

Review

Integrating Non-Targeted Ecosystem Services into Assessment of Natural Stormwater Treatment Systems

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Abstract: Natural stormwater treatment systems (NTS) are built ecosystems designed to capture and treat stormwater runoff via natural processes. Although NTS design typically targets water services, the biological communities associated with NTS (i.e., plants, animals, and microbes) can provide non-targeted functions that can result in ecosystem services, such as biodiversity, pollination, and climate regulation, or in some cases disservices. Additional co-benefits of NTS include recreation, education and outreach opportunities, and aesthetic value. A review of NTS ecosystem services and co-benefits is provided with specific examples from Los Angeles County, highlighting the need for ecosystem services indicators, standard measurements, and monitoring. As NTS become globally widespread, best practices must include the ability to holistically assess NTS performance in ways that extend beyond water treatment services. Three models are presented that can be used to evaluate NTS performance. Such information can be important in advancing NTS design, choosing spatial placement, and making choices between NTS and more traditional stormwater treatment options.

Keywords: urban runoff; urban ecology; nature-based solutions; natural treatment systems; biofilters; ecosystem services; monitoring and evaluation; planning and management



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1. Introduction

Development and urbanization transform landscapes by replacing vegetation with impermeable surfaces. Subsequent precipitation events can lead to altered levels of water infiltration, modified water flows, and introduction of contaminants into stormwater runoff [1,2]. As a result, flooding and property damage, increased safety and health risks, and environmental damage can occur [3]. Urban planners and developers have traditionally addressed stormwater runoff issues by building drainage systems that connect directly to large bodies of water (e.g., streams, oceans) or treatment plants.

Natural stormwater treatment systems (NTS) are an alternative urban runoff management strategy [4]. NTS (also referred to as low-impact development or sustainable drainage systems) are human-made systems that use natural processes (e.g., gravity-driven hydrology, plant absorption of water and nutrients) to capture and treat urban runoff. We use the term NTS to encompass the different types of installations following current usage by collaborators [5,6]. They come in different forms: bioretention systems (e.g., biofilters, bioswales, rain gardens), infiltration basins and trenches, permeable pavements, dry wells and ponds, treatment wetlands, and combinations of these. They are part of a larger framework that now is often referred to as the sponge city [7]. The sponge city concept was developed in China to address urban water issues through “natural storage, natural infiltration, and natural purification” [8]. A sponge city seeks to retain rainwater, prevent flooding, and increase water quality through natural and semi-natural solutions [7,9]. The focus of this paper is on bioretention systems (i.e., biofilters) because they are explicitly

intended to host biological communities as part of their design and less oriented toward hardscape infrastructure; however, they can offer numerous, often unrecognized benefits beyond the water services targeted in their initial design.

NTS can support diverse ecosystem services, defined as the direct and indirect benefits humans obtain from ecosystems [10,11] (Figure 1). Non-water (i.e., non-targeted) ecosystem services associated with NTS have long been acknowledged [5,12] and are only beginning to be meaningfully considered by spatial planning [13,14], engineering-based design, monitoring programs [15], and economic valuation efforts [16], which have been generally limited to targeted water functions. Ecosystem services described for other green spaces (e.g., parks, green roofs, urban forests) include offsetting carbon emissions [17,18], cooling local temperatures [19], cultural services (e.g., recreation, education and outreach, aesthetic value; [20]), and benefits to human health and well-being [21]. The incorporation of ecosystem services and other co-benefits into NTS design can present urban planners and developers with additional benefits, costs, and tradeoffs to consider [22,23].

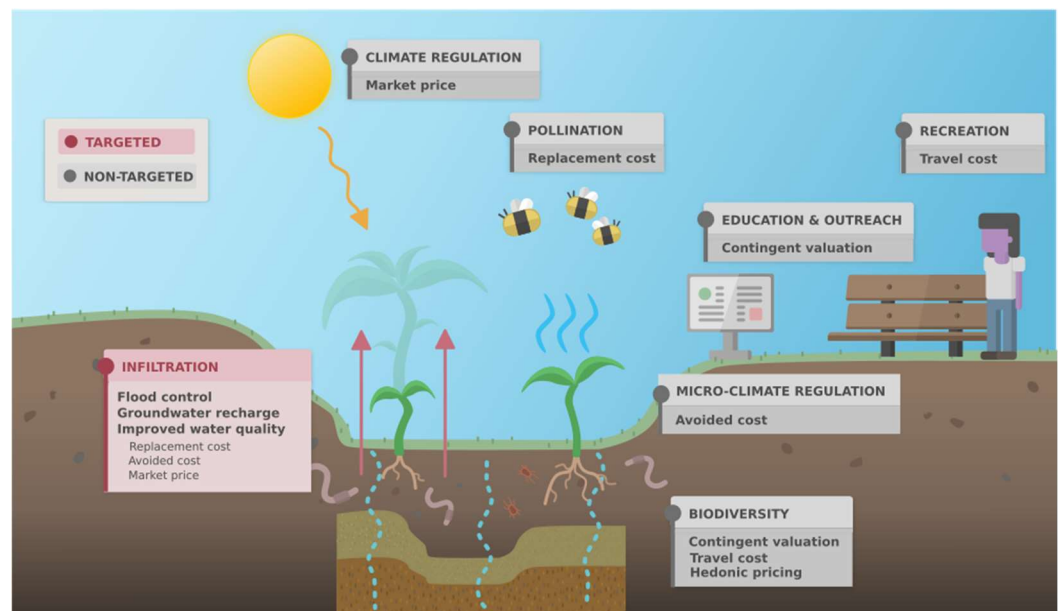


Figure 1. Diagram of targeted and non-targeted ecosystem services associated with natural stormwater treatment systems (a bioretention system pictured here) and methods used to assign a value to them.

We use Los Angeles County to focus this first comprehensive overview of NTS services because it hosts a dense human population near the coast where urban runoff has a large influence on local water quality [24], is in a Mediterranean climatic zone where periodic droughts are common, and expects to experience hydrological changes due to climate change [25]. Los Angeles County also has policy in place to encourage NTS infrastructure. California has passed several propositions to protect water supply and quality (e.g., AB-1471 2014). In 2004, Los Angeles passed Proposition O, which allowed the city to issue up to 500 million USD to fund projects that improve local water quality. In 2012, Los Angeles adopted its Low Impact Development Ordinance (RA-2012-0175) requiring development and redevelopment projects that alter impervious areas to mitigate runoff by capturing precipitation and utilizing natural resources where possible. A subsequent low impact development standards manual was published in 2014 [26]. As a result of these environmental conditions and political momentum, green infrastructure and NTS have been broadly distributed throughout Los Angeles County (Figure 2 [27]; <https://www.ar.cgis.com/apps/dashboards/c41e288cd1cf4bf18b28404423c58735> (accessed on 31 January 2023)) and continue to be implemented. This study uses a small subset of Los Angeles NTS to illustrate potential ecosystem services.

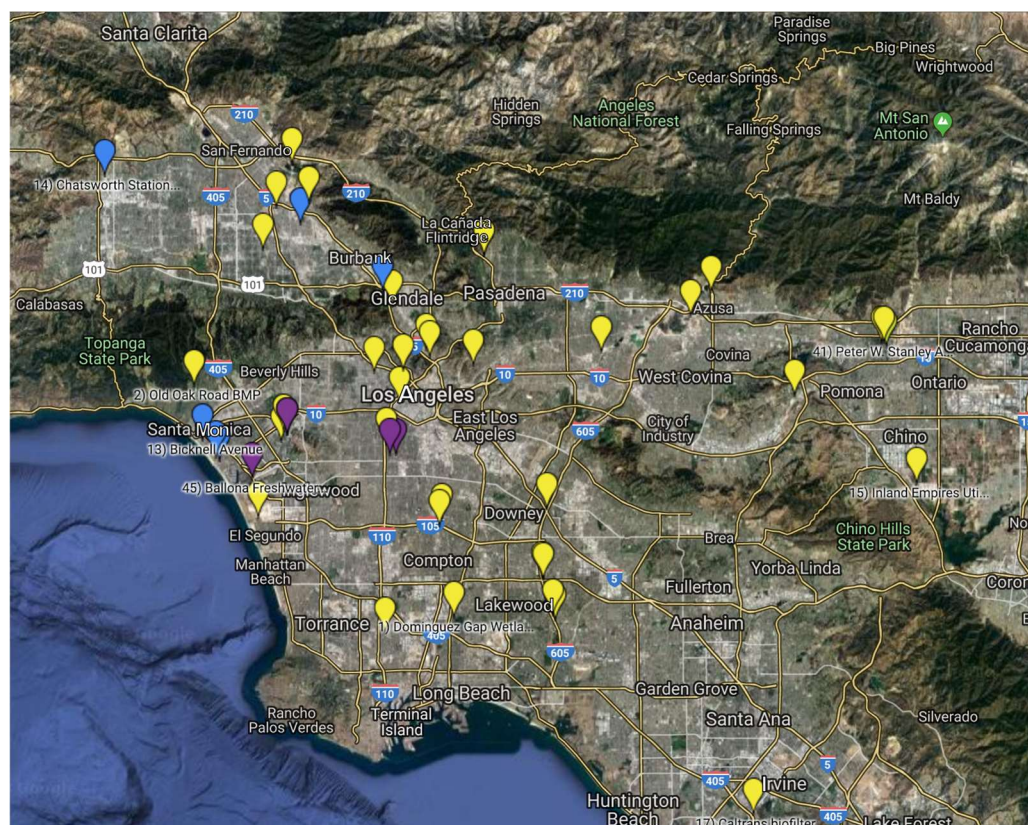


Figure 2. Location of natural stormwater treatment systems in Los Angeles County [27]. Blue indicates sites visited in 2015. Purple indicates sites visited in 2016. View the interactive Google map here: <https://goo.gl/76sswN> (accessed on 31 January 2023).

This paper is a narrowly focused literature review on targeted and non-targeted ecosystem services associated with NTS using Los Angeles County to provide specific geographic context. As there is an existing wealth of literature on targeted water services [28], they are reviewed here in summary for presentation alongside non-targeted ecosystem services. No attempt is made to systematically review the larger literature that is growing rapidly and, at some point, will be able to support informative meta-analyses concerning specific structures and functions underlying NTS. However, there are elements of a semi-systematic review in its broad coverage of multidisciplinary research [29]. The present lack of quantitative hydrologic and ecological NTS information in the context we examine highlights the need for robust data collection. Measurement of ecosystem services and indicators is seen as the starting point. However, U.S. regulatory frameworks, specifically a series of Presidential executive orders [30], require cost–benefit assessment of different options so the translation from biophysical impacts to the monetary valuation comparisons policymakers need is emphasized. An ecosystem services framework can offer alternative design options that maximize overall NTS value and introduce areas of improvement for urban stormwater management [31].

2. Targeted Water Services

2.1. Stormwater Infiltration

NTS are designed to capture stormwater runoff for infiltration or reuse and have been shown to be effective [32], although methods to evaluate infiltration vary [33]. Most bioretention systems are oriented vertically, using gravity to direct water flow through several layers that generally consist of a ponding area with vegetation, porous filter media, and a drainage zone (Figure 3). Infiltration rates can vary widely depending on variables such as size [34], age [35], filter media [36,37], and other design factors [38]. For example,

NTS with internal water storage or submerged zones can have elevated levels of infiltration, evapotranspiration, and nutrient removal (specifically denitrification) but may not be suitable for areas with impermeable soils [39]. Another example is an underdrain that can help ensure desired water retention times but can be prone to clogging [40]. Vegetation also plays a role by intercepting precipitation and water flows [41] and preventing clogging of filter media to maintain infiltration capacity [42,43]. Additionally, with proper design, evapotranspiration by plants can contribute significantly to reduced volumes of stormwater runoff [44,45].

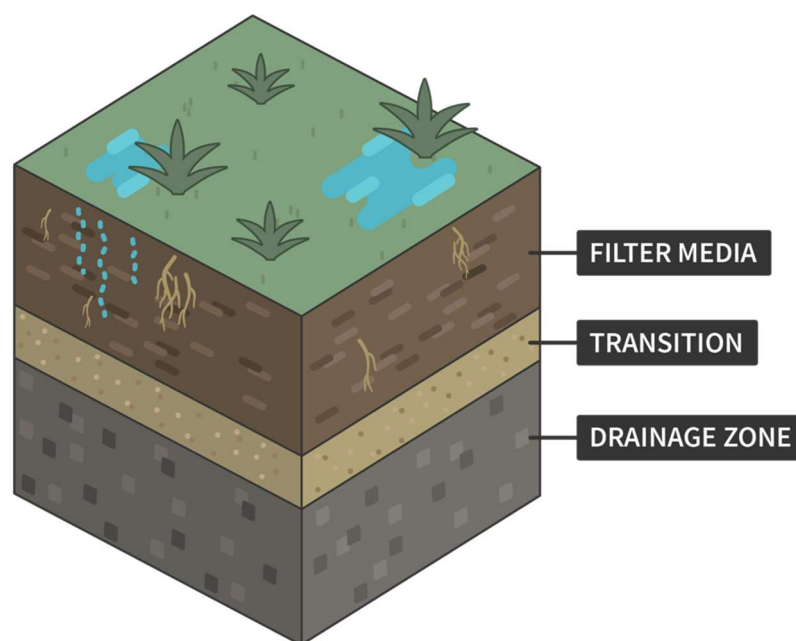


Figure 3. Diagram of a bioretention system with vertical layers.

Stormwater infiltration is important in urban areas with low permeable surface area that are prone to flooding and changes in groundwater recharge [3,46]. Los Angeles lacks the infrastructure to handle large volumes of stormwater [47], and flooding can occur with heavy rainfall resulting from atmospheric rivers. This issue is occurring in a region that experiences episodic drought [48], highlighting the need for proper stormwater management and use, which can include NTS as a strategy that provides additional benefits.

2.1.1. Flood Control

Flood risk is measured as a combination of hazard (e.g., runoff volume, base and peak flows, flood plain) and vulnerability (e.g., infrastructure, population density). Fluvial flooding is caused by overflow of river or lake systems, whereas pluvial flooding is caused by extreme or heavy rainfall. By altering landscapes and hydrology, urbanization can lead to an increased flood risk for both types [49]. NTS have been shown to significantly reduce runoff volume and the magnitude of high-flow events by capturing and storing stormwater runoff. Three bioretention cells in humid continental Ohio reduced both runoff by 45.6% on average and peak flows ranging from 24 to 96%, performing best when peak flows occurred before the bulk of rainfall volume [50]. During the 13 months of observation, 140 storm events were recorded with antecedent dry periods ranging from 0.3 to 20 days and maximum peak flows of 105 L s^{-1} [50]. In humid subtropical North Carolina, 125 storm events were observed over 22 months with antecedent dry periods ranging from 0.3 to 31.3 days and maximum peak flows of approximately 38 L s^{-1} [51]. The study found that a Filterra™ system in an impervious parking lot captured 72% of runoff volume and reduced peak flows by 57% [51]. Hatt et al. (2009) found an average of 33% reduction in runoff volume, as well as an 80% reduction in peak flow reductions in three bioretention systems in Australia. Data were collected during 32 natural and simulated

storm events with maximum peak flows of approximately 40 L s^{-1} and an average return interval of 3 months for simulated events [42]. In a more recent field study, Bonneau et al. (2020) reported a 35% reduction in stormwater volume and an 80% reduction in peak flow in a bioretention basin in Australia during rainfall events over 3 years, with average peak flows of approximately 33 L s^{-1} [52]. Relative to Australia, southern California generally has larger NTS built exclusively for groundwater recharge and longer dry periods that can decrease contaminant removal rates [53].

Most Los Angeles NTS exhibited visual indicators of flood control services: permeable surfaces that allow for water infiltration, graded landscaping to help direct runoff, and ponding areas designed to temporarily store water. For example, Elmer Avenue Green Street was constructed specifically to address street flooding during precipitation events by incorporating bioswales, biofilters, permeable pavements, and rain barrels [54]. However, additional data are needed to confirm whether they are effective. Spatially explicit measurements for flood hazard may be relevant (e.g., soil porosity, basin size, changes to magnitude and timing of flood peaks; [55]), as well as those for flood resilience (e.g., population and area exposed to changes in flood frequency; [56]). There may be a return period at which NTS infiltration rates and storage capacity can no longer provide flood control services, which likely depends on NTS characteristics such as size, filter media, and maintenance frequency [57]. Additionally, Los Angeles is expected to experience a sea level rise in some areas, which may make some types of NTS (e.g., treatment wetlands) that can serve as living shorelines more suitable than others [58].

The value of flood control has been studied in the context of wetlands [59], generally by assessing differences in property damage along a spectrum of wetland area (e.g., reduction in damages as proxied by replacement cost). Brander et al. (2006) conducted a meta-analysis to estimate the value of flood control by wetlands that resulted in a median of 20–30 USD (1995) per hectare annually [60]. Watson et al. (2016) estimated a net present value of less than 100 USD per hectare of wetland annually, which may be lower than comparable studies due to the small beneficiary population [61]. NTS generally operate on a more localized scale than major wetland restoration projects, so one unknown is how different NTS designs vary in their spatial extent of flood control.

2.1.2. Groundwater Recharge

Groundwater is used by more than half the U.S. population, and its recharge is an essential component of the water cycle [62]. Major sources of recharge in urban environments include runoff infiltration and leakages from the water supply and sewage systems [46]. Urbanization can decrease groundwater recharge due to the installation of impermeable surfaces [1]. However, the importation of large volumes of water to meet demand in highly populated urban areas can also lead to significant leakages and water recharge.

NTS can contribute to groundwater recharge by providing permeable surfaces and pore space in their filter media that allow stormwater runoff to pass into the soil subsurface. The Avalon Green Alley project in south Los Angeles is designed to allow water to percolate into the soil and recharge the water table [63]. Beneath the permeable pavement of the green alley, catch basins store stormwater temporarily, where it can be bioremediated before flowing into surrounding soil. Quantifying groundwater recharge can be challenging, but several methods exist to do so, such as physical measurements [64] and numerical modeling techniques [65].

The value of groundwater recharge can be calculated using various methods; the most appropriate is dependent on the end-use of the water. For example, in 2010, California withdrew 12,700 million gallons of groundwater per day, of which approximately 22.2% was used for domestic purposes [62]. The value of groundwater recharge can therefore be associated with the price of water to consumers. Replacement costs can also be used to assign a value to groundwater recharge. Artificial groundwater recharge is the spread of water on land to increase infiltration or the injection of water directly into the aquifer;

its cost can provide an estimate of the value of groundwater recharge. These actions have associated costs and can be used to estimate a value for the same service performed by NTS.

2.2. Improved Water Quality

As stormwater runoff flows over urban surfaces, it can acquire contaminants such as polycyclic aromatic hydrocarbons (PAH), pesticides, pharmaceuticals, and other organic pollutants [66]. The “first flush” phenomenon is defined as elevated levels of stormwater pollution at the beginning of storm events [67,68]. First flush can be difficult to model because it is dependent on a variety of factors, such as climate, precipitation, catchment size, and land use type [68]. Southern California receives little precipitation and has long periods without rainfall, even during the “wet” season, which allows for the build-up of contaminants and results in first flush. These contaminants can then enter larger bodies of water (e.g., rivers, oceans) and degrade the local environment [69]. Many highly urban areas, such as Los Angeles, are coastal; this can exacerbate the issue of water quality because stormwater runoff can drain directly into the ocean with little opportunity (i.e., distance) for treatment. Treatment can depend on NTS water retention times, which are influenced by storage basin depth and type and amount of filter media [70]. Short retention times do not allow for adequate biofiltration, but long retention times can present hazards in the form of flood risk and mosquito reproduction [71], so there are tradeoffs to consider.

There is a range of common urban pollutants in stormwater runoff; these include heavy metals (e.g., PAH, Cd, Cu), total suspended solids and nutrients (mainly nitrogen and phosphorus), and pathogens. Müller et al. (2020) provides a comprehensive review of sources [72]. Heavy metals can persist in the environment and accumulate in sediment, plants, and animals, leading to the degradation of environmental and human health [73]. The input of excess nutrients and organics into streams, lakes, and the ocean (i.e., eutrophication) can be damaging to local ecosystems by generating harmful algal blooms, hypoxia, and anoxia [74]. Pathogens also pose a risk to human health through exposure (e.g., from recreation activities and stormwater reuse). Lim et al. (2015) found that captured stormwater can be used for toilet flushing with acceptable risk, but it does not meet required standards for showering and food-crop irrigation [75]. Beach closures and advisories are often the result of bacteria levels exceeding water quality standards [76]. In addition to the threat to human health, the resulting closures have associated economic costs, e.g., less use of parking lots, restaurants, and shopping [77].

NTS remove contaminants through several pathways. Physical filtration removes debris, particle-bound contaminants, and suspended solids, which can lead to clogging and subsequent deterioration of bioremediation functions. Informed NTS design, such as plant selection, can help maintain infiltration capacity [43]. Contaminant molecules can also be removed from runoff by adsorption (sticking of contaminant molecules onto porous surfaces with uneven or leftover attractive forces [78]) and assimilation (uptake of contaminants by plants; [79]). Adsorption can be enhanced with soil amendments, such as biochar; the type of amendment may depend on the targeted contaminant [78]. A significant portion of bioremediation is performed by soil microbial communities that can be stimulated by moisture [80]. In drought-prone areas such as southern California, extended dry conditions can decrease microbial abundance and activity, which can negatively impact enzyme activity and nutrient cycling [81]. Drought-resistant microbes can be introduced to NTS soil to help promote plant growth and continued phytoremediation under stressful conditions [82]. NTS can prevent contaminants from traveling further to pollute local bodies of water, but they can also concentrate pollutants in plants and filter media [83]. These concentrated contaminants can leach into surrounding soils, e.g., due to lower oxygen levels that increase metal solubility. As a result, some maintenance is likely required to prevent build up and transport of contaminants into the environment [28]. Maintenance costs, such as for plant or substrate renewal, can be uncertain [84] but potentially minimized through good design and regular inspection [85].

Contaminant removal may be the most well-studied service provided by NTS. Figure 4 shows examples of systems installed to remove debris and contaminants from runoff. Water infiltration systems can be installed into sidewalk tree wells to capture urban runoff before it can reach larger bodies of water. The Filterra™ system (Contech Engineered Solutions, West Chester, PA, USA) has been shown to effectively filter suspended solids, phosphorous, nitrogen, and zinc, with mean removal efficiency of 92%, 54%, 33%, and 66%, respectively [51]. The removal rates of heavy metals (copper, zinc, lead, and cadmium) by bioretention systems can be quite high (above 90%) [75], but not in all cases. Smolek et al. (2017) found that the Filterra™ system did not remove copper [51]. The type of filter media can influence the removal of metals, which accumulate in the top 5 cm of soil [75]. Heavy metal concentrations are unlikely to exceed soil quality standards for human health over the NTS lifetime [83]. However, ecological thresholds may be reached to varying extents. For example, Waara and Johansson (2022) measured concentrations of cadmium, copper, zinc, silver, and antimony that put aquatic organisms at risk in Swedish stormwater ponds [86]. In contrast, heavy metal concentrations in stormwater ponds in Denmark did not pose a risk to habitat function but were reflected in biomass so ecological risk could increase over time [87]. Sediment and nutrient removal by NTS have also been found to be relatively high (more than 50% in most cases) in several laboratory experiments [88,89]. However, at a watershed-level, NTS may be better suited for reducing contaminant load (the rate at which contaminants are discharged) into local waters rather than meeting concentration-based water quality standards [90]. Although these laboratory experiments provide a deep understanding of how NTS may function under specified conditions (e.g., dry vs. wet conditions, high vs. low temperatures), in situ studies are also needed to put laboratory experiments into context. How NTS operate over both long (e.g., months to seasons) and short (e.g., period of a storm) time scales are an open question, as is how the timing of water quality measurements (e.g., beginning or end of the storm, post-saturation) can influence perceived effectiveness.



Figure 4. Examples of Los Angeles systems designed to remove debris and contaminants from runoff: (a) biofilter along Elmer Avenue Paseo, (b) biofilter in the Avalon Green Alley, and (c) Filterra™ bioretention system on Grand Boulevard.

There are many studies that estimate the value of improved water quality using a variety of methods, with the two most common being a production function approach and contingent valuation. A production function approach can value improved water quality by comparing the cost of alternative methods for contaminant removal, such as a stormwater treatment plant. This is the approach generally used by Stanford’s Natural Capital project [91] coupled with a measure of replacement cost. Several of their water-related modules of the InVEST workbench (i.e., urban flood risk mitigation, urban stormwater retention, water purification) can be useful starting points for examining the impacts of different NTS and can often accept location-specific parameter values [92–95]. Contingent valuation, including discrete choice experiments, asks a sample of respondents about their willingness to pay (WTP) for a spectrum of water quality [96,97]. The specific variant of a method is dependent on the fate of the stormwater and the final ecosystem service it provides, e.g., improved intake water quality for drinking water or improved water quality in lakes, rivers, and streams that can host higher levels of biodiversity.

3. Non-Targeted Ecosystem Services

NTS can provide a range of non-targeted ecosystem services, linked to their utilization of natural structures and functions, and other co-benefits [98,99]. Filter media and plant communities, which increase infiltration and remove contaminants, host biodiversity that contributes to ecological processes that can result in beneficial ecosystem services [6]. These ecosystem services (or costs, in the case of disservices) are not generally considered during the design and assessment of NTS. One unique feature of NTS is that they are human made so can be designed to provide specific benefits, which are discussed here to further expand design options that can enhance NTS value.

3.1. Biodiversity

Vegetated NTS act as man-made ecosystems that contain a diversity of plants, animals, and microbes from which ecosystem services can be generated [5,100] (Figure 5). They provide patches of habitat within an urban landscape and potentially act as corridors through which organisms can move. This can be important for population connectivity and resilience in a changing environment due to removal of natural habitat, habitat fragmentation, and climate change [101].



Figure 5. Examples of biodiversity that can support ecosystem services in Los Angeles natural stormwater treatment systems: (a) plant diversity at the South Los Angeles Wetland Park, (b) Bicknell manzanita tree as a bee attractant, and (c) signage illustrating the biodiversity of the Ballona Freshwater Marsh.

Whereas NTS biodiversity (here loosely defined to encompass plant, animal, and microbial species richness, abundance, and distribution) can be measured using a range of accepted methods (e.g., visual surveys, fauna collections, eDNA surveys), how this biodiversity translates into ecosystem services is more complex and will need targeted studies. There can be synergies between NTS design and landscape architecture, such as planning larger project areas [102], adaptive and flexible systems [103], and the redevelopment of un- or underutilized land [104,105]. Plants act as ecosystem engineers in bioretention systems, influencing both hydrological and ecological features and, therefore, plant selection can affect many of the services discussed in this paper [105]. Vegetation captures precipitation [41], undergoes evapotranspiration [44,45], maintains media porosity with roots, and assimilates pollutants [43]. Plants determine photosynthesis and respiration rates, organic matter in soil, and, ultimately, carbon sequestration and storage in NTS [106]. Additionally, plant communities influence microbial and infaunal communities, which subsequently impact function. Despite this, plant selection in NTS design typically emphasizes stress tolerance and competitiveness rather than specific factors influencing ecosystem services [107]. Microbial communities in NTS are most often assessed in the literature with

respect to the harmful taxa present (e.g., fecal-indicator bacteria; [108]) or as functional groups (i.e., denitrification, greenhouse gas emissions). Fauna, except in wetland settings, are usually not considered in NTS design, despite their role in facilitating targeted functions and services. Mehring et al. (2016) identify common biofilter taxa, such as Megadrilacea (earthworms), Enchytraeidae (potworms), and Collembola (springtails) [109]. Earthworms are known to increase water infiltration via burrows [110], whereas springtails can impact plant growth and nutrient cycling [6]. As a result, these soil invertebrates can be considered ecosystem engineers that move and aerate soil, shaping the microbial, floral, and faunal communities from which more ecosystem services can stem. Because urban NTS can receive more water than native ecosystems, they can host elevated biodiversity of local soil invertebrates relative to natural habitats [111]. Higher biodiversity can be beneficial if they enhance service provision or detrimental if they involve invasive species that disrupt function. Wetland bird species contribute to local diversity and provide recreational services in the form of birdwatching. NTS also have the potential to provide bird habitat patches within an urban landscape [112].

Studies exist on the economic value of biodiversity in urban and engineered settings (e.g., constructed wetlands, agriculture) [113]. These employ the standard suite of non-market valuation techniques [114]: the production function approach, contingent valuation, travel cost analysis, and/or the hedonic property pricing methods to estimate society's willingness to pay (WTP) for biodiversity and its conservation. The production function approach tends to be used when the NTS alters an input to some process such as sewage treatment so that it is possible to estimate the reduction in cost of that activity relative to the status quo without the NTS. Contingent valuation is a stated preference approach that is widely employed because it can largely emulate the other techniques by constructing the relevant market in a survey context. Travel cost analysis is heavily used when NTS influence the quantity or quality of outdoor recreation. This method is based on the notion that it costs time and money to travel to the recreational site. Variation in those costs acts like a market price influencing the amount of the recreational activity undertaken. Hedonic pricing tends to be used when an ecosystem service is incorporated in housing or land prices in a manner similar to school quality. The value of NTS biodiversity has not been assessed, but studies in urban ecosystems may be a useful starting point. For example, Dupras et al. (2014) estimated that urban forests in the Greater Montreal area in Canada host biodiversity that creates a value of CAD (2013) 2623 per hectare annually [115]. Biodiversity associated with other human-made ecosystems, such as agricultural land [116], may also be relevant.

3.2. Climate Regulation Related to Carbon

Carbon dioxide emissions are the largest contributor to anthropogenic climate change [117] and, as a result, climate-regulating services related to carbon (i.e., carbon sequestration and storage) have become increasingly important, especially in urban areas that contribute disproportionately to global emissions [118]. NTS plants have the potential to contribute to this effort by converting atmospheric carbon dioxide into biomass through photosynthesis. How long this carbon is subsequently stored is dependent on several factors. Although some carbon is quickly rereleased during respiration, some is stored as plant biomass and soil detrital compounds. Turnover rates vary with type of biomass, soil moisture, soil oxygenation, soil organic matter, and microbial communities [119,120]. Some bioretention systems contain saturated or submerged zones designed to create anaerobic conditions for denitrification [88,121] but may also help prevent microbial breakdown of organic matter.

Quantifying carbon sequestration and storage would necessitate measurements that include net carbon fluxes, soil and plant carbon density, and biomass turnover rates. This has been performed in urban green spaces and could also be performed in NTS. Nowak et al. (2013) estimated annual carbon sequestration in U.S. urban forests to be 25.6 million tons [122], which at 36 USD (2015) per ton of carbon [123], has a value of over 900 million USD (2015) annually. On smaller scales, green roofs have also been shown to sequester

carbon and decrease carbon emissions due to lowered electricity usage for cooling [124,125]. NTS likely operate on scales more similar to green roofs than urban forests. The Stanford Natural Capital InVEST Workbench [91] has developed modules that allow for assessing carbon sequestration that may also be useful in specific contexts [126–128]. The monetary valuation of any carbon sequestered from the U.S. regulatory vantage point is driven by the standardized social cost per ton of carbon promulgated by the U.S. Environmental Protection Agency [129].

3.3. Micro-Climate Regulation

Micro-climate regulation is complex and highly dependent on geographic context. In addition to physically storing carbon, increased green space can reduce air and surface temperatures [19,130], reducing electricity use and emissions of greenhouse gases. The urban heat island effect occurs due to increased air temperature in urban settings relative to undeveloped areas as a result of replacing vegetation with pavement [131,132]. Pavements, such as asphalt and cement, have lower surface albedo than natural vegetation and therefore absorb more radiative energy. Non-vegetated surfaces also convert absorbed radiative energy into convective heat, which contributes to the urban heat island effect at higher rates than vegetation; these rates are dependent on the thermal properties of the material [133]. Evapotranspiration also contributes to plant regulation of micro-climates by increasing the amount of water in the air, i.e., humidity. In tropical contexts, increased humidity can counteract air cooling effects [134]. However, in arid southern California, the decrease in air temperature can be more important than the increased humidity in preventing heat impacts and mortality [135]. Additionally, vegetation can provide shade. Even small green spaces (e.g., green roofs) can have a significant impact on microclimate [19]. Factors that affect microclimate regulation include UV intensity, wind, and size of the green space.

The value of microclimate regulation by urban green space can, in many instances, be calculated using avoided costs methods, which can be seen here as a variant of the production function method. For example, if a green space makes an area cooler, people are likely not to run their air conditioning for as long or as intensively, in the same way as would be achieved by better insulation. The energy savings produced could be used to assign an economic value to the microclimate regulating services provided by the green space.

3.4. Pollination

Animal-mediated pollination is an important ecological process that supports many benefits. For example, bee pollination can increase agricultural crop quantity, food quality, and market value [136]. However, bee populations have been declining due to changing land use and management, pesticides, pollution, higher pathogen prevalence, and climate change [137]. Additionally, development and urbanization cause habitat fragmentation, which can lead to changes in species and functional diversity [138]. NTS can provide patches of habitat and refuge for animals within urban areas. Pollinators, such as bees and birds, can connect these habitat patches as they move among plants to feed and collect pollen (Figure 6). Increased suitable habitat and connectivity may facilitate the recovery of pollinator populations and create more resilient communities that can recover from disturbances, e.g., disease or long periods of intense drought [139]. Habitat patches have been shown to maintain distinct bee communities that, in aggregate, retain a significant amount of local species diversity [140].

Pollination services are typically seen as an input to the agricultural process, with improvements to pollination associated with increases in agricultural productivity [141]. They have also been evaluated in urban settings. For instance, Breeze et al. (2015) estimated the WTP for non-market pollination services in the United Kingdom using a contingent valuation survey deploying a discrete choice experiment [142]. Their estimates suggest taxpayers are willing to pay GBP 13.4 annually per person to maintain these benefits. Visual indicators for potential pollination services include the presence of animal-pollinators (e.g.,

bees, birds) as well as flowering plants. Quantification of this service requires data on the frequency of animal-to-flower visits as well as connectivity among NTS and other areas.

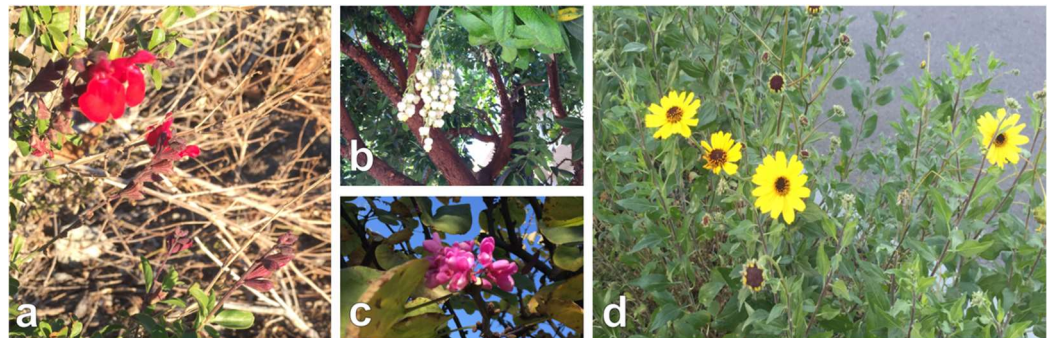


Figure 6. Flowering plants that could provide pollination services observed in bioretention systems at: (a) Elmer Avenue, (b) Bicknell Avenue, (c) Grand Boulevard, and (d) Los Angeles Zoo.

3.5. Other Co-Benefits

The following co-benefits have been separated from other ecosystem services because their provision does not directly employ ecological processes. However, biodiversity and ecological processes associated with NTS can enhance these co-benefits.

3.5.1. Recreation

NTS can have built-in public spaces that human communities can utilize. Walking trails, bike lanes, benches, and wildlife viewing sites can provide recreational services (Figure 7). The recreational use of urban green spaces can depend on amenities such as dog areas, playgrounds, barbecue areas, and landscaping [143]. Urban green spaces have been linked to improvements in physical and mental health [21,144,145]. They have also been linked to more active and healthy lifestyles overall [146]. In Los Angeles County, which is the most populous county in California [147], these types of spaces can be important in the midst of a densely populated, heavily urbanized area. The travel cost method is most often used to calculate the value of recreational services [148] but may not be appropriate for hyper-local neighborhood amenities if there is little to no cost associated with access. Contingent valuation and hedonic pricing have also been employed [149]. Sociocultural and socioeconomic characteristics may play a role: people of color and lower-income communities utilize urban green spaces at lower rates than other groups [150,151]. In Porto, Portugal, Graça et al. (2018) found that lower socioeconomic areas have the most green space, but they are unlikely to be developed in ways that provide services to the community [152]. This suggests the possibility that poorer communities can be served by NTS that enhance existing green spaces in a way that make them more accessible.



Figure 7. Visual indicators of recreation at Los Angeles natural stormwater treatment systems: (a) walking trail on Elmer Avenue Paseo, and (b,c) signage and drinking fountains at South Los Angeles Wetlands Park.

3.5.2. Education and Outreach

NTS present an opportunity for education and public outreach regarding stormwater issues, pollution, watershed and urban ecology, urban planning and management, and climate change. For example, Ocean View Growing Grounds (OVGG, San Diego, CA, USA) is a community garden within a food desert (defined as an area that lacks access to fresh produce and whole foods (often in low socioeconomic areas)) that utilizes bioswales to prevent flooding. UC San Diego researchers have partnered with community leaders to host outreach events about hydrology, soil, and urban ecology. Greater understanding and awareness of NTS and the services they provide may lead to safer gardening practices and more efficient water use. In Los Angeles, many of the sites have educational information posted about the project, their goals, and their motivations (Figure 8). As part of the Elmer Avenue Green Street project, local residents participated in the planning and design processes, actively engaging in stormwater issues and how to address them.

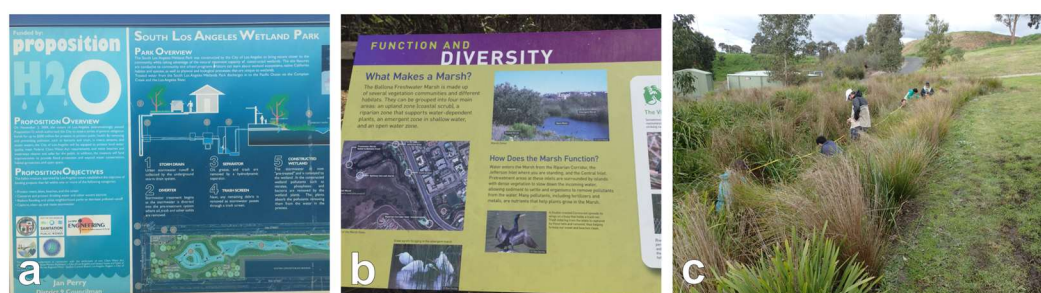


Figure 8. Examples of education and outreach services provided by natural stormwater treatment systems: (a) South Los Angeles Wetlands Park, (b) Ballona Freshwater Marsh, and (c) students conducting fieldwork as part of the National Science Foundation Partnerships for International Research and Education.

3.5.3. Aesthetic Value and Other Non-Use Values

Aesthetic value has been attributed to urban green spaces [153], which can increase surrounding property value [154]. NTS may provide similar services to enhance visual, auditory, and olfactory environmental features that have been linked to human well-being [155,156]. Green roofs and walls can dampen road traffic noise by up to 7.5 dBA [157]. Urban green spaces provide habitat for “natural” sounds (e.g., birds), which are preferred over traffic noises [158]. Exposure to green spaces has also been associated with better cognitive development [159] and reduced physiological stress [158].

3.6. Disservices and Unanticipated Costs

NTS can potentially introduce undesired services, such as installation of unattractive elements, accumulation of pollutants, and proliferation of disease vectors. The aesthetics of NTS may not be favorable to all people, especially when they are not regularly maintained. Regular maintenance can not only help plant survival but also prevent build-up of debris and pollutants, which NTS are designed to intercept. Heavy metals can leach into surrounding soil and groundwater [42,160]. It is also possible that NTS, despite having vegetation, can be sites of net greenhouse gas emissions (carbon dioxide and methane) rather than carbon sinks [161]. Ponding areas, which allow microbial communities to remove contaminants, can also provide habitat for mosquitoes that pose health hazards in the form of infectious diseases and allergies. For example, two Los Angeles NTS sites had advisories about West Nile virus and its carriers (August 2016). Vegetation and soil media can also provide habitat for urban pests, such as rodents and ticks [162].

Increases in urban green space have been linked to decreases in violent crime [163]; however, the potential of urban parks to help foster various types of crime is well known. An account of assault was cited in the South Los Angeles Wetland Park (<http://abc7.com/news/arrest-made-in-connection-to-sex-assault-attempts-in-south-la-park/1297020/>) (ac-

cessed on 31 January 2023)). These issues can generally be avoided at some cost, whether it is more frequent monitoring, improved lighting, or increased maintenance. The main warning here is that whereas these costs are not usually prohibitively expensive, they do need to be considered during planning and budgeting processes.

4. Potential Quantitative Models to Assess Ecosystem Services Performance in Natural Stormwater Treatment Systems

One approach to better internalize ecosystem services associated with NTS into decision making is to (1) determine the quantity or rate at which the ecosystem service is provided (i.e., biophysical value) and (2) determine the value (whether economic or not) of that quantity or rate. Although non-targeted ecosystem services are acknowledged [12], field studies that quantify these services are still lacking [164]. Here, we highlight three potential models for ecosystem services performance assessment in NTS that can be used as a starting point and improved upon as more data become available.

Benefit transfer approaches use regression models, often built on meta-analyses, to provide an estimate of the dependent variable (i.e., the rate or value of an ecosystem service). Examples of potential explanatory variables include study site size, geographic location, scale of the study (e.g., local, regional, national, global), gross domestic product per capita, valuation method, and sample size. These preliminary estimates can then be used further, such as in cost–benefit analysis, because primary studies are not always feasible.

Stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are production function modelling techniques that create a “best practice frontier” as a benchmark of efficiency [165,166]. This benchmark is generated using input and output data from multiple sources (e.g., firms, projects, NTS), creating one scenario (normalized to be the best practice frontier) against which the efficiency for other scenarios can be compared and evaluated. Thus, these approaches provide a measure of how efficient a particular NTS is at providing an ecosystem service relative to a benchmark and by extension to competing NTS configurations. SFA includes a stochastic error term that may make it suitable for urban systems that are subject to environmental variation, e.g., drought and precipitation events. However, SFA requires an a priori assumption regarding the production function form, i.e., the mathematical relationship between inputs and outputs (e.g., Cobb–Douglas, Leontief), which can have a substantive influence on results if it does not provide a reasonably good approximation to the actual production function.

DEA is a nonparametric approach that does not require prior knowledge of the production function form but has the weakness that it does not formally accommodate idiosyncratic random shocks. DEA handles multiple outputs better than SFA, which may make it more appropriate for NTS-associated ecosystem services. A recent comparison of DEA and SFA for rice production is contained in [167].

The benefit transfer approaches, SFA, and DEA results can be used to evaluate how well an NTS site is performing and may help point to how to improve its functioning. Table 1 provides a characterization of benefit transfer, DEA, and SFA from the perspective of NTS ecosystem services.

Table 1. Advantages and disadvantages of benefit transfer approaches, stochastic frontier analysis, and data envelopment analysis for assessing the value of ecosystem services in natural stormwater treatment systems. Adapted from [168].

	Benefit Transfer Approaches	Stochastic Frontier Analysis	Data Envelopment Analysis
Assumptions	Policy site is equitable to study site	A priori production function	Deterministic approach
Error	due to differences in site characteristics	Incorporated as stochastic variable	cannot be separated from inefficiency

Table 1. Cont.

	Benefit Transfer Approaches	Stochastic Frontier Analysis	Data Envelopment Analysis
Multiple outputs	Single ecosystem service	Weighted basket of ecosystem services	Allows for multiple ecosystem services
Relationship to independent variables	Relationship built into regression model	Relationship built into regression model	Need additional regression model
Interpretation of results	Associated value and drivers	Benchmark for efficiency	Benchmark for efficiency

We would like to have been able to directly compare results from an SFA and DEA analysis for our Los Angeles sites. This cannot be easily performed due to the lack of readily available data. There are no standard data collection or monitoring programs for Los Angeles NTS. This makes it difficult to compare across time and across sites, and to date the authors know of no monitoring of ecosystem services associated with NTS. More intensive monitoring and a standardized set of protocols for reporting such data could help identify transparent and effective management strategies [169], e.g., timing of maintenance, and improve the above quantitative models for more accurate estimates of value and efficiency. In situ, mesocosm studies are also needed to evaluate NTS performance under actual environmental conditions [79]. Other questions that still need to be addressed include how networks of NTS compare with single systems regarding both targeted and non-targeted ecosystem services and how NTS operate over time.

Nonmonetary valuation approaches may be required for some ecosystem services, such as cultural ones that are difficult or inappropriate to assign a monetary value. For example, a deliberative mapping survey was used to assess the local perception of and assign a social value to landscape services provided by the Mekong Delta in Vietnam [170]. Other non-monetary valuation approaches include interviews, oral histories, scaling (e.g., “very good” through “very bad”, numerical 1–10), and ranking options into an order [171]. Another alternative to monetary valuation is the use of benefit-relevant indicators that link ecological responses to management decisions and human well-being [172]. These indicators can support environmental decision making both on their own and as a step towards valuation [172].

5. Conclusions

Because NTS, such as bioretention systems and treatment wetlands, rely on natural structures and functions, they provide built ecosystems that can support a host of targeted and non-targeted benefits. A lack of standardized monitoring data and programs makes it difficult to assess whether these systems are generating the services they are built to provide as well as any potential co-benefits. The proposed ecosystem service measurements and indicators presented above are a first step towards quantification, verification of their utility, and identification of design improvements. Although there are few data on the quantification of these NTS benefits specifically, examples from relevant systems can be used to get an idea of how these processes may work and on what scale. There also exist many valuation techniques that can be employed to assign a value to these ecosystem services for incorporation into urban design and management given the widespread use of cost–benefit analyses in decision making. Most NTS are implemented to meet water quality regulations and, although expensive, some of these costs may be offset by the value of non-targeted ecosystem services provided. However, long-term monitoring is necessary to assess whether the benefits of non-targeted services actually accrue, and research is needed to determine how to optimize their collective performance. Better understanding the co-benefits provided could also garner support for the use of NTS from local governing bodies and the public. In places such as southern California, where water issues are in sharp focus in policy debates, effective management of stormwater runoff can reduce

flooding and enhance the water supply while improving microclimate, wildlife habitat, biodiversity, pollination, recreation, education, or other valuable services. Consideration of non-targeted ecosystem services by NTS can provide one tool to help urban planners, community groups, and developers make better decisions.

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