different tree species, finding that coniferous trees outperformed both their deciduous and natural forest counterparts. The mean rainfall interception capacity (RIC) of conifers was over 1.5 times that of broadleaf deciduous trees. Xiao and McPherson (2016) attributed this to morphological factors such as surface roughness. The relative benefits of coniferous trees are only apparent in smaller magnitude storms (Liu and Chang, 2019; Zabret *et al*., 2018). In contrast, other studies have found that increases in canopy cover and plant area index (PAI) are more important at determining runoff reduction (Livesley *et al*., 2014; Inkiläinen *et al*., 2013). Increased canopy cover was also found to be better for predicting throughfall volumes than LAI, which can be an unreliable predictor of hydrological response for deciduous trees due to the unpredictable rates of fallout (Huang *et al*., 2017). Given the importance of increased canopy cover, evergreen species are especially beneficial in winter periods and this should be acknowledged to avoid biased conclusions (Xiao and McPherson, 2011).

Although species selection is important in determining impacts on urban hydrology, there is also a need for planting areas to complement the rooting system of the chosen tree (Rahman *et al*., 2019). Rahman *et al.* (2019) found *R. pseudoacacia* had a higher growth rate with finer roots which consequently increased infiltration, yet *T. cordata* was able to influence deeper percolation of water via its deeper rooting system.

Other factors influencing the maximum amount of rainfall that can be intercepted by trees are highlighted by Kuehler *et al*. (2017).They found leaf area and morphology to be significant. Those species with more rigid leaves performed better for example.

In order to achieve optimal tree growth, and thus ecosystem service performance, consideration of favourable soil type for different species is also important (Day and

Dickinson, 2008). The same authors suggest the largest trees with the best developed root systems remove the greatest volume of water from stormwater reservoirs.

4.4.1 Robustness and consistency of evidence

The size of interventionareas varied from around 25m^2 (Tirpak *et al.,* 2019) to 502km^2 (Holder and Gibbes, 2017), but this did not have a significant influence on results. Overall, although the tree species and type (coniferous or deciduous) is important, tree characteristics are more significant in determining the magnitude of impact on hydrologic regimes. Canopy morphology, leaf density, LAI, RIC, bark roughness, tree health and maturity, are all pivotal in determining the volume of runoff, interception, throughfall and stemflow. The findings of studies analysing tree species variation amongst other characteristics are relatively consistent and corroborative despite variation in robustness scores.

4.5 Synthesis of evidence statements

Evidence statements are the aggregated conclusions made by papers reviewed into categories such as ‘reduced runoff’. To indicate the reliability of the final evidence statements, an evidence statement index (ES) was created to provide a more accurate weighting of each statement based on both their critical appraisal score (CA), and monitoring/modelling score (MM). Averages for each evidence statement were calculated to provide the CA and MM scores in Table 3. The ES index was calculated by averaging these two. All hydrological outcomes were hindered by the MM scores of their respective studies. There is little variation in the ES index values of outcomes.

The most robust outcomes found were related to evapotranspiration loss and canopy interception loss. Although these outcomes are similar, they were kept separated regarding their definitions. There were 27 studies reporting reduced runoff, Although the MM scores of these hindered their overall ES index value, they provide a substantial evidence base from which to make a summary of quantified effects. In the evidence base, 14 studies report runoff reduction attributable to tree establishment as a percentage. These are comparable and from a graphical synthesis (Figure 7) it is readily apparent that establishment of trees on impermeable ground (i.e. street trees on urban roads) is highly effective at reducing runoff. The establishment of trees on a range of urban fabric comprising a mix of permeable and permeable surface provides less but still substantial benefit.

There is little conflict in terms of positive and negative outcomes. All studies reported a significant benefit from increased tree cover, yet the claims made are still tentative due to their low to moderate MM scores and thus ES index values. For more conclusive results, studies with more robust methodologies are needed.

The issues covered by the studies identified to address the primary and secondary questions are summarised to illustrate where research effort has been focused (Figure 8). Pie charts within the diagram indicate that especial attention has been made on runoff relative to other hydrological impacts, and on individual rather than groups or lines of trees. A distinction between evidence from natural and engineered planting is also apparent, as are effects of tree management and monitoring of health; both aspects are discussed below.

4.6 Other findings

In addition to the primary objectives of the REA, additional findings of a substantial and pervasive nature were apparent, these are summarised in three sections.

4.6.1 Green infrastructure and trees

The implementation of trees within green infrastructure was prevalent within the literature found, e.g. bioswales, green roofs, tree filter boxes etc. Berland *et al*. (2017) highlighted an improved performance of trees, in terms of stormwater management, when coupled with green infrastructure technologies such as bioswales. This is not a significant conclusion in other primary studies, but it does indicate potential for the integrated use of trees in urban environments. Tree performance can be hindered by lack of consideration to the planting area of the tree (Day and Dickinson, 2008; Rahman *et al*., 2019).

Increased impervious cover due to urbanisation is one of the main driving factors affecting urban hydrology and the risk of flooding. Nou and Charoenkit (2020) found that an increase in pervious cover by 44% can reduce peak runoff by 1.55 m^3s^{-1}. However, they also found that permeable pavements were the most effective form of green infrastructure at reducing total runoff. Contrastingly, Deutscher *et al*. (2019) reported that treed landcover had performed better in terms of reducing surface runoff than park lawns which had much less impervious cover. However, Armson *et al*. (2013) revealed that whilst trees in pits surrounded by asphalt were able to remove as much as 62% of runoff, grass lawns eliminated almost all runoff. The importance of increased infiltration due to the size of the pit in which the tree was planted was recognised as a significant factor affecting the reduction of runoff. The reduction of runoff measured was more than interception alone could have caused, which suggests the infrastructure in which trees are planted can be just as significant as the tree itself.

In contrast to the studies supporting the planting of trees, Zölch *et al*. (2017) show that green roofs performed better in terms of runoff reduction than when trees were used as the main intervention. This is likely due to the larger permeable surface that green roofs create (10.1%) compared to tree planting (3.9%), despite similar green cover (~15%). The differences are only small, however, with green roofs leading to 0.6% greater surface runoff reductions than tree planting.

4.6.2 Tree management and health

Grey *et al*. (2018a) found that to achieve the optimum benefits of trees, management is also important. Passive irrigation of trees with stormwater can reduce growth and even cause death of the tree. Technologies and tree planting strategies in future must focus on avoiding the waterlogging of tree pits.

Some studies have highlighted the importance of management in terms of the medium in which trees are planted and the opportunity for successful growth. Nielsen *et al*. (2007) reported increased tree growth in urban parks compared to non-irrigated street trees. Grey *et al*. (2018a) showed that tree health can also be improved by the addition of an underdrain in the tree pit technology. In addition, Rahman *et al*. (2019) specified that pits in which trees are planted must be designed to complement the species of tree. Some have greater rooting zones which can be confined by the size of the pit, with health and function deteriorating as a result. Grey *et al*. (2018b) reported that increased tree pit area and density as opposed to tree density would also have a significant impact on runoff reduction. By increasing the tree pit area to catchment ratio to 4.4%, a 90% reduction in runoff could be achieved.

When choosing tree species for bioswale planting considerations should be made regarding the rate of stomatal conductance and the total leaf area (size) at maturity, and in addition, the health and condition of the trees is of key importance (Scharenbroch *et al.*,2015)). Despite this, Asadian and Weiler (2009) showed that in some cases whilst healthier tree species do capture a greater proportion of rainfall, trees in poor condition may still intercept more than others. The evidence on the extent to which tree health can impact catchment hydrology is robust but conflicting. Evidence regarding other ecosystem services, such as carbon sequestration, has found that larger and more mature trees perform better (Turner-Skoff and Cavender, 2019), but this difference has not arisen clearly in the evidence found by this REA. Some characteristics such as canopy size and density are related to tree maturity, but very few studies have explicitly stated maturity as a significant variable. Trees take time to mature and provide greater ecosystem services. This is something that needs to be addressed in further research if trees are to be used effectively.

4.6.3 Other quality indicators

Although this study focused primarily on the impacts of trees on hydrology, there were studies that had other foci too. Examples include Soares *et al*. (2011) who calculated that the reduction of runoff caused by street trees in Lisbon led to greater savings ($1.97m) than that of energy saving and improved air quality. Over a 35-year period, McPherson *et al*. (2011) estimated that the one million trees project would reduce runoff by 51-80 million m^3, which was valued at $97-153m. Trees can provide directly measurable economic benefits as well as environmental ones. Baró *et al.* (2019) also measured the beneficial effects of trees on temperature and air pollution. Alike their noted impacts on runoff reduction, the total ecosystem value provided by these trees was mostly correlated to the density of trees within each district. Unsurprisingly, review studies also had multi-disciplinary foci. Roy *et al*. (2012) reported a wide range of other impacts, observing positive effects of trees in terms of social issues, economic benefits, health improvements, enhanced aesthetics, reduced noise pollution, mitigation of heat island effects, reduced energy use and better air quality.

5 Conclusions and recommendations

This rapid evidence assessment (REA) has been undertaken to establish the robustness of evidence available supporting whether the implementation of urban forestry has beneficial impacts on hydrology and what those impacts are. More specifically, we identified whether evidence explicitly related to NBS implementation, such as bioswales, green roofs and tree filter boxes. The evidence statements (Table 3) have been weighted based on scores for each individual paper. The scores themselves constituted an aggregate of criteria based on relevance, robustness, and rigour of monitoring/modelling. Consistent beneficial impacts were found at local level, with trees reducing runoff and increasing infiltration.

The REA has identified shortcomings regarding the robustness of studies, but there is potential for bias within the methodology, excluding recent research for example. The overall lack of grey and unpublished literature that passed the full-text screening was due to the lack of reference to primary data, which was part of the inclusion/exclusion criteria.

The presence of controls/comparators and intervention to catchment area ratio were important factors to consider. Without a control, or a baseline, conclusions on the effectiveness of trees for stormwater management are limited. Only ten primary studies incorporated a control period, although 39 of 49 studies did have valuable comparator (e.g. increase in tree cover). Furthermore, very few studies reported the size of intervention area and/or catchment areas, and there was thus a lack of contextualisation to the results found. There was little evidence of larger scale effects of trees on hydrology, a finding consistent with previous research on flooding impacts (e.g. Stratford *et al*., 2016). Only a minority of studies identified effects in water bodies, but trees may still be beneficial to urban environments at a more local scale. Additionally, studies found that trees were effective at mitigating a vast amount of runoff in smaller storms but less effective in larger scale storms. Regarding methodological robustness (MM scores), studies were rarely of sufficient length to identify long-term temporal variations. In order to account for these, interventions must be monitored more frequently and over a longer timescale. Infrequent monitoring cannot capture potentially significant short-term fluctuations.

Studies based on modelling approaches rarely reported any model testing against observations. Although some studies *did* report model performance, a general lack of testing suggests that modelling studies might not be robust enough to make conclusive remarks on their findings. As with monitoring studies, there is a lack both of control periods and sufficiently extended intervention periods for such studies. There is need for further primary observational research on the wider scale of these impacts in order to apply models confidently in potentially valuable situations comprising relatively large intervention/catchment areas.

The location and arrangement in which urban trees are planted was also found to be inconclusive in terms of how best to maximise the benefits of trees. There is need for more studies implementing both linear and grouped trees, for example, as much existing research focuses on individually spaced trees. In urban landscapes there is often limited potential for tree planting due to the vast inter-connected impervious cover and so evidence regarding the optimal arrangement or spacing at which trees should be planted to achieve the desired ecosystem functions (e.g. runoff reduction) would be invaluable. Most studies referenced tree density as one of the most important factors determining the level of benefits they provide.

Of the secondary questions investigated, tree species was the most comprehensively researched. Species has not been found to have a significant impact in the variation of outcomes observed although in broader terms some studies favoured evergreen trees over deciduous. There was little impact between tree species during larger storm events; instead, rainfall interception capacity of each tree appeared a controlling factor of runoff volume. It could be beneficial to compare the impacts of tree characteristics to meteorological influences on outcomes such as interception rates, for example. In terms of mitigating Urban Heat Island effects, the size and maturity of trees is pivotal, and this aspect should be further investigated in terms of hydrological impacts for which there is only indirect evidence.

Acknowledgements

The authors wish to thank Kevin Clemitshaw for his constructive criticisms during the supervision of Henry Baker's MSc thesis which has helped shape the critical nature of this study. Mike Hutchins and James Miller acknowledge funding from UK ESRC and European Union, which respectively cover the DeSCIPHER (co-ordinated by JPI Urban Europe and NSFC) and REGREEN (EU Horizon 2020) projects investigating urban Nature Based Solutions.

References

Armson, D., Stringer, P. and Ennos, A.R., 2013. The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. *Urban Forestry and Urban Greening*, 12 (3), 282–286.

Asadian, Y. and Weiler, M., 2009. A New Approach in Measuring Rainfall Interception by Urban Trees in Coastal British Columbia. *Water Quality Research Journal of Canada*, 44 (1), 16–25.

Baró, F., Calderón-Argelich, A., Langemeyer, J. and Connolly, J.J.T., 2019. Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona. *Environmental Science and Policy*, 102, 54–64.

Bartens, J., Day, S.D., Harris, J.R., Dove, J.E. and Wynn, T.M., 2008. Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management? *Journal of Environmental Quality*, 37 (6), 2048–2057.

Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Herrmann, D.L. and Hopton, M.E., 2017. The role of trees in urban stormwater management. *Landscape and Urban Planning* [online], 162, 167–177. Available from: https://dx.doi.org/10.1016/j.landurbplan.2017.02.017

Carlyle-Moses, D.E. and Schooling, J.T., 2015. Tree traits and meteorological factors influencing the initiation and rate of stemflow from isolated deciduous trees. *Hydrological Processes*, 29 (18), 4083–4099.

Center for Watershed Protection, 2017. *Review of the Available Literature and Data on the Runoff and Pollutant Removal Capabilities of Urban Trees* [online]. Center for Watershed Protection, Ellicott City, MD. Available from: https://owl.cwp.org/?mdocs-file=9300 (Accessed 12 August 2020)

Collins, A.M., Coughlin, D., Miller, J., and Kirk, S., 2015. *The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide.* [online] Available from: http://nora.nerc.ac.uk/id/eprint/512448/ (Accessed: 16 August 2020)

Day, S.D. and Dickinson, S.B., 2008. Managing stormwater for urban sustainability using trees and structural soils. *Virginia Polytechnic Institute and State University, Blacksburg, VA*, 1-33.

Deutscher, J., Kupec, P., Kučera, A., Urban, J., Ledesma, J.L.J. and Futter, M., 2019. Ecohydrological consequences of tree removal in an urban park evaluated using open data, free software and a minimalist measuring campaign. *The Science of The Total Environment*, 655, 1495–1504. Available from: https://dx.doi.org/10.1016/j.scitotenv.2018.11.277

Frosi, M.H., Kargar, M., Jutras, P., Prasher, S.O. and Clark, O.G., 2019. Street Tree Pits as Bioretention Units: Effects of Soil Organic Matter and Area Permeability on the Volume and Quality of Urban Runoff. *Water Air and Soil Pollution*, 230 (7), 152. Available from: https://doi.org/10.1007/s11270-019-4197-7

Gough, D.A., Oliver, S. and Thomas, J., 2013. *Learning from research: systematic reviews for informing policy decisions: a quick guide*. London: Nesta. Available from: https://www.alliance4usefulevidence.org/assets/Learning-from-research.pdf

GreenBlue Urban, 2015. *The Importance of Urban Trees in Stormwater Management*. Available from: https://greenblue.com/gb/the-importance-of-urban-trees-in-stormwater-management/ (Accessed: 12 August 2020)

Grey, V., Livesley, S.J., Fletcher, T.D. and Szota, C., 2018a. Establishing street trees in stormwater control measures can double tree growth when extended waterlogging is avoided. *Landscape and Urban Planning*, 178, 122–129. Available from: https://dx.doi.org/10.1016/j.landurbplan.2018.06.002

Grey, V., Livesley, S.J., Fletcher, T.D. and Szota, C., 2018b. Tree pits to help mitigate runoff in dense urban areas. *Journal of Hydrology*, 565, 400–410.

Guevara-Escobar, A., González-Sosa, E., Véliz-Chávez, C., Ventura-Ramos, E. and Ramos-Salinas, M., 2007. Rainfall interception and distribution patterns of gross precipitation around an isolated Ficus benjamina tree in an urban area. *Journal of Hydrology*, 333 (2-4), 532–541.

Guo, J., Yu, B., Zhang, Y. and Che, S., 2017. Predicted models for potential canopy rainfall interception capacity of landscape trees in Shanghai, China. *European Journal of Forest Research*, 136 (3), 387–400.

Haddaway, N.R., Collins, A.M., Coughlin, D. and Kirk, S., 2015. The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *PloS one* [online], 10 (9), . Available from: https://doi.org/10.1371/journal.pone.0138237

Holder, C.D. and Gibbes, C., 2017. Influence of leaf and canopy characteristics on rainfall interception and urban hydrology. *Hydrological Sciences Journal*, 62 (2), 182–190.

Huang, J.Y., Black, T.A., Jassal, R.S. and Lavkulich, L.L., 2017. Modelling rainfall interception by urban trees. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, 42 (4), 336-348.

Hurlimann A., Wilson E., and Keele S., 2017. Framing Sustainable Urban Water Management: A Critical Analysis of Theory and Practice. *In*: Bell S., Allen A., Hofmann P., Teh TH., eds. Urban Water Trajectories. Future City, vol 6. Springer, Cham. Available at: https://doi.org/10.1007/978-3-319-42686-0_4

Inkiläinen, E.N.M., Mchale, M.R., Blank, G.B., James, A.L. and Nikinmaa, E., 2013. The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA. *Landscape and Urban Planning*, 119, 91–103.

Isaifan, R. and Baldauf, R., 2020. Estimating economic and environmental benefits of urban trees in desert regions. *Frontiers in Ecology and Evolution* [online], 8 (16), 1-14. Available from: https://doi.org/10.3389/fevo.2020.00016

Kim, G. & Coseo, P., 2018. Urban Park Systems to Support Sustainability: The Role of Urban Park Systems in Hot Arid Urban Climates. *Forests* [online], 9 (7), 439. Available from: https://dx.doi.org/10.3390/f9070439

Kim, J., Lee, J., Song, Y., Han, H. & Joo, J., 2018. Modelling the Runoff Reduction Effect of Low Impact Development Installations in an Industrial Area, South Korea. *Water* [online], 10 (8), 967. Available from: <https://doi.org/10.3390/w10080967>

Kuehler, E., Hathaway, J. and Tirpak, A., 2017. Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network. *Ecohydrology* [online], 10 (3). Available from: https://doi.org/10.1002/eco.1813

Liu, X. and Chang, Q., 2018, September. The Rainfall Interception Performance of Urban Tree Canopy in Beijing, China. *International Conference on Urban Drainage Modelling.* . Springer, Cham, (46-51)

Livesley, S.J., Baudinette, B. and Glover, D., 2014. Rainfall interception and stem flow by eucalypt street trees – The impacts of canopy density and bark type. *Urban Forestry and Urban Greening*, 13 (1), 192–197.

Livesley, S.J., Mcpherson, E.G. and Calfapietra, C., 2016. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environmental Quality* [online], 45 (1), 119–124. Available from: https://dx.doi.org/10.2134/jeq2015.11.0567

Maniquiz-Redillas, M.C. and Kim, L.H., 2016. Evaluation of the capability of low-impact development practices for the removal of heavy metal from urban stormwater runoff. *Environmental Technology*, 37 (18), 2265–2272.

Matteo, M., Randhir, T. and Bloniarz, D., 2006. Watershed-scale impacts of forest buffers on water quality and runoff in urbanizing environment. *Journal of Water Resources Planning and Management*, 132 (3), 144-152.

McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal* [online], 61 (13), 2295–2311. Available from: https://dx.doi.org/10.1080/02626667.2015.1128084

McPherson, E.G., Simpson, J.R., Xiao, Q. & Wu, C., 2011. Million trees Los Angeles canopy cover and benefit assessment. *Landscape and Urban Planning*, 99 (1), 40–50.

Miller, J.D. and Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology Regional Studies* [online], 12, 345–362. Available from: https://dx.doi.org/10.1016/j.ejrh.2017.06.006

Miller, J.D., Kim, H., Kjeldsen, T.R., Packman, J., Grebby, S. and Dearden, R., 2014. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology* [online], 515, 59–70. Available from: https://dx.doi.org/10.1016/j.jhydrol.2014.04.011

Nielsen, C.N., Bühler, O. and Kristoffersen, P., 2007. Soil water dynamics and growth of street and park trees. *Arboriculture and Urban Forestry* [online], 33 (4), 231-245.

Nou, C., and Charoenkit, S., 2020. The Potential of Green Infrastructure (GI) for Reducing Stormwater Runoff in a Phnom Penh Neighborhood. *Geographia Technica*, 10 (1), 112-123.

Rahman, M.A., Moser, A., Anderson, M., Zhang, C., Rötzer, T. and Pauleit, S., 2019. Comparing the infiltration potentials of soils beneath the canopies of two contrasting urban tree species. *Urban Forestry and Urban Greening*, 38, 22–32.

Revelli, R. and Porporato, A., 2018. Ecohydrological model for the quantification of ecosystem services provided by urban street trees. *Urban Ecosystems* [online], 21 (3), 489–504. Available from: https://dx.doi.org/10.1007/s11252-018-0741-2

Romano, O. and Akhmouch, A., 2019. Water Governance in Cities: Current Trends and Future Challenges. *Water* [online], 11 (3), p.500. Available from: https://dx.doi.org/10.3390/w11030500

Roy, S., Byrne, J. & Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban Forestry & Urban Greening*, 11 (4), 351–363.

Scharenbroch, B.C., Morgenroth, J. and Maule, B., 2016. Tree Species Suitability to Bioswales and Impact on the Urban Water Budget. *Journal of Environmental Quality*, 45 (1), 199–206.

Shepherd, J.M., Pierce, H. and Negri, A.J., 2002. Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *Journal of applied meteorology*, 41 (7), 689-701.

Soares, A.L., Rego, F.C., Mcpherson, E.G., Simpson, J.R., Peper, P.J. and Xiao, Q.. 2011. Benefits and costs of street trees in Lisbon, Portugal. *Urban Forestry and Urban Greening* [online], 10 (2), 69–78. Available from: https://dx.doi.org/10.1016/j.ufug.2010.12.001

Song, P., Kim, G., Mayer, A., He, R. and Tian, G., 2020. Assessing the Ecosystem Services of Various Types of Urban Green Spaces Based on i-Tree Eco. *Sustainability* [online], *12*(4), . Available from: https://doi.org/10.3390/su12041630

Stratford, C., Miller, J., House, A., Old, G., Acreman, M., Dueñas-Lopez, M.A., Nisbet, T., Newman, J., Burgess-Gamble, L., Chappell, N. and Clarke, S., 2017. *Do trees in UK-relevant river catchments influence fluvial flood peaks* [online]. Wallingford, UK: Environment Agency and Forest Research. Available from: http://nora. nerc. ac. uk/id/eprint/517804/7/N517804CR. pdf.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G. and Gaston, K.J., 2007. Urban form, biodiversity potential and ecosystem services. *Landscape and Urban Planning*, 83 (4), 308–317.

Tirpak, R.A., Hathaway, J.M., Franklin, J.A. & Kuehler, E., 2019. Suspended pavement systems as opportunities for subsurface bioretention. *Ecological Engineering*, 134, 39–46.

United Nations Educational, Scientific and Cultural Organisation, 2019. *Urban Water Management Programme (UWMP)* [online]. Available at: https://en.unesco.org/uwmp (Accessed 6 March 2020).

Wang, J., Endreny, T.A. and Nowak, D.J., 2008. Mechanistic Simulation of Tree Effects in an Urban Water Balance Model1. *JAWRA Journal of the American Water Resources Association*, 44 (1), 75–85.

Warhurst, J.R., Parks, K.E., McCulloch, L. and Hudson, M.D., 2014. Front gardens to car parks: changes in garden permeability and effects on flood regulation. *Science of the Total Environment*, 485, 329-339.

Xiao, Q. and McPherson, E.G., 2011. Rainfall interception of three trees in Oakland, California. *Urban Ecosystems*, 14 (4), 755–769.

Xiao, Q. and McPherson, E.G., 2016. Surface water storage capacity of twenty tree species in Davis, California. *Journal of environmental quality*, 45 (1), 188-198.

Xiao, Q., McPherson, E.G., Simpson, J.R., and Ustin, L., 1998. Rainfall Interception by Sacramento's Urban Forest. *Journal of Arboriculture*, 24 (4), 235-244.

Xiao, Q., McPherson, E.G., Ustin, S.L., Grismer, M.E. and Simpson, J.R., 2000. Winter rainfall interception by two mature open-grown trees in Davis, California. *Hydrological processes*, 14 (4), 763-784.

Yao, L., Chen, L., Wei, W. & Sun, R., 2015. Potential reduction in urban runoff by green spaces in Beijing: A scenario analysis. *Urban Forestry & Urban Greening* [online], 14 (2), 300–308. Available from: https://dx.doi.org/10.1016/j.ufug.2015.02.014

Zabret, K. and Šraj, M., 2015. Can urban trees reduce the impact of climate change on storm runoff? *Urbani izziv*, 26, 165-178.

Zabret, K. and Šraj, M., 2019. Rainfall Interception by Urban Trees and Their Impact on Potential Surface Runoff. *CLEAN - Soil Air Water* [online], 47 (8)] Available from: https://doi.org/10.1002/clen.201800327

Zabret, K., Rakovec, J. and Šraj, M., 2018. Influence of meteorological variables on rainfall partitioning for deciduous and coniferous tree species in urban area. *Journal of Hydrology*, 558, 29–41.

Zölch, T., Henze, L., Keilholz, P. and Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions – An assessment at the micro-scale. *Environmental Research*, 157, 135–144.

Tables

Table 1: PICO elements to be used in the basis of search strings (adapted from Collins et al., 2015) with keywords and search strings highlighted for each.

Search topic	**Keywords**
Population *(the subject of study, i.e. surface waters)*	Urban, cities, towns, water body, streams, groundwater, lake, river
Intervention *(the proposed management technique)*	Tree, planting, arrangement, canopy, green-blue infrastructure,
Comparator *(control or difference in tree cover)*	No trees, absence, other vegetation, imperviousness
Outcome *(the effects observed as a result of the intervention)*	Hydrology, runoff, drainage, interception, infiltration, flooding
	Search string
Population	TS=(urban* OR cit* OR town*)
Intervention	TS=((tree*) AND “green infrastructure” OR “green space” OR “nature based solution*” OR NBS or “low-impact development” OR LID)
Outcome	TS=(hydrol* OR flood* OR runoff OR flow OR regime)

Table 2: Total hits and irrelevant evidence at each stage of screening. These results are based on searches made on 4th June 2020. The original search results (pre-screening) included studies related to water quality (using another separate outcome search) but these were later removed for the purpose of this study – screening values represent only hydrology related studies. Relevant results are not cumulative but represent the number of studies deemed relevant at that stage of screening.

Search engine	**Screening category**	**Irrelevant**	**Uncertain**	**Relevant**
Web of Science	Pre-screening	-	**1,142**	**0**
	1st Title	689	**423**	**25**
	2nd Abstract	397	**0**	**43**
	3rd Full-text	21	**0**	**26**
Google Scholar	Pre-screening	-	**200**	**-**
	1st Title	Unbiased screening limited by text preview		
	2nd Abstract	26	**-**	**36**
	3rd Full-text	8	**-**	**31**

Table 3: ES index values for hydrology outcomes found from evidence based on their mean CA and mean MM scores. Cell colours red (poor, <4), yellow (moderate, >4 and <7), and green (good, >7) indicate score categories for CA score, MM score, and ES Index.

Hydrological Outcomes	**CA score**	**MM score**	**ES Index**
Reduced runoff	7.4	3.0	5.20
Increased interception	7.8	3.2	5.50
Stemflow to reduce throughfall and runoff	9.0	3.0	6.00
Stormwater affecting tree health	6.0	6.0	6.00
Meteorological controls	8.3	4.0	6.20
Increased infiltration	9.0	4.2	6.60
Canopy interception loss	9.0	4.3	6.70
Evapotranspiration loss	9.0	4.4	6.70

Figure captions

Figure 1: The number of study types categorised as quantitative experimental (QE), quantitative observational (QO), and review (R) split into their study designs.

Figure 2: a) The different categories of population found in the evidence database, which have been plotted running clockwise from the top. Total number of populations are above 64 as some studies have more than one population; b) The geographical location of each piece of evidence categorised by region with those focusing on multiple locations being classed as ‘multiple’. Those pieces of evidence with multiple foci within one region were categorised by the appropriate region and not ‘multiple’.; c) Distribution of the arrangement of trees within primary studies found in database searches. Those part of a green infrastructure technology were reported as their configuration within that technology.

Figure 3a) The length of modelling/monitoring intervention periods categorised by the monitoring frequency; b) The length of modelling/monitoring control periods categorised by the length of their intervention periods.

Figure 4a): Number of studies achieving different critical appraisal scores from both primary and secondary evidence. Unachievable scores and scores with a study count have been removed from the score axis; b): The monitoring/modelling scores and the number of studies that achieved each score. Both Figure 4a and 4b categorised as green: high; yellow: moderate; and red: low. Please note: both graphs have been plotted with categories running clockwise from the top.

Figure 5: Study counts of the outcomes found in studies based on hydrology. There are more than 49 reported outcomes as some studies reported more than one. Outcomes are coded by colour. Green: positive impact on hydrology. Blue: neutral impact or not applicable. Canopy interception loss involves evapotranspiration partly but was categorised differently as it involves both canopy storage via interception too (Van Stan II et al., 2015).

Figure 6: Samples of urban green spaces in Luohe, taken from Song et al. (2020): a) public park; b) protective green space; c) square green space; d) attached green space.

Figure 7: Effectiveness of urban tree planting on runoff reduction differentiated by the substrate on which they were planted. Data is based on all primary studies reporting reduced runoff as an 'outcome' which also make the substrate in which trees are planted clear.

Figure 8: Map of evidence covered in terms of tree characteristics and hydrological response. The quantitative breakdown in the pie charts into types of hydrological impact and tree arrangement is based on aggregated ES scores of the relevant studies. Substantial attention on factors related to substrate and physiography was also apparent, but by their inherent nature the studies could not be readily categorised for a similar quantification to be appropriate or meaningful.

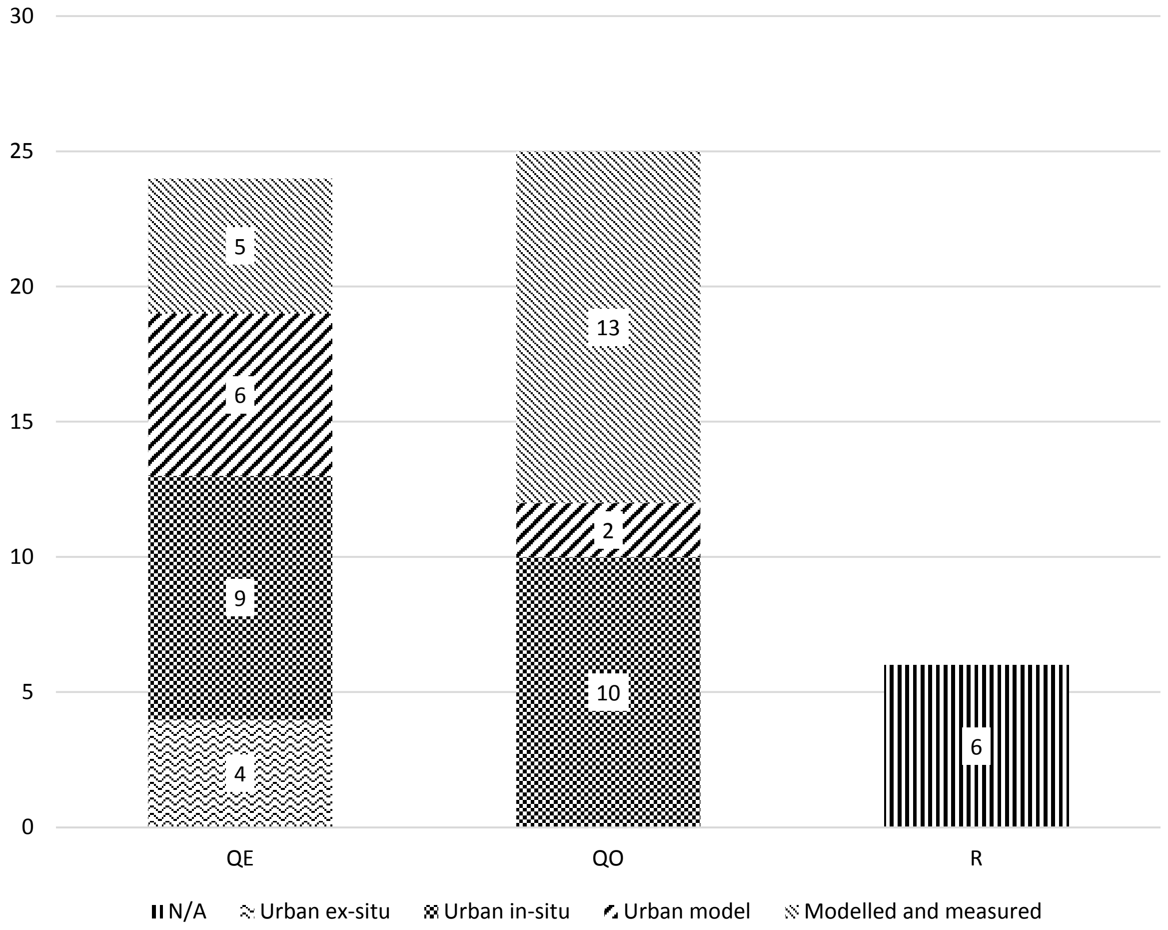

30
25
20
15
10
5
0
5
6
9
4
13
2
10
6
QE
QO
R
N/A
Urban ex-situ
Urban in-situ
Urban model
Modelled and measured

Figure 1

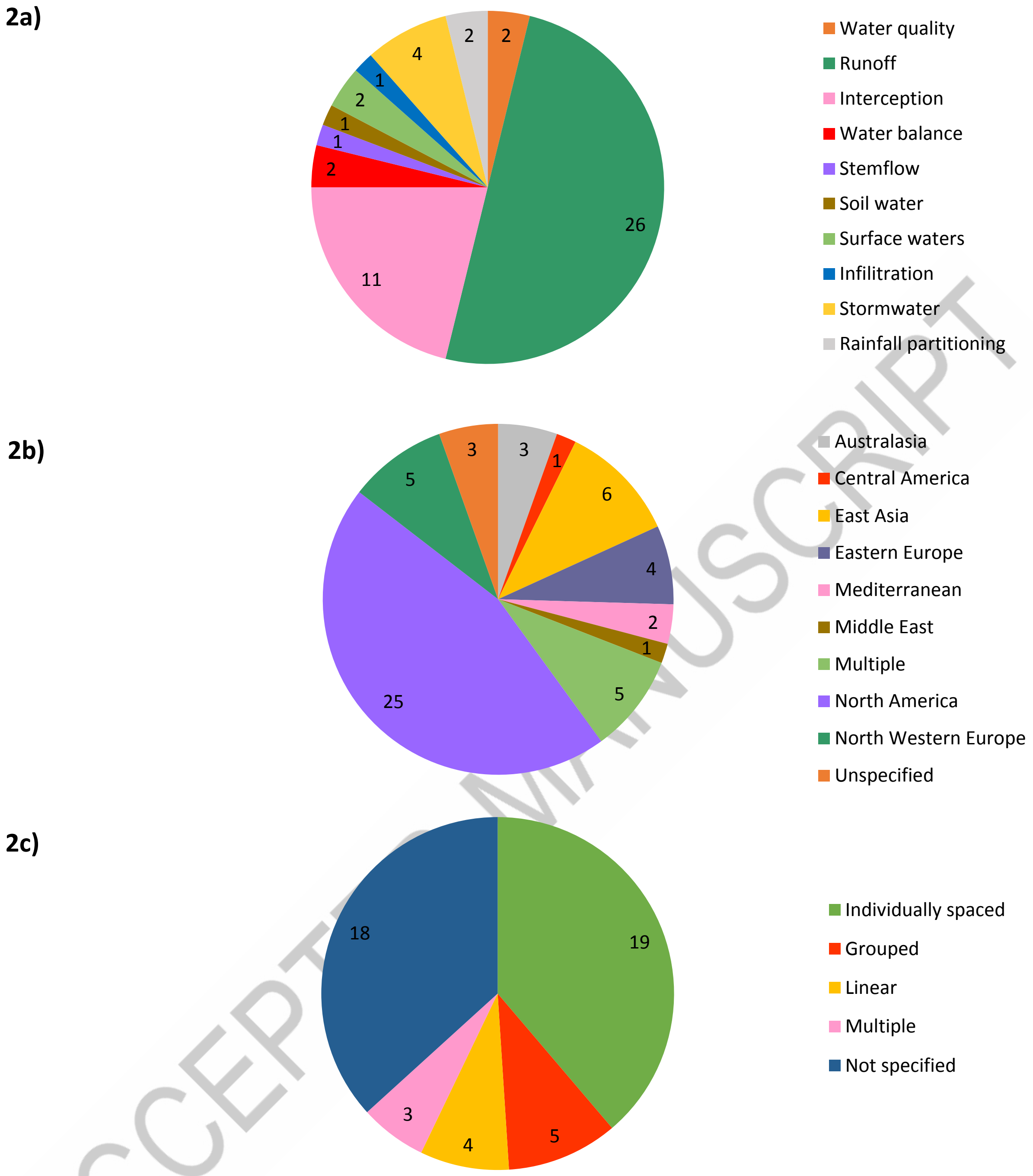
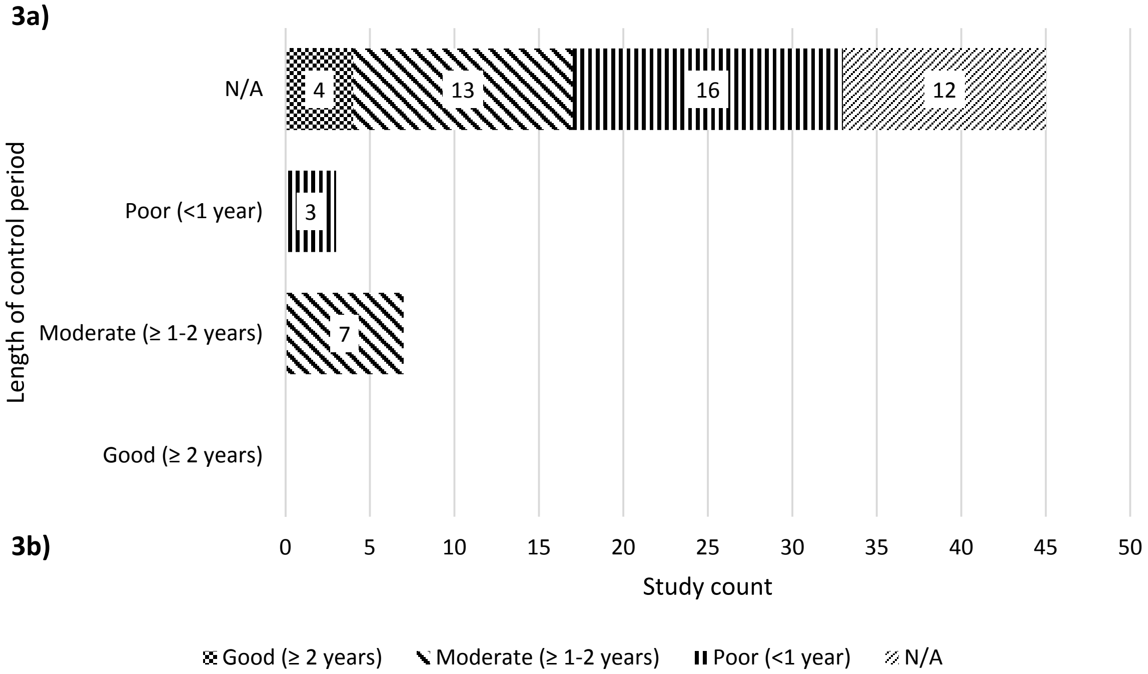

2a)
2
2
4
1
2
1
1
2
26
11
Water quality
Runoff
Interception
Water balance
Stemflow
Soil water
Surface waters
Infiltration
Stormwater
Rainfall partitioning
2b)
3
3
1
6
5
4
2
1
5
25
Australasia
Central America
East Asia
Eastern Europe
Mediterranean
Middle East
Multiple
North America
North Western Europe
Unspecified
2c)
18
19
3
4
5
Individually spaced
Grouped
Linear
Multiple
Not specified

Figure 2

3a)



3b)

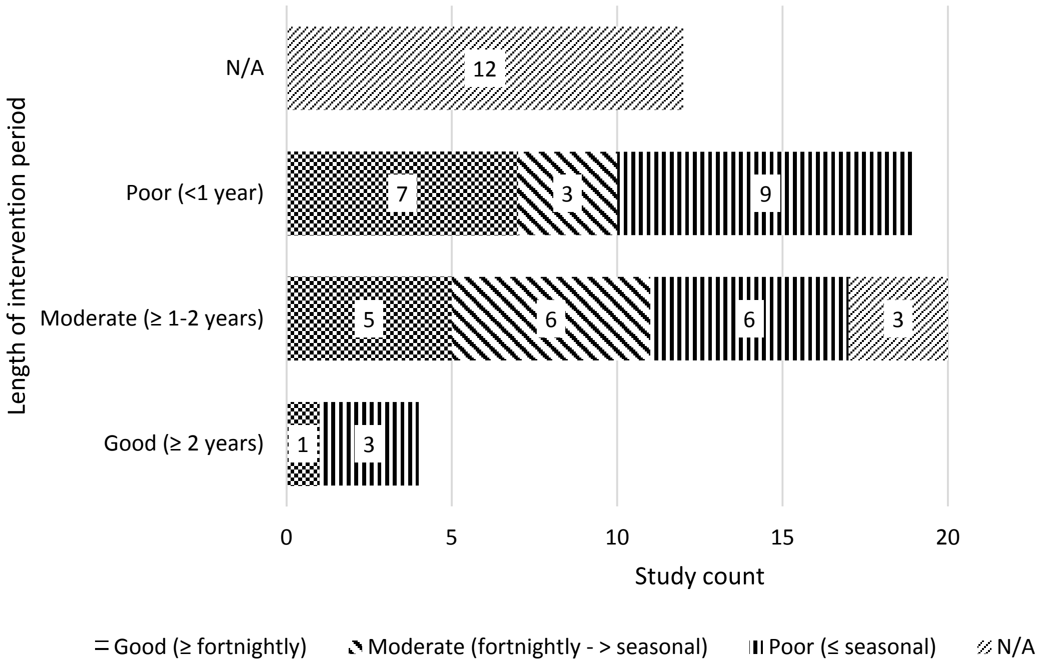


Figure 3

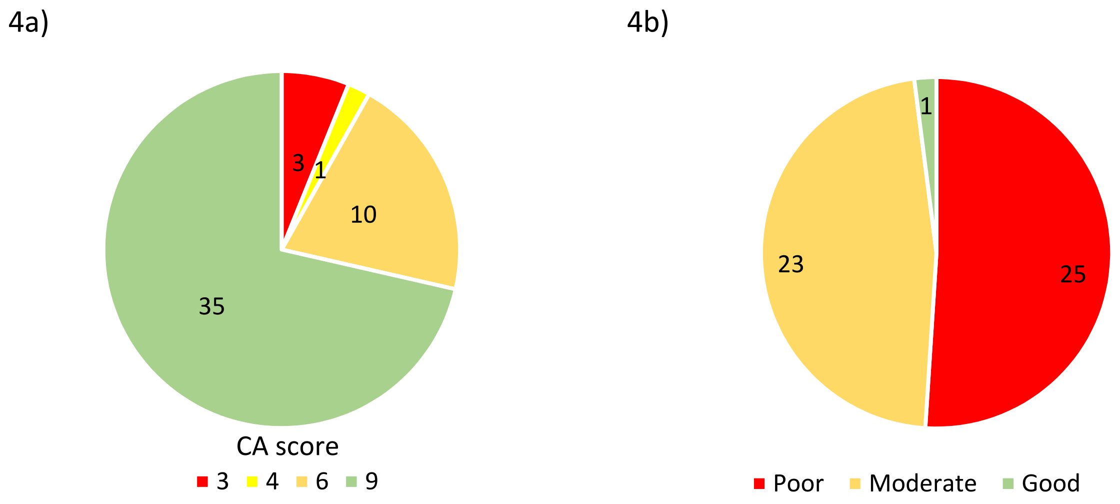


Figure 4

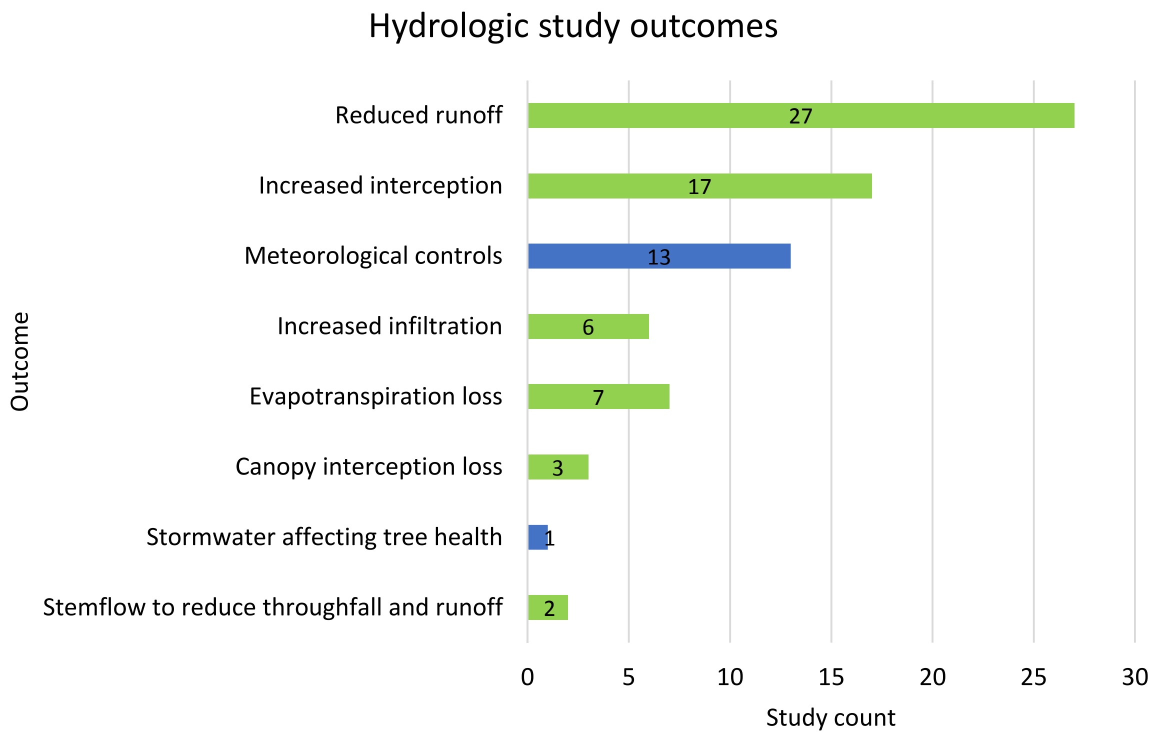

Hydrologic study outcomes
Outcome
Reduced runoff
Increased interception
Meteorological controls
Increased infiltration
Evapotranspiration loss
Canopy interception loss
Stormwater affecting tree health
Stemflow to reduce throughfall and runoff
27
17
13
6
7
3
1
2
0
5
10
15
20
25
30
Study count

Figure 5

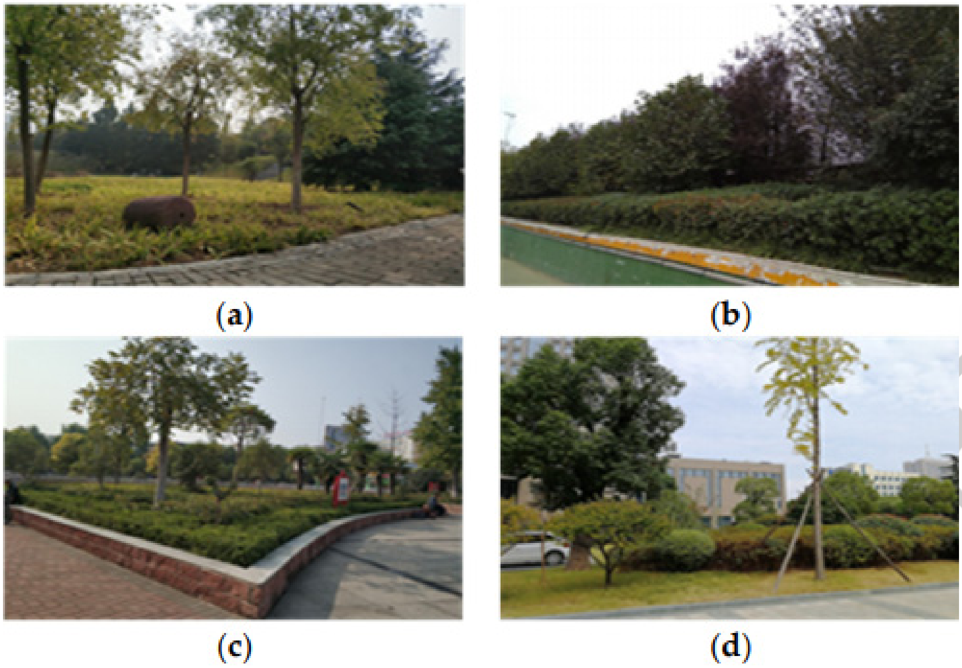
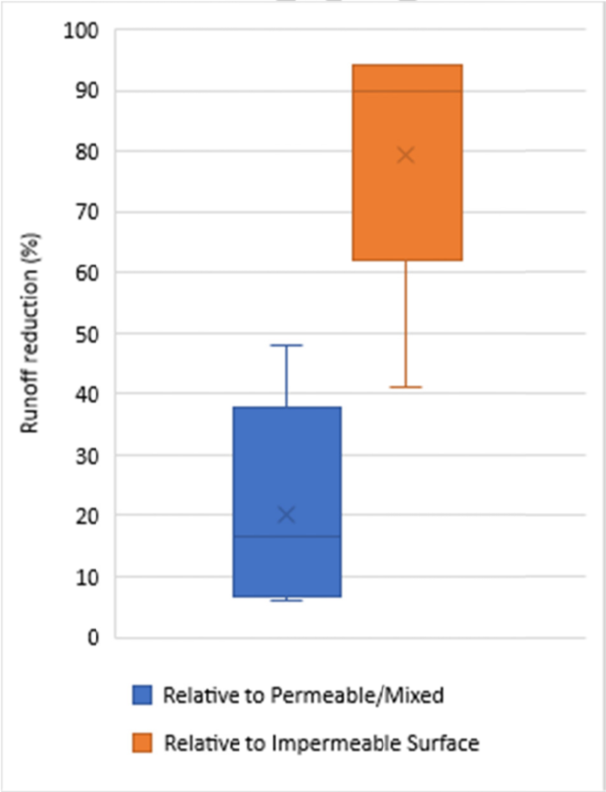


Figure 6



Average ES index: 6.57

n=7

Average ES index: 5.79

n=7

Figure 7

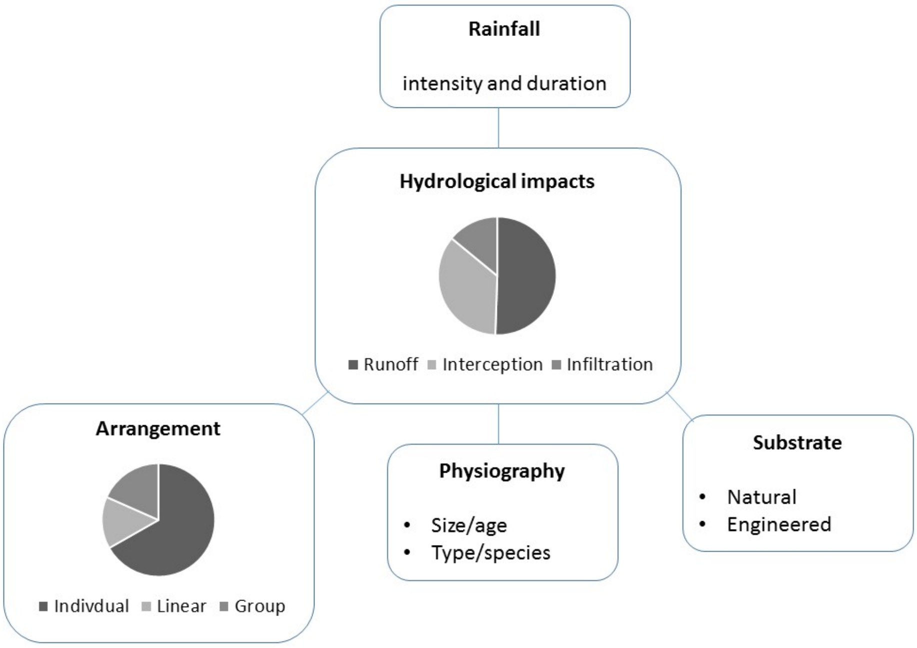


Figure 8

Appendix A1 - Screening criteria

- Study was based in urban areas or related to urbanisation
- Hydrological impacts must be based in urban areas or downstream from the urban population
- The impacts of trees or tree planting outside of urban areas were included, if the study is being used to model the impacts of urban trees
- Studies based on the impacts of urbanisation on hydrology without trees was included
- If trees were used as part of a nature-based solution or green infrastructure technology, they were included

Appendix A2 – Database categories

1. Evidence type: peer-reviewed or grey literature
2. Study type: quantitative experimental, quantitative observational or review (as defined by Collins *et al*., 2015)
3. Study design
    a. Urban *in-situ*: trees in the study were already planted, e.g. trees within an urban area, or were planted in an urban area as part of the study.
    b. Urban *ex-situ*: trees planted outside of urban areas for experimental purposes, in greenhouses for example, or individual study plots
    c. Urban model: trees that have not been physically planted; their existence is modelled
    d. Modelled and measured: trees that have been planted and modelled
    e. N/A: the study design has not been mentioned or is not applicable, i.e. for reviews.
4. The population studied, e.g. stormwater runoff
5. The geographical location or context, e.g. the location of observational study or the location of experimental study
6. Tree type, i.e. the species being studied
    a. If evidence monitored more than five species of trees, the species were classed as 'mixed'
7. Tree configuration, i.e. the planting arrangement (e.g. linear or grouped)
    a. If trees were used as part of a green infrastructure intervention, the configuration was categorised based on the trees' arrangement within the intervention used, i.e. singular trees within bioretention pits were classed as 'individually spaced'
8. Evidence of riparian planting
9. Details of hydrology impacts, e.g. reduced stormwater runoff
    a. For hydrological impacts, the location in which the outcomes are observed will also be noted where reported (i.e. adjacent to tree, or downstream)
10. The impact category, i.e. reduced runoff, increased interception, etc.
11. Length of monitoring/monitoring under control and intervention conditions

    a. High (≥ 2 years)
    b. Moderate (≥1 – 2 years)
    c. Low (<1 year)
    d. N/A (the evidence does not have a control, or does not report it)

12. Monitoring frequency
    a. High (≥ fortnightly)
    b. Moderate (fortnightly - > seasonal)
    c. Low (≤ seasonal)
    d. N/A (there is no monitoring)
13. Evidence for answering secondary questions, e.g. differentiation of impacts between tree species, differences in tree arrangement or location of planting, and a comparison of measured against modelled impacts.
14. Comparator presence, i.e. was the impact of trees compared to anything, e.g. a control, or mentioning differences between higher or lower tree cover

Appendix A3 – Robustness scoring criteria

Table A3: The criteria for evidence when assigning robustness scores for the categories of general, methodology, and analysis. Some of these have been adapted from those highlighted in Collins et al. (2015). For all studies, both general criteria had to be fulfilled to pass. For QE and QO studies, three out of four methodology and analysis criteria had to be fulfilled to pass. As for R studies, two out of three criteria for methodology and analysis had to be fulfilled to pass.

Study type	**General**	**Methodology**	**Analysis**
Quantitative Experimental (QE)	Are questions addressed clearly identified? Related research clearly identifiable?	Sample population representative of population in study? Are interventions well described? Control group? Interventions representative in context of evidence statement?	Analytical methods? Magnitude of effects? Precision (confidence/p-values)? Multiple explanatory variables?
Quantitative Observational (QO)		Sample population representative of population in study? Exposure and control group? Limiting factors controlled? Reliable outcomes?	
Review (R)		Search strategy outlined? Minimised publication bias? Rationale for study inclusion?	Does synthesis minimise bias? Do conclusions relate to the evidence found?

Appendix B1 – Final list of studies

Table B1: Studies that passed the final, full-text screening to be evaluated in the results and discussion.

Title	Author	Year
The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK	Armson, D; Stringer, P; Ennos, AR;	2013
A new approach in measuring rainfall interception by urban trees in coastal British Columbia	Asadian, Yeganeh; Weiler, Markus;	2009
Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona	Baro, F; Calderon-Argelich, A; Langemeyer, J; Connolly, JJT	2019
Can urban tree roots improve infiltration through compacted subsoils for stormwater management?	Bartens, Julia; Day, Susan D; Harris, J Roger; Dove, Joseph E; Wynn, Theresa M;	2008
Transpiration and root development of urban trees in structural soil stormwater reservoirs	Bartens, Julia; Day, Susan D; Harris, J Roger; Wynn, Theresa M; Dove, Joseph E;	2009
The role of trees in urban stormwater management	Berland, A; Shiflett, SA; Shuster, WD; Garmestani, AS; Goddard, HC; Herrmann, DL; Hopton, ME	2017
Tree traits and meteorological factors influencing the initiation and rate of stemflow from isolated deciduous trees	Carlyle-Moses, DE; Schooling, JT;	2015
Managing stormwater for urban sustainability using trees and structural soils	Day, Susan Downing; Dickinson, Sarah B;	2008
Ecohydrological consequences of tree removal in an urban park evaluated using open data, free software and a minimalist measuring campaign	Deutscher, J; Kupec, P; Kucera, A; Urban, J; Ledesma, JLJ; Futter, M	2019
Street Tree Pits as Bioretention Units: Effects of Soil Organic Matter and Area Permeability on the Volume and Quality of Urban Runoff	Frosi, MH; Kargar, M; Jutras, P; Prasher, SO; Clark, OG	2019
Establishing street trees in stormwater control measures can double tree growth when extended waterlogging is avoided	Grey, Vaughn; Livesley, Stephen J; Fletcher, Tim D; Szota, Christopher;	2018a
Tree pits to help mitigate runoff in dense urban areas	Grey, Vaughn; Livesley, Stephen J; Fletcher, Tim D; Szota, Christopher;	2018b
Rainfall interception and distribution patterns of gross precipitation around an isolated Ficus benjamina tree in an urban area	Guevara-Escobar, A; González-Sosa, E; Véliz-Chávez, C; Ventura-Ramos, E; Ramos-Salinas, M;	2007

Predicted models for potential canopy rainfall interception capacity of landscape trees in Shanghai, China	Guo, JK; Yu, BQ; Zhang, Y; Che, SQ	2017
Influence of leaf and canopy characteristics on rainfall interception and urban hydrology	Holder, Curtis D; Gibbes, Cerian;	2017
Modelling rainfall interception by urban trees	Huang, Jie Ying; Black, TA; Jassal, RS; Lavkulich, LM Les;	2017
The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA	Inkiläinen, Elina NM; McHale, Melissa R; Blank, Gary B; James, April L; Nikinmaa, Eero;	2013
Estimating Economic and Environmental Benefits of Urban Trees in Desert Regions	Isaifan, RJ; Baldauf, RW	2020
Urban Park Systems to Support Sustainability: The Role of Urban Park Systems in Hot Arid Urban Climates	Kim, G; Coseo, P	2018
Modeling the Runoff Reduction Effect of Low Impact Development Installations in an Industrial Area, South Korea	Kim, J; Lee, J; Song, Y; Han, H; Joo, J	2018
Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network	Kuehler, E; Hathaway, J; Tirpak, A	2017
The Rainfall Interception Performance of Urban Tree Canopy in Beijing, China	Liu, XW; Chang, Q	2019
Rainfall interception and stem flow by eucalypt street trees - The impacts of canopy density and bark type	Livesley, SJ; Baudinette, B; Glover, D	2014
The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale	Livesley, SJ; McPherson, EG; Calfapietra, C;	2016
Watershed-scale impacts of forest buffers on water quality and runoff in urbanizing environment	Matteo, Michelle; Randhir, Timothy; Bloniarz, David;	2006
Million trees Los Angeles canopy cover and benefit assessment	McPherson, E Gregory; Simpson, James R; Xiao, Qingfu; Wu, Chunxia;	2011
A review of benefits and challenges in growing street trees in paved urban environments	Mullaney, Jennifer; Lucke, Terry; Trueman, Stephen J;	2015
Soll Water Dynamics and Growth of Street and Park Trees	Nielsen, Christian Nørgård; Buhler, O; Kristoffersen, Palle;	2007
THE POTENTIAL OF GREEN INFRASTRUCTURE (GI) FOR REDUCING STORMWATER RUNOFF IN A PHNOM PENH NEIGHBORHOOD	Nou, C; Charoenkit, S	2020

Institutionalizing urban forestry as a “biotechnology” to improve environmental quality	Nowak, David J;	2006
The capacity of urban forest patches to infiltrate stormwater is influenced by soil physical properties and soil moisture	Phillips, TH; Baker, ME; Lautar, K; Yesilonis, I; Pavao-Zuckerman, MA	2019
Comparing the infiltration potentials of soils beneath the canopies of two contrasting urban tree species	Rahman, MA; Moser, A; Anderson, M; Zhang, C; Rotzer, T; Pauleit, S	2019
Ecohydrological model for the quantification of ecosystem services provided by urban street trees	Revelli, Roberto; Porporato, Amilcare	2018
A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones	Roy, Sudipto; Byrne, Jason; Pickering, Catherine;	2012
Urban vegetation impacts on the hydrology of Dayton, Ohio	Sanders, Ralph A;	1986
Tree Species Suitability to Bioswales and Impact on the Urban Water Budget	Scharenbroch, BC; Morgenroth, J; Maule, B	2016
Benefits and costs of street trees in Lisbon, Portugal	Soares, Ana Luísa; Rego, Francisco Castro; McPherson, EG; Simpson, JR; Peper, PJ; Xiao, Q;	2011
Assessing the Ecosystem Services of Various Types of Urban Green Spaces Based on i-Tree Eco	Song, PH; Kim, G; Mayer, A; He, RZ; Tian, GH	2020
Transpiration by established trees could increase the efficiency of stormwater control measures	Thom, JK; Szota, C; Coutts, AM; Fletcher, TD; Livesley, SJ	2020
Investigating the hydrologic and water quality performance of trees in bioretention mesocosms	Tirpak, R. Andrew; Hathaway, Jon M.; Franklin, Jennifer A.	2019a
Suspended pavement systems as opportunities for subsurface bioretention	Tirpak, RA; Hathaway, JM; Franklin, JA; Kuehler, E	2019b
Urban form, biodiversity potential and ecosystem services	Tratalos, Jamie; Fuller, Richard A; Warren, Philip H; Davies, Richard G; Gaston, Kevin J;	2007
Transitioning from gray to green (G2G)-A green infrastructure planning tool for the urban forest	Tsegaye, S; Singleton, TL; Koeser, AK; Lamb, DS; Landry, SM; Lu, S; Barber, JB; Hilbert, DR; Hamilton, KO; Northrop, RJ; Ghebremichael, K	2019
Mechanistic simulation of tree effects in an urban water balance model 1	Wang, Jun; Endreny, Theodore A; Nowak, David J;	2008
Surface Water Storage Capacity of Twenty Tree Species in Davis, California	Xiao, QF; McPherson, EG	2016
Rainfall interception by Santa Monica's	Xiao, Qingfu; McPherson, E Gregory;	2002

municipal urban forest		
Performance of engineered soil and trees in a parking lot bioswale	Xiao, Qingfu; McPherson, E Gregory;	2011a
Rainfall interception of three trees in Oakland, California	Xiao, Qingfu; McPherson, E Gregory;	2011b
Rainfall interception by Sacramento's urban forest	Xiao, Qingfu; McPherson, E Gregory; Simpson, James R; Ustin, Susan L;	1998
Winter rainfall interception by two mature open-grown trees in Davis, California	Xiao, Qingfu; McPherson, E Gregory; Ustin, Susan L; Grismer, Mark E; Simpson, James R;	2000
Potential reduction in urban runoff by green spaces in Beijing: A scenario analysis	Yao, L; Chen, LD; Wei, W; Sun, RH	2015
Rainfall Interception by Urban Trees and Their Impact on Potential Surface Runoff	Zabret, K; Sraj, M	2019
Influence of meteorological variables on rainfall partitioning for deciduous and coniferous tree species in urban area	Zabret, Katarina; Rakovec, Jože; Šraj, Mojca;	2018
Can urban trees reduce the impact of climate change on storm runoff?	Zabret, Katarina; Šraj, Mojca;	2015
Regulating urban surface runoff through nature-based solutions - An assessment at the micro-scale	Zolch, T; Henze, L; Keilholz, P; Pauleit, S	2017

Appendix B2 - Study area to catchment area ratio

Table B2: The reported intervention areas of each study. The entire catchment area of the study (where quoted) is given in brackets. Smaller areas up to 10,000 m^2 are quoted in m^2, with larger areas expressed in km^2.

Reference	Size of study area (size of catchment area)
Deutscher et *al*. (2019)	$0.0619km^2$
Grey et *al*. (2018b)	$0.6m^2$
Holder and Gibbes (2017)	$502km^2$ ($2409km^2$)
Kim and Coseo (2018)	$14.0004km^2$ ($194.45km^2$)
Kim et *al*. (2018)	$0.0328km^2$ ($0.411183km^2$)
Matteo et *al*. (2006) **C**	$82.96km^2$
Nou and Charoenkit (2020)	($0.358km^2$)
Rahman et *al*. (2019)	$8500m^2$
Scharenbroch et *al*. (2016)	$0.02km^2$
Song et *al*. (2018)	$33.19km^2$
Tirpak et *al*. (2019)	$27m^2$ and $22.3m^2$ (138.5 and $183m^2$)
Wang et *al*. (2008)	$14.3km^2$
Yao et *al*. (2015)	($667.1km^2$)
Zabret and Šraj (2015)	$600m^2$
Zabret and Sraj (2019)	$600m^2$
Zabret et *al*. (2018)	$600m^2$

Appendix B3 - Species studied

Table B3: List of tree species mentioned within the evidence database, coded by the type of tree: deciduous (D), evergreen (E), or unknown (U).

Species studied	**Type**	**Reference**
Sydney blue gum (*E. saligna*) and narrow-leaved black peppermint (*E. nicholii*)	E, E	Livesley et *al*. (2014)
Field maple (*Acer campestre*)	D	Armson et *al*. (2013); Grey et *al*. (2018a); Grey et *al*. (2018b)
Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*)	E, E	Asadian and Weiler (2009)
Black oak (*Quercus velutina* Lam.) red maple (*Acer rubrum* L.)	D, D	Bartens et *al*. (2008)
Green ash (*Fraxinus pennsylvanica*) and swamp white oak (*Quercus bicolar* Willd.)	D, D	Bartens et *al*. (2009)
Ficus benjamina (L.)	E	Guevera-escobar et *al*. (2007)
White oak, Norway maple, green ash and *Prunus sp*.	D, D, D, U	Huang et *al*. (2017)
Tilia cordata	D	Nielsen et *al*. (2007)
pear tree (*Pyrus calleryana*, 'Bradford'), cork oak (*Quercus suber*)	D, E	Xiao et *al*. (2000)
Black pine (*Pinus nigra Arnold*), birch (*Betula pendula* Roth.)	E, D	Zabret et *al*. (2018); Zabret and Šraj (2015)
Gingko (*Ginkgo biloba*), sweet gum (*Liquidambar styraciflua*), lemon tree (*Citrus limon*).	E, D, E	Xiao and McPherson (2011a)
Platanus x acerifolia 'Bloodgood'	D	Xiao and McPherson (2011b)
Acacia tortilis, Ziziphus spina-christi, Phoenix dactylifera	E, E, E	Isaifan and Baldauf (2020)
Robinia pseudoacacia, Tilia cordata Mill.	D, D	Rahman et *al*. (2019)
Lophostemon confertus	E	Thom et *al*. (2020)
Birch (*Betula pendula* Roth.), pine (*Pinus nigra* Arnold)	D, E	Zabret et *al*. (2019)
Red maple (*Acer rubrum*), Loblolly pine (*Pinus taeda*), Pin oak (*Quercus palustris*)	D, E, D	Tirpak et *al*. (2019a)
Bald cypress	D	Tirpak et *al*. (2019b)