Chapter 9
Designing with Nature: Incorporating Hydrologic Services in Engineering Projects

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9.1 Introduction

Today's water challenges can be summarized pretty simply: too much water or too little water of sufficient quality. Extreme flooding events touch millions of people annually, with a human or economic cost higher than any other natural disaster (Jha et al. 2012). At the same time, droughts or poor water management leave some regions short of the necessary resources for domestic, industrial, or environmental uses. Climate change is expected to exacerbate this reality, and water managers seek solutions to overcome the shortfalls of conventional engineering approaches. Integrated water resource management (IWRM) was developed with this goal, using a systemic approach to understand how social, technical, and environmental factors can increase the resilience and sustainability of water resources (see Schoeman et al. 2014).

Important components of the solutions to water challenges are nature-based solutions (NBSs). They are defined as "actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits" (IUCN 2016). NBSs are getting increased attention in both academic and policy realms, as they hold the promise of meeting both environmental and development goals.

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With regard to IWRM, there are three main services provided by NBSs: flood risk mitigation, water quality improvement, and water supply. For these services to be incorporated into engineering design, key questions need to be answered related to NBSs' efficacy: To what extent can NBSs reduce the amount of runoff and peak flows? To what extent are they able to remove contaminants and purify waters? To what extent can they increase streamflows during low-flow periods and/or increase groundwater recharge?

The answers to these questions and the potential for nature-based designs to address water-resources challenges depend on the social, technical, and environmental context (Keeler et al. 2019). Due to the natural processes NBSs rely on, climate and geography will influence their behavior. For example, more intense precipitation or steeper slopes will result in more runoff, reducing the capacity of natural vegetation to infiltrate precipitation. In addition, social and technical contexts affect water challenges themselves, and hence the likelihood that NBSs will address them. For instance, water demand management or the construction of a desalination plant will impact water resources management and the place of NBSs in the strategy.

The complex interactions between social, technical, and environmental factors mean that the potential of NBSs will require cooperation between scientists in various disciplines as well as water engineers. The science of ecosystem services (ES) – the benefits people derive from nature – has developed over the past decades to improve our understanding of the interdependence of nature and people and to quantify the value of natural capital in providing key benefits to people (Guerry et al. 2015). In this chapter, we illustrate how the science of ES, and all the disciplines it draws on, may support IWRM in several ways: by producing information on ecological functions to support engineering design; by developing new approaches to incorporate people in the design phase, as beneficiaries and contributors of knowledge; and by facilitating the communication on the value of nature to a broad range of stakeholders.

The following sections describe how NBSs are becoming part of the water engineering discussion by reviewing the potential of these solutions, highlighting their cobenefits and trade-offs, and finally discussing the opportunities offered by ES science to support IWRM.

9.2 Potential of Nature-Based Solutions for Water Services

This section provides an overview of the functions performed by NBSs with regard to the three main water services: flood risk mitigation, water supply, and water quality management. Common types of NBSs include street trees, parks and open space, engineered stormwater management devices (bioswales, raingardens, etc.), green roofs, waterways and wetlands, upland forests or grasslands, and community/allotment gardens (Table 9.1 and Fig. 9.1). We review the factors moderating the level of service and practical implications for engineering design. Of note,

Table 9.1 Suite of nature-based solutions and their cobenefits

	Nature-based solutions						
Urban ecosystem services	Street trees	Parks & open space	Engineered devices (bioswales, raingardens, etc.)	Green roofs	Waterways & wetlands	Restoration or protection of upland forests or grasslands	Community/allotment gardens
Flood risk reduction		X	X		X	X	
Water quality management	X	X	X	X	X	X	X
Water supply	X	X	X			X	X
Air quality improvement	X	X					
Carbon sequestration	X	X					
Coastal protection						X	
Urban heat reduction	X	X		X	X		X
Recreation		X			X	X	
Mental health	X	X	X		X		X
Urban agriculture		X					X

Adapted from Keeler et al. (2019)

Fig. 9.1 Examples of NBSs that provide hydrologic services in urban or rural environments: (from left to right, top and bottom rows) urban parks, community gardens, afforestation or forest protection, street trees, wetlands, and green roofs

we focus here on the ecological and technical factors, while acknowledging that socioeconomic factors affect the level of risk associated with each service and therefore the risk mitigation service provided by natural infrastructure. For example, low-quality housing may be more vulnerable to flooding, making the service provided by NBSs (or traditional infrastructure) more valuable (see Keeler et al. 2019, for a review of socioeconomic factors affecting water services).

9.2.1 Flood Risk Mitigation

Flooding occurs for multiple reasons: when river flow cannot be contained within the natural or man-made channel (riverine flooding); when rainfall intensity exceeds infiltration capacity over an area (pluvial flooding, with the particular case of stormwater flooding in urban areas); and when large storm systems or rising sea levels affect coastal areas (coastal flooding). We focus here on the first two, associated with freshwater rather than coastal water, while acknowledging that sea-level rise or storm surge may interact with freshwater flooding in coastal environments.

Following are the main functions of NBSs with regard to flood-risk mitigation:

- Reduce runoff production
- Slow surface flows
- Create space for water (in floodplains or basins)

The functions are distinct and natural infrastructure may perform one or several of them to a different extent. This partially explains the inconsistencies in the literature, with some authors claiming that the role of natural infrastructure in flood risk reduction is overestimated (Calder and Aylward 2006). In fact, several ecological and technical factors moderate the effect of natural infrastructure, meaning that the relevance of a given type of natural infrastructure varies widely with context. Starting with ecological factors, the characteristics of a storm event (in particular intensity and duration), type of soil, and location and type of natural infrastructure all influence the risk-mitigation effect (Keeler et al. 2019). For example, landscape interventions in the UK were found to reduce peak flow for moderate rainfall events, but their effect in large basins for extreme events is limited (Dadson et al. 2017). Soils with low infiltration capacity, either naturally or due to compaction, will also generate more runoff and therefore reduce the performance of NBSs with regard to flood risk.

In addition, the type and location of built infrastructure will affect flood-hazard reduction. For example, the presence of natural infrastructure (recreation or protected areas) in a flood plain will not only reduce flood risk downstream but also reduce exposure, since it restricts housing and built infrastructure in flood-prone areas. Another example of built infrastructure affecting NBSs is the presence of a dam, which makes natural flood control less valuable. In urban environments, the density and quality of the stormwater sewer network, if present, will also affect the value of NBSs with respect to volume reduction (but generally not undermining the effect on stormwater quality, see Sect. 9.2.3).

Because of these multiple interactions, evidence for the effect of NBSs may seem inconsistent. However, some facts emerge from the literature. First, for smaller events, the reduction in runoff production from most types of NBSs is uncontested. Second, engineered systems such as vegetated retention basins have the capacity to reduce floodwaters. Third, large vegetated areas such as forest or riparian vegetation can reduce risk by preventing development (which might otherwise create impervious areas or compact soil, thereby increasing runoff production), and by reducing exposure in the case of floodplains. Finally, NBSs have cobenefits related to sediment retention, which are also relevant to flood risk: sediment not only reduces flood storage capacity in reservoirs, but also changes river morphology in floodplains, with sediment build-up reducing the capacity to accommodate flood waters downstream.

From an engineering standpoint, the variability in performance due to ecological or technical factors calls for designing flood-risk reduction projects with a mix of green and gray infrastructure. Depending on the project, whether it addresses riverine or pluvial flood risk, and for prevention or risk reduction, several tools can support the design process.

Stormwater flood risk reduction A number of urban hydrology models now allow users to represent the effect of NBSs on stormwater flow (e.g., SWMM, MUSIC; Elliott and Trowsdale 2007). These models can be used to assess a single storm event and quantify peak flow reduction associated with NBSs. The increased interest in NBSs for stormwater management also prompted the development of dedicated tools (e.g., SUSTAIN, Gwang Lee et al. 2012; InVEST flood risk reduction tool, Sharp et al. 2019) that typically require less hydrologic skill and little calibration. These tools can support siting or preliminary design for engineering projects.

Preventing flood risk The effect of protecting or restoring forests on peak flow or runoff volume can be assessed through simple approaches like the NRCS Curve Number method or the rational method (for small urban watersheds). If greater accuracy or spatial differentiation is needed, semidistributed hydrologic models like SWMM, MIKE-SHE (e.g., in Dadson et al. 2017), or distributed models like TOPMODEL (Beven and Kirkby 1979), LISFLOOD (Van Der Knijff et al. 2010), and CADDIES (Guidolin et al. 2016) can be used. One caveat for the use of these models is that they require extensive calibration or, in the case of global models, they may not focus on vegetated land use (Ward et al. 2015). To facilitate project assessment (in particular, comparison among management options), analytical methods are being developed to quantify the effect of existing natural assets such as wetlands (Watson et al. 2016).

Reducing existing flood risk In addition to estimating the effect of peak flow reduction by NBSs, hydraulic models like HEC-RAS (Brunner 2001) or LISFLOOD-FP (Bates et al. 2010) can be used to understand the effect of floodplain reconnection – for example, the Yolo by-pass project in California (Opperman et al. 2009). The more complex models cited above (fully distributed models) can produce flood extent maps that can help assess the extent of the flood reduction, with the caveats related to model calibration and poor representation of NBSs.

9.2.2 Water Supply

With respect to water supply, that is, the availability of liquid water for human use (domestic, industrial, irrigation, hydropower, cooling), the landscape performs three functions:

- Concentrates water in space; precipitation that falls over an expansive area is collected in streams and funneled to large rivers and, eventually, the oceans.
- Disperses water in time; precipitation that occurs at punctuated moments is spread out through time as it makes its way through the landscape to rivers and oceans.
- Converts solid and liquid water to water vapor; some of the precipitation that falls on the landscape is evaporated and transpired and is no longer available for local use – although that vapor will subsequently precipitate somewhere else (Ellison et al. 2012).

To a large extent, topography and geology govern the first function, and this chapter will focus on the latter two functions. In the presence of a large reservoir (e.g., greater than 10% of mean-annual streamflow, Guswa et al. 2017), the dispersal of water in time provided by the landscape is irrelevant to water supply, and the effects of the landscape are straightforward: more evapotranspiration means less water. Multiple reviews indicate that reduction in forest cover results in less evapotranspiration and more available water (Andréassian 2004; Bosch and Hewlett 1982; Brown et al. 2013; Bruijnzeel 2004). Similarly, Filoso et al. (2017) synthesized results from 167 papers that reported the effects of forest restoration on water yield from 308 sites globally; 80% of the sites reported a decline in water yield following restoration.

When reservoir storage is not available (or only modestly available), however, the timing of water availability, not just the total amount, becomes important. In such cases, the interaction of two functions – the loss of water to evapotranspiration and the dispersion of water in time – leads to complexity in the system and prevents the development of simple rules of thumb for the effects on water supply. Some investigators have found that increased forest cover leads to increased low flows (e.g., Ogden et al. 2013; Price 2011), whereas others have found that forests lead to both lower average yield and lower low-flows (e.g., Brown et al. 2013; Scott and Lesch 1997). The ambiguity is consistent with the synthesis by Filoso et al. (2017) who found that forest restoration resulted in a reduction of baseflow for 63% of the sites and an increase or no change in baseflow for 37% of sites.

These contradictions are sometimes explained by separating the effects of vegetation from soils (Bruijnzeel 2004). While taller vegetation and increased leaf area (e.g., forest vegetation) results in increased evapotranspiration, uncompacted soils with high organic content and macropores (e.g., forest soils) increase infiltration and extend the residence time of water in the soil. Another hypothesis is based on the seasonality of low flows. If the seasonality of low flows coincides with the seasonality of precipitation, that is, if low flows are due to precipitation drought (as they are in Mediterranean climates), then increases in forest cover that increase infiltration during the wet season may increase low flows (Guswa et al. 2007). However, if the seasonality of low flows coincides with the seasonality of actual evapotranspiration (as it does in the eastern USA), then increases in forest cover may further reduce low flows (Guswa et al. 2017).

The uncertainty of the effect of landscape change on low flows makes simple predictions of the effect of natural infrastructure on water supply challenging. Depending on the decision context and the precision required, a number of models and tools are available to the engineer.

Estimates of water yield with reservoir storage Guswa et al. (2017) provide a methodology for determining the potential impacts of landscape change on water supply as a function of reservoir size. Another example using integrated modeling is proposed by Guo et al. (2000). Large reservoirs obviate the need for the temporal dispersion function of a watershed, and a simple model of annual water yield may suffice. Examples include the InVEST annual water-yield model (Sharp et al. 2019) and others that are based on the Budyko curve (Budyko 1961).

Annual estimates of yield without reservoir storage In this case, estimates of annual water yield need to be supplemented by the separation of that yield into baseflow and stormflow components, and it is the baseflow that provides the steady, reliable supplies. Guswa et al. (2018) developed a simple model based on the NRCS curve-number approach to separate annual streamflow into baseflow and stormflow components.

Monthly estimates of yield without reservoir storage A number of parsimonious hydrologic models operate at the monthly scale, for example, abcd (Thomas et al. 1983), HBV (Bergström 1995), and DWBM (Zhang et al. 2008). These models are simpler than semidistributed and fully distributed daily models, though the connection between landscape changes and effects on model parameters is less direct. Nonetheless, Hamel et al. (2017) demonstrated that the DWBM model provides estimates of the relative changes in minimum monthly flows due to changes to the landscape that are robust with respect to parameter uncertainty. The InVEST seasonal water-yield model is a spatially explicit model of monthly flows that enables the spatial attribution of baseflow generation (Sharp et al. 2019).

Daily estimates of water yield Trading simplicity for sophistication are a set of models that operate at the daily or subdaily timescale and represent space in a semidistributed or fully distributed way. Semidistributed models, such as SWAT (Neitsch et al. 2011), PRMS (Leavesley et al. 1983), VIC (Liang et al. 1994), and TOPMODEL (Beven and Kirkby 1979), separate the landscape into a set of hydrologically similar groups based on topography, soils, and land-cover. Fully distributed models, such as MIKESHE (DHI 1998), GSFLOW (Markstrom et al. 2008), and HSPF (Bicknell et al. 1997), represent the landscape as a grid of connected pixels, each with its own characteristics. All of these models have a significant level of complexity and require a knowledgeable user to implement for a particular site.

9.2.3 Water Quality Management

When it comes to attributes of water quality (sediment, nutrients, and pathogens), the effects of natural versus human-modified landscapes are clearer, though often difficult to quantify. With respect to water quality, the landscape and ecosystem perform a set of functions:

- Generation – in addition to point sources of pollution, landscapes serve as non-point-sources of sediment, nutrients, and pathogens.
- Physical retention and dilution – topography, flowpaths, and land-cover will dictate which parts of the landscape have the potential to retain contaminants from upgradient.
- Transformation – biogeochemical processes operating on the landscape have the potential to transform nutrients and pathogens and remove them from water.

In the United States, the water-supply system for the city of New York is a famous example of the value of these processes to water quality. From the early 1990s through 2017, New York spent over $1.7 billion on natural infrastructure so as to avoid a $10 billion filtration facility with a $100 million/year operational cost (Hu 2018). The cities of Boston, MA; San Francisco, CA; Portland, OR; and Seattle, WA, also avoid the need to filter their water supplies via the benefits of natural landscape processes and watershed management. Globally, McDonald et al. (2016) examined the effects of watershed degradation on water treatment costs for large cities from 1900 to 2005; average pollutant yields for degraded watersheds increased by 40% for sediment, 47% for phosphorus, and 119% for nitrogen. For 29% of cities, watershed degradation led to increased treatment costs: 53% increase in O&M and 44% increase in capital costs (McDonald et al. 2016).

In contrast to low flows (see above), the direction of change of the effects of landscape change on sediment, nutrients, and pathogen concentrations can usually be predicted. However, quantification of the magnitude of the effect can be highly uncertain. Therefore, reliance on natural infrastructure to achieve water quality goals is best suited for sediment and nutrients, that is, those constituents for which the impact results from an aggregate effect and for which the tolerance for variability in performance is higher. For pathogens (e.g., bacteria, viruses, parasites), tolerance for uncertainty is less, as even a low concentration or localized outbreak can have a significant impact (Jasper et al. 2013). While natural landscapes do play a significant role with respect to human health and infectious disease (e.g., Herrera et al. 2017; McFarlane et al. 2013), the ability to design natural-infrastructure solutions with the required level of certainty is still developing.

With respect to sediment, natural landscapes both limit generation and can provide physical retention. In the northeast United States, erosion from forests is quite low, with sediment yields of 25 kg/ha/r to 250 kg/ha/yr (Patric 1976; Patric et al. 1984; Wolman and Schick 1967). Erosion from agricultural land is 10–100 times as much (de la Cretaz and Barten 2007). Yields from urban construction and development, if not properly mitigated, can be even greater, and Wolman and Schick (1967) reported yields of 7000 to 490,000 kg/ha/yr. for sites in Maryland.

When positioned downgradient from sources, both wetlands and riparian buffers have been shown to reduce sediment loads to receiving water bodies. While both forest and grass strips are effective at trapping sediment, grasses are particularly effective due to both the density of vegetation cover at the ground surface and to their tendency to spread water over a large area (de la Cretaz and Barten 2007). Trapping efficiencies range from 50% to nearly 100% and vary with buffer width, vegetation type, and grain-size distribution of the sediment (de la Cretaz and Barten 2007).

In addition to retaining nutrients that are transported with sediment (e.g., phosphorus and ammonium), riparian wetlands and vegetated buffers can also transform nitrate to nitrogen gas via denitrification – an anaerobic process. Vegetation also takes up both nitrogen and phosphorus, though much of those nutrients may be returned as litter fall at another time, and overall removal efficiency is uncertain. Studies of nitrate reduction show removal rates that range from 25% to 95%

(de la Cretaz and Barten 2007); phosphorus removal is even more varied, with some studies showing an increase in phosphorus from best management practices (Schechter et al. 2013).

Because of the significant uncertainty associated with the natural transport and transformation of water contaminants, modeling tools for design are few. For simple assessments of the effects of land-cover and land-management on the generation, transport, and transformation of sediment and nutrients, the InVEST model (Sharp et al. 2019) provides annual estimates of nutrient and sediment loads. Operating at the daily to sub-daily timescale, the Soil-Water Assessment Tool (SWAT) is a semi-distributed model developed for agricultural management that has seen wide application for the simulation of water, nutrients, and sediment transport (Neitsch et al. 2011). For urban environments, the US EPA distributes and maintains the Storm Water Management Model (SWMM). This dynamic hydrologic and hydraulic model simulates water quantity and quality and can incorporate green infrastructure, such as rain gardens, green roofs, and permeable pavement (Rossman 2015). HSPF (Hydrological simulation program – FORTRAN) is a fully-distributed, dynamic model that simulates the transport of both point and non-point sources of pollution at the watershed scale (Bicknell et al. 1997), as does the MIKE series of models (DHI 1998).

9.3 Designing with a Mix of Conventional Infrastructure and Nature-Based Solutions

9.3.1 Systemic Approach: Cobenefits, Disservices, and Beneficiaries

Cobenefits and Disservices

While natural infrastructure is not always superior to gray infrastructure, there are cobenefits associated with natural infrastructure that are not present with gray. Table 9.1 presents the suite of cobenefits, ranging from provisioning services (e.g., food production in community gardens), to regulating services (air quality improvement, carbon sequestration), and cultural services (tourism, mental health). These benefits are now well accepted, and ES scientists have developed methods to analyze and quantify their contributions to society (Haase et al. 2014; Pataki et al. 2013).

On the other side of these benefits, there are potential disservices associated with NBSs. We already mentioned the disservices related to water resources management in Sect. 9.2: the use of water by vegetation, which reduces availability for other uses, and the potential net source of nutrients, which can be detrimental to freshwater ecosystems. In addition to those, NBSs may negatively impact human health and well-being through potential disservices that mirror the cobenefits listed in Table 9.1. For example, street trees and urban vegetation may produce allergenic pollens, thereby reducing air quality. Urban vegetation may provide habitat for unwanted species. Other disservices include potential insecurity (in the case of poorly lit areas and potentially dangerous wildlife in urban parks) or net positive carbon budget associated with construction or maintenance of NBSs (Keeler et al. 2019). These disservices need to be included in assessment of NBSs and alternative management solutions to consider the full impact of engineering decisions.

Beneficiaries

Central to the concept of ecosystem services is the definition of beneficiaries, that is, people benefiting from the implementation of a NBSs. Beneficiaries of hydrologic services are mainly determined from their exposure and vulnerability to water-related risks – flooding and water scarcity. For flood risk, the position on the landscape, for example, in flood plains and low-lying areas, will be a primary determinant, together with metrics of social vulnerability (e.g., age group, language) or vulnerability of built infrastructure (housing quality). For water scarcity, whether it results from a water quality or quantity issue, beneficiaries will depend on the local and regional water resources management: whether people source water from surface or subsurface water, which treatment options are available, etc. Assessing beneficiaries and understanding the potential equity issues associated with management options can be facilitated by ecosystem services tools such as those cited above (e.g., InVEST, ARIES).

9.3.2 Practical Opportunities and Constraints

In addition to ecological factors, there are practical opportunities and constraints associated with NBSs. An important consideration is cost, which is difficult to evaluate in generic terms. Sometimes, NBSs have a clear economic advantage (e.g., New York City, in Sect. 9.2.3, and São Paulo, in Sect. 9.4.1); in other cases, the cost of NBSs may be greater than conventional engineering solutions, especially when accounting for both construction and maintenance costs. Indeed, in a 2017 survey, 26 of 31 US municipalities reported green infrastructure was more challenging than gray infrastructure with respect to developing project operation and maintenance cost estimates (U.S. Government Accountability Office 2017). Uncertain and potentially higher costs may present opportunities for partnerships when ecosystem cobenefits are taken into consideration. For example, a subterranean concrete box for stormwater retention may be cheaper than a bioretention basin; however, the latter may provide an opportunity for a water utility to partner with another public agency (e.g., parks and recreation), a private institution (e.g., golf course), or nonprofit group or neighborhood association.

Additionally, since they rely on ecosystem functions, NBSs are less generalizable across geographies than gray infrastructure (Pataki 2015). And, since the designs are visible (as opposed to buried), natural infrastructure also requires greater attention to community norms and values (Nassauer and Raskin 2014). Similarly, local legal and regulatory frameworks vary in their acceptance of nature-based solutions and may require long-established technologies. Thus, when compared with traditional engineering designs, place and location take on greater significance for natural infrastructures and NBSs require greater collaboration with ecologists, landscape architects, planners, and regulators.

9.3.3 Incorporating Synergies and Trade-Offs into Engineering Projects

The last two sections have illustrated the multiple dimensions defining the performance or feasibility of NBSs. To incorporate these dimensions into engineering projects, a suite of tools is available from the fields of policy analysis, engineering, and integrated environmental modeling (Jakeman et al. 2008). Often, the goals of an assessment are to synthesize multiple objectives, reduce or quantify uncertainty, and facilitate comparison among different solutions. Classical decision-support tools like multicriteria decision analyses, economic valuation and cost-benefit analyses, or robust decision-making are among the most common examples, and ad hoc tools have also been developed to support decisions related to NBSs. For example, RIOS (Vogl et al. 2015) was developed to aggregate biophysical information, costs, and other practical constraints to support the siting of NBSs for a range of water-related objectives. For stormwater management objectives, SUSTAIN supports stormwater engineers to evaluate the cost-effectiveness of NBSs in their watersheds (U.S. EPA 2011).

While the above tools were designed to address specific questions, the eco-engineering decision scaling approach developed by LeRoy Poff et al. (2015) is a holistic framework that aims to support an entire project. It was developed to explicitly address multiple objectives and perspectives on water management (from ecologists and engineers), and deal with hydrologic or future climate uncertainties. The framework comprises five steps: (i) stakeholder engagement to define management options, performance indicators, and failure points; (ii) development of a systems decision model representing the important relationships between hydrologic variables, performance indicators, and external drivers; (iii) vulnerability analysis to assess the response to a change in climate or external drivers; (iv) comparison of available management options and definition of alternatives; and (v) assessment of the feasibility of the solutions. Importantly, step ii) requires a good understanding of the performance of NBSs proposed in the project and is subject to the modeling constraints described in Sect. 9.2. Similar practical frameworks are being developed by engineering companies and multilateral banks, such as the World Bank guidebook “Integrating Green and Gray (Browder et al. 2019)”.

9.4 Case Studies

9.4.1 Water Supply: Green-Gray Infrastructure Planning in São Paulo

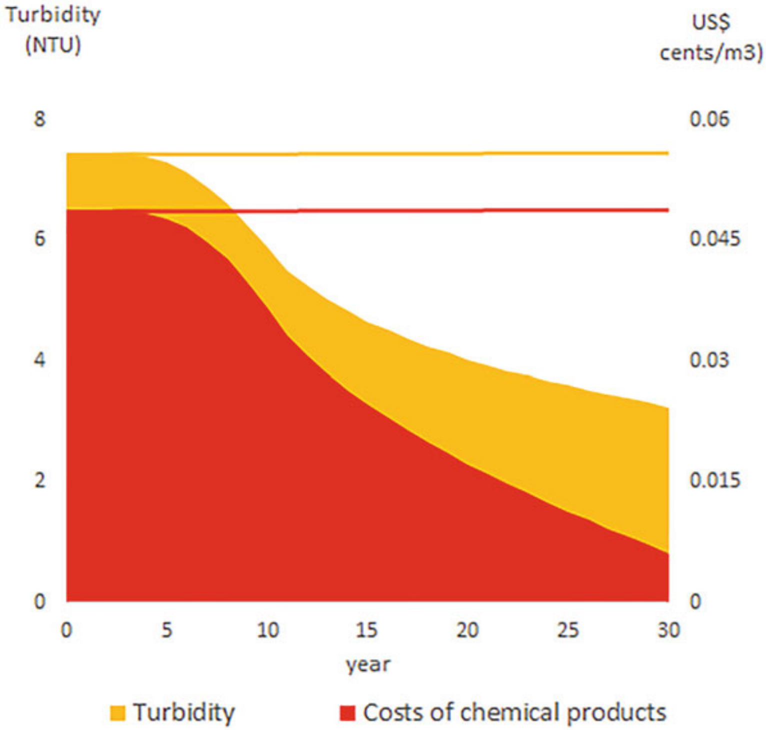
The São Paulo Metropolitan region faced a major drought in 2014–2015. By February 2015, the production of the Cantareira system, the city's primary water-supply system, had fallen to less than half of its typical production, with reservoir levels reaching a historical low. This crisis had important political and financial implications – the estimated losses for the water utility were around US$470 million (Sabesp 2015) – and it renewed discussions about the resilience of the water system. In 2016, a consortium of organizations (The World Resources Institute, The FEMSA Foundation, The Nature Conservancy, the International Union for Conservation of Nature, Instituto BioAtlântica, and the Boticario Group Foundation) joined forces to assess the value of green and gray infrastructures as a water-supply strategy.

The assessment built on the green-gray infrastructure methodology developed by WRI (World Resources Institute 2013), a framework to compare NBSs and traditional infrastructure in a systematic way. The assessment compared several scenarios of reforestation and conservation in the Cantareira system by assessing their effect on sediment export and sediment treatment costs. The analyses found likely cost savings, through reduction in water-treatment costs, from forest restoration and conservation in target areas (Ozment et al. 2018). These savings increased as initial investments were made, assuming a rate of vegetation growth (and therefore sediment retention service) over 30 years. Location of forest restoration or protection projects within the watershed strongly affected the estimated impact, given the role that near-stream ecosystems play in retaining sediment flows.

Two points are worth reflecting on in this study: first, large uncertainties were noted in the sediment and baseflow modeling analyses. The potential baseflow increase due to increased infiltration was not included in the financial analysis due to large uncertainties. Knowledge gaps in hydrological modeling thus remain one barrier to information. Second, even with this uncertainty, the business case was an opportunity to engage diverse groups of stakeholders (water utilities, investors, NGOs) in a reflection on the value of green infrastructure, and provide a concrete road map for the group (Ozment et al. 2018). It spurred a conversation on the multiple facets of forest protection, in particular with regard to the participation of rural communities whose lands are affected by projects.

9.4.2 Water Quality: Combining Infrastructures to Address Combined-Sewer Overflows in Boston Harbor

The clean-up of Boston Harbor in the late 1990s and early 2000s is one of the great environmental success stories of recent history (Dolin 2008). The construction



of the massive wastewater treatment facility (peak capacity of 1.2 billion gallons per day) transformed Boston Harbor from "the dirtiest harbor in America" to one that is swimmable in only a few years (MWRA 2014). Despite this success, the historic infrastructure of the Boston area that combines stormwater with sanitary sewage continues to present challenges; during times of heavy rain, some of the combined sewage is discharged directly to Boston Harbor. In August 2012, the U.S. Environmental Protection Agency (U.S. EPA) issued a consent decree that required the Boston Water and Sewer Commission (BWSC) to "minimize the discharge of sewage and other pollutants into the water bodies in and around Boston" (U.S. Department of Justice 2012).

Problems of combined-sewer overflows (CSOs) are not unique to Boston, and the U.S. EPA has articulated that combinations of gray and green infrastructures can provide viable and cost-effective solutions (U.S. EPA 2014). Gray infrastructure solutions include sewer separation and off-line storage (i.e., storage of wet-weather flows in tanks or basins to be treated later). By reducing the quantity and/or rate of stormwater flows into combined sewers, green infrastructures – such as bioretention basins, green roofs, and tree trenches – can reduce the size and need for gray infrastructure (U.S. EPA 2014). Because green infrastructure affects both the quantity and timing of runoff, the integration of hydrologic and hydraulic models improves predictions of the effects on combined-sewer overflows (U.S. EPA 2014).

In Boston, projects to demonstrate the efficacy of integrated gray and green strategies are underway. In October 2017, the BWSC celebrated the completion of a green infrastructure project at the Washington Irving Middle School. That project – a partnership between the BWSC and the Boston Public Schools – comprises replacement of paved areas with green space, the construction of a vegetated swale, and the addition of an outdoor classroom and bioretention area (City of Boston 2014). Additional projects are being designed or implemented for four other public schools, along with other sites, including City Hall Plaza.

9.5 Discussion

9.5.1 Synergies Between Engineering and Ecosystem-Services Science

In the introduction, we proposed that ES science could contribute to IWRM by (i) incorporating ecological functions as opportunities and constraints in engineering design, (ii) developing approaches to better incorporate people into the design phase, and (iii) better communicating the value of nature to a broad range of stakeholders. The case studies illustrated key points related to each of these potential benefits.

First, with regard to ecological functions, the São Paulo case study highlighted the role of ecology and ecohydrology in supporting the implementation of NBSs. Engineering projects will benefit from more knowledge on the behavior of NBSs with regard to sediment retention and baseflow, especially how the type, location, or maintenance of vegetated systems will affect their performance. Second, forest protection and restoration projects in São Paulo spurred reflections on the operational constraints and opportunities, for different beneficiary groups: the water utility, a direct beneficiary of the services, but also rural communities who are key stakeholders in these projects. ES science recommends the use of participatory approaches to better incorporate the knowledge and interests of these communities into project design. Finally, both case studies illustrated that NBSs can serve to raise awareness and educate the public. The NGO consortium in São Paulo helped advance the conversation on green infrastructure by evaluating the economic benefits of NBSs (and their potential cobenefits). The Boston stormwater management demonstration projects contributed to raise awareness on the role of nature among students, who learn about the water cycle, pollution control, and ecological issues.

9.5.2 Implications for Teaching Water-Resources Engineering

The incorporation of natural infrastructure and hydrologic ecosystem services into water-resources designs merits a shift in mindset when it comes to teaching water-resources engineering. Three facets characterize the shift from traditional engineering thought.

Borrowing from medicine, the first shift is a reorientation to first look for opportunities for prevention over treatment. That is, as our cities and urban areas grow and expand, look first to the preservation of landscape characteristics that benefit water resources, such as infiltration. The ability to recognize such features and to create designs that retain such features will be important skills for engineers of the future.

The second shift is to complement reductionist approaches with integrative thinking. The ability to break a complex system into simpler component parts is a powerful skill in engineering. At the same time, cobenefits that reach across multiple sectors are a primary strength of natural infrastructure. Design engineers must be able to articulate to clients and stakeholders the worth of these multiple benefits along with the achievement of the primary water-resources objectives. This requires an ability to work with experts across multiple disciplines, including ecology, economics, and landscape architecture.

Third is to shift from designing-to-avoid-failure to creating designs that acknowledge and tolerate uncertainty in performance. This shift is necessitated by both the greater degree of uncertainty associated with natural infrastructure and the recognition that our climate is changing. Design approaches that require stationarity and well-understood materials are not suitable for incorporating natural infrastructure into water-resources engineering under a changing climate.

More than new tools or models, engineering education must include this expansion of the engineering mindset – loss prevention, integrative thinking, embracing uncertainty – in order to effectively incorporate natural infrastructure into water-resources designs.

9.6 Summary and Outlook

This chapter presented the state-of-the-art on the role of NBSs for providing three water services: flood risk mitigation, water supply, and water quality management. The key processes through which NBSs provide water services are well accepted, allowing, in theory, an understanding of when NBSs may usefully complement traditional infrastructure. However, uncertainties related to the magnitude of these processes impede the incorporation of NBSs into the engineering toolbox.

To promote the adoption of green infrastructure, hydrologic research needs to further progress to improve process understanding: in particular, to better quantify the magnitude of hydrologic services and disservices provided by NBSs. In addition, the development of new tools and approaches in engineering will facilitate the implementation of NBSs, in replacement of or in combination with traditional infrastructure. Such approaches include participatory approaches to include stakeholders in the design of NBSs, valuation methods to quantify cobenefits and disservices, and multicriteria assessment methods to compare engineering solutions across multiple dimensions. In parallel to the research conducted in each of these directions, engineering education needs to adapt to the new paradigms in IWRM – teaching students to consider the downsides of traditional infrastructure and design solutions that reflect our rapidly changing world.

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