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Performance, Appearance, Economy, and Working Method

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19 Green Infrastructure
Performance, Appearance, Economy, and Working Method

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19.1 INTRODUCTION

As the 20th-century infrastructure of the "developed" world degrades, rusts, and decays, it needs a more sustainable, resilient replacement (Bélanger 2013). The 20th-century modernist-functionalist urban infrastructure reflects single-purpose efficiency thinking and depends on energy-intensive materials and performance (National Academy Press 1986). If the predominately urban world of the 21st century embraces the global aspiration for sustainability, replacement of 20th-century urban infrastructure should not rely on such modernist, specialized single-purpose

Urban infrastructure continuum

			
Infrastructure type	Engineered/grey	Hybrid/landscape	Greenways/ecosystems services–oriented
References	Novotny et al., 2010 National Academy Press 1986	Margolis and Robinson 2010 Bélanger 2013 European Commission 2013 FHWA 2006, UNEP 2013	Benedict and McMahon 2006 Maryland Dept Nat Resources The Conservation Fund 2013 Sustainable Sites Initiative 2009
Construction cost	High	High-moderate	Low
Resilience	Inflexible-rigid	Variable, including rigidand regenerative	Regenerative, living systems–based
Planning strategies	Offensive	Opportunistic, offensive	Protective
Spatial genesis	Transportation utility corridors, property ownership/easements	Interstitial, complementary	Physiographic, topographic, dendritic
Functionality	Limited/single function	Explicitly multifunctional, ecosystem services–based	Ecosystem services–based, wildlife/conservation corridors

FIGURE 19.1 An urban infrastructure continuum.

infrastructure (Benedict and McMahon 2006; The Conservation Fund 2014). Rather it should employ a "green infrastructure" that provides a diverse and broad suite of biophysical and cultural ecosystem services and contributes to urban sustainability, assuring that infrastructure redundancy builds urban resilience—the ability to absorb disturbance and recover without changing to a different state. This green infrastructure—built on a multifunctional, performance-based foundation—holds the potential to reshape and redefine an aesthetic character that will define the cultural identity of future cities and urban landscapes. If green infrastructure can provide an " immersive, aesthetic experience, it can lead to recognition, empathy, love, respect, and care for the environment" (Meyer 2008). Another infrastructure is also needed in the emerging urban metropolis of the developing world. In the world's most rapidly growing cities and urban regions, urbanization often precedes infrastructure development of any type (Davis 2006). The world's emerging and developing cities therefore have the unique opportunity to "get it right the first time" and "leapfrog" the modernist/industrial phase of monofunctional, low-performance, unsustainable industrial infrastructure—and start de novo with a multifunctional ecosystem services–oriented green infrastructure. Landscape intervention experiments in Brazil and Argentina explored a range of working methods with residents of informal urban developments meaningfully engaged and local materials and building practices employed (Beardsley and Werthman 2008). In the context of developed and developing world infrastructure, urban infrastructure can be understood as a continuum from conventional/grey to green or ecosystem services–based (Figure 19.1). Engineered infrastructure is the status quo of the developed world. It is single purpose, expensive to build and maintain, inflexible and rigid to disturbance, and monofunctional. Because it is built for single functions, its spatial genesis is anthrocentric and ~~offensive~~. Hybrid or landscape infrastructure integrates engineered with ecosystem-based systems to deliver multiple functions (FHWA 2006). Its cost can vary, depending on context and function. It often occupies interstitial urban space guided by an opportunistic or offensive planning strategy. Hybrid/landscape infrastructure seeks innovative approaches to add essential ecosystem services to conventional and familiar urban forms, including roads, parking lots, and buildings. It can be understood as the infrastructure of urban sustainability. Greenways or ecosystem-based infrastructure is a protective or pre-urban development approach that is appropriate for peri-urban and urban fringe landscapes to retain functional ecological integrity (Benedict and McMahon 2006). The urban infrastructure continuum is proposed as a rubric to explain or understand infrastructure in an ecosystem services and physical form context. It is not intended as an argument for a particular typology on the continuum.

19.2 CHALLENGES FOR GREEN INFRASTRUCTURE ACCEPTANCE

Green infrastructure is defined as "spatially and functionally integrated systems and networks of protected landscapes supported with protected, artificial and hybrid infrastructures of built landscapes that provide multiple, complementary ecosystem and landscape functions to the public, in support of sustainability" (Ahern 2007). Articulating the ecosystem services provided by green infrastructure is an emerging research theme (Landscape Architecture Foundation 2014; Center for Neighborhood Technology 2014; Sustainable Sites Initiative 2009). Green infrastructure addresses the "imperative to act" to make future urban environments more sustainable through "learning by doing" in a context of rapid urban expansion or redevelopment. Green infrastructure delivers measurable ecosystem services and benefits that are fundamental to the concept of the sustainable city (Ahern 2013; Habitat U.N. 2006). Because green infrastructure is, by definition, multifunctional, the ecosystem services concept is a useful concept to apply to explicitly identify and assess its multiple functions. Landscape architecture has an unprecedented opportunity to lead in planning and designing green infrastructure in both developed and developing urban contexts. To capture this opportunity, landscape architects will need to address challenges, including performance, appearance, economy, and working method for green infrastructure.

The introduction of the term "green infrastructure"—a counterpoint to engineered infrastructure—has raised a series of questions and inspired a set of experiments, as shown here, that promise to deepen our understanding from "ecology in the city to ecology of the city" and thereby providing the tools needed to have cities that function economically but also that provide the ecosystem services that the city needs to be sustainable (Pickett et al. 2001).

But is green infrastructure technically effective? Is it cost-effective? Is it valued by the public as attractive? Can a network of protected and adapted open spaces be assessed and measured as other infrastructure networks can? Could such assessments aid decisions that concern the best solutions for urban form to support both urban resilience and development? For replacing old, single-purpose infrastructure or as a new conception? These are the challenges that a vision of landscape as infrastructure must overcome to be truly viable and applicable in different urban contexts and stages of development.

19.2.1 Performance

The multiple functions provided by green infrastructure can be understood as ecosystem services (Habitat U.N. 2006). Although these functions and ecosystem services are conceptually well understood, empirical measurements of specific functional performance are not familiar to most design professionals nor are they routinely collected or analyzed. Two recent initiatives in the United States promote monitoring of green infrastructure performance. The Landscape Performance Series is a program sponsored by the Landscape Architecture Foundation to document and assess the ecological/ecosystem performance of specific landscape projects. The series provides online resources and tools for designers to evaluate ecosystem performance and make the case for sustainable landscapes (Landscape Architecture Foundation 2014). The LAF series classifies benefits into seven categories: land, water, carbon energy and air quality, habitat, economic, materials and waste, and social. The Sustainable Sites Initiative is a "green certification" program that rates and classifies landscape projects for their overall ecological and environmental performance system for sustainable landscape certification. The initiative provides a set of economic, environmental, and social arguments for the use of sustainable landscape practices

(Sustainable Sites Initiative 2009). In answer to this challenge for performance measures, this chapter presents an original case study with empirical testing and monitoring for storm water treatment alternatives in São Paulo, Brazil.

19.2.2 Appearance

Green urban infrastructures are challenged to provide a recognizable visual, experiential expression of urban sustainability and resilience. As the modernist infrastructures manifested an industrial aesthetic and ideology, green infrastructure may give form and meaning to sustainable urban landscapes. To be accepted by the public and to realize long-term public support, sustainable cities of the future need to have both sound ecosystem-service performance and provide high-quality aesthetic and cultural character that is recognized, understood, and valued by the general public and by local resident stakeholders (Mussachio 2011; Nassauer et al. 2009). Elizabeth Meyer (2008) asks, can landscape increase the sustainability of the biophysical environment through the experience it affords?

On the reference list, Mussachio is spelled Musacchio. Please confirm the spelling and ensure it is correct throughout.

Green infrastructure employs living systems, sharing the biotic capacity to process information and learn. This intrinsic regenerative ability derives from both abiotic and biotic processes (Margolis and Robinson 2010). When this biotic/regenerative capacity of green infrastructure is legible, it contributes to a new urban aesthetic of sustainability in which performance is integral with appearance.

19.2.3 Economy

The new green infrastructure must function efficiently in economic terms if it is to be sustainable. Infrastructure must support each city in realizing its economic potential. Green infrastructure is often less expensive than conventional engineering (European Commission 2013). If green infrastructure is economically inefficient, it will likely fail as a passing fashion or green indulgence. Both the Sustainable Sites Initiative and the Landscape Performance Series in the United States emphasize explicit measures of green infrastructure economic performance, including cost comparisons with conventional infrastructure systems (Sustainable Sites Initiative 2009; LAF 2013; City of New York Parks and Recreation 2013). Cities that have actively pursued sustainability through green infrastructure practice cost accounting to monitor economic cost and performance.

On the reference list, the LAF citation is dated 2014. Please confirm the date and ensure it is correct throughout.

19.2.4 Working Method

To achieve high-performance infrastructure that is supported by the public and contributes to cultural identity will require new "transdisciplinary" working methods engaging all design professions with stakeholders and decision makers—so that all contribute to and are invested in the GI solutions. Without legitimate, tested, and verified performance, green infrastructure may ultimately fail in the realm of public and political acceptance. A truly transdisciplinary approach engages design professionals, scientists, decision makers, and stakeholders and integrates an inclusive diversity of human perspectives and values throughout the design or planning process. In an interdisciplinary working method, design professionals may consult with stakeholders at the "scoping" stage of a project and again to consider alternative proposals. In a transdisciplinary approach, knowledge and information is generated and flows multilaterally and continuously among the participants (Tress et al. 2005). Consequently, a transdisciplinary approach is more likely to be understood and valued by the urban community over time.

19.3 ADAPTIVE DESIGN AND DESIGNED EXPERIMENTS

Adaptive design is a transdisciplinary method for planning and design that addresses uncertainty and promotes innovation through a "learning by doing" approach in which designs and plans are conceived as experiments that can adapt if the results fail or to learn new approaches and practices if the experiments succeed (Jansson and Lindgren 2012; Ahern 2011; Nassauer and Opdam 2008; Felson and Pickett 2005). Adaptive design tests, in situ, new solutions and combinations of functions. And it is well suited to "safe-to-fail" design experiments in which innovations are implemented and monitored in an experimental but fine-scale mode in which the possibility of failure is understood and acceptable. Because these small-scale designs are true experiments, the possibility of failure is real, but the risks of failure are explicitly understood and accepted by decision makers and stakeholders (Ahern 2011). Urban design experiments are defined as collaborations among scientists, planners, and designers collaborating to insert experiments into the urban mosaic, balancing ecological goals with context, aesthetics, amenity, and safety (Musacchio 2011; Rottle and Yocum 2011; Felson and Pickett 2005; Lister 2007; Pickett et al. 2004).

Adaptive design starts by articulating an explicit set of planning or design goals or objectives, presented as specific, desired ecosystem services, for example, hydrology, climate mitigation, habitat provisioning, or cultural/social services. These goals are then prioritized in a transdisciplinary process, including scientists, design professionals, decision makers, and stakeholders. The prioritization decision incorporates social concerns and economic and scientific feasibility (Dickinson et al. 2012). With the goals prioritized, designs are structured as "safe-to-fail" experiments to test alternative spatial configurations and treatments. Indicators and metrics are identified to measure the performance of the respective design experiments in terms of the specific, prioritized ecosystem services. These metrics may include, among others, water-quality parameters, storm water infiltration rates, observations of social use and activity, biodiversity indicators, and economic cost-effectiveness. At this point, the data obtained from monitoring of design experiments can support an adaptive design process in which designs or management practice are modified, "adapted" based on the performance of the design experiment. Because specific goals were preestablished for particular ecosystem services, the monitoring results will show to what extent the built experiments produced the desired results. If the results meet expectations, the design experiment is confirmed, and perhaps an innovative approach has been validated. If the results do not meet the desired goals, the design experiment is not a failure but rather an example of "learning by doing." Figures 19.2 and 19.3 illustrate monitoring methods and systems to monitor the ecosystem service performance of green infrastructure for water-quality improvement and biodiversity support.

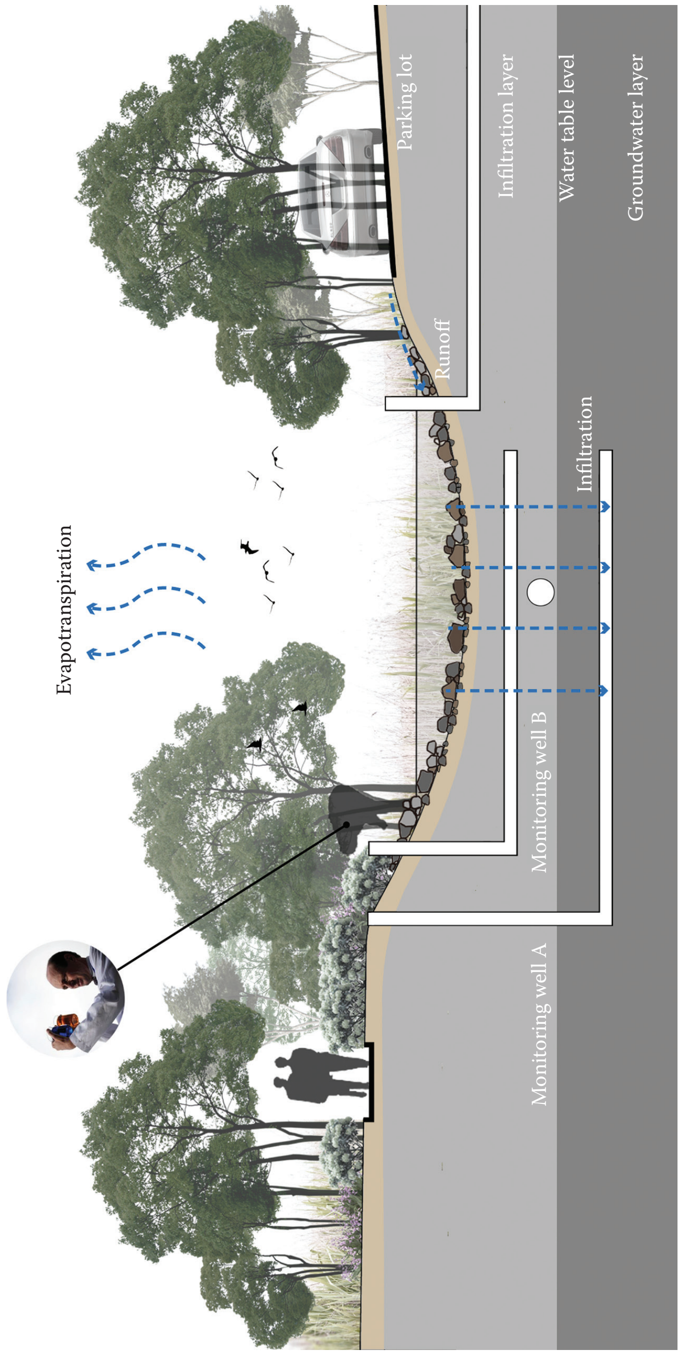

FIGURE 19.2 Monitoring water quality with monitoring wells installed at multiple depths to test the performance of rain-garden soils to improve storm water quality. (Image courtesy of Zhangkan Zhou.)

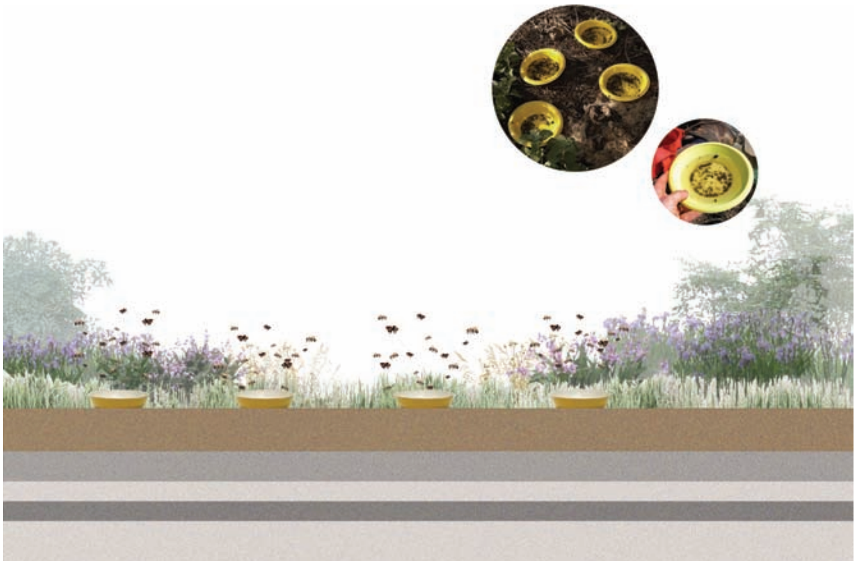

FIGURE 19.3 Monitoring insect pollinators in green infrastructure. The pan-trap method attracts insect pollinators with yellow-colored pans filled with soapy water. The number and diversity of species can be monitored at regular intervals to document the pollinating ecosystem service, for example, from a green roof. (Image courtesy of Bin Liu.)

19.4 GREEN INFRASTRUCTURE, CLIMATE CHANGE, AND THE INCREASE IN EXTREME RAINFALL IN THE STATE OF SÃO PAULO, BRAZIL

The most common motivation for and the application of urban green infrastructure is to manage storm water quantity and water quality (White 2010). This water-centric trend is likely to continue because hydrology is a fundamental physical and ecological process: All life depends on water; government regulations address water resources, water transports materials and nutrients, and cities are increasingly facing challenges to manage larger amounts and frequencies of extreme rainfall (Novotny et al. 2010).

The pattern of rainfall in southeastern South America analyzed by Re and Barros (2009) from 1959 to 2002 found an increasing trend in annual rainfall and increases in the frequency of high-precipitation events, defined as 50–150 mm/day. A specific study for the state of São Paulo, Brazil, from 1950 to 1999 identified a significant increase in the number of days with rainfall above 20 mm and of the maximum rainfall in five-day periods (Dufek and Ambrizzi 2008). Future climate change scenarios for South America developed by the Intergovernmental Panel on Climate Change (Alley et al. 2007) and Grimm (2011) predict a significant increase in extreme precipitation events. In the state of São Paulo, the concurrences between simulations and recent empirical observations of extreme precipitation events reinforce the likelihood of increased intensity and frequency of extreme climatic events in the future (Marengo et al. 2009). Projections by the Brazilian National Institute for Space Research (INPE) for the Metropolitan Area

On the reference list, the Nobre et al. citation is dated 2010. Please confirm the date and ensure it is correct throughout.

of São Paulo (MASP) between 2070 and 2100 predict a doubling in the number of days with over 10 mm of rainfall (Nobre et al, ~~2011~~). There is therefore a clear consensus regarding the increase in the frequency and intensity of the heaviest rains in the state and metropolitan region of São Paulo. This trend provides a strong rationale to reevaluate existing storm water management policies and practices and to consider a green infrastructure approach. Here an adaptive approach to green infrastructure planning and design could be an important part of the solution—promoting "learning by doing" and design experiments to promote a culture of experimentation and innovation.

The current scenario of rapid urban development and urban sprawl in a context of increasing heavy precipitation has favored conventional solutions to urban drainage. Because these conventional, monofunctional engineered solutions have provided effective flood control until recently, they have gained respect and acceptance and have been widely implemented (Marengo et al. 2009). The promise of control and precise predictability supports a flood-management philosophy favoring rapid conveyance to detention reservoirs without prior treatment. However, these systems have already reached or exceeded their capacity without consideration for expected increases in extreme precipitation associated with climate change. This conveyance-based, monofunctional flood control infrastructure causes significant impacts including non-point source water pollution and sedimentation in the receiving rivers. In addition, this conventional infrastructure provides few, if any, of the collateral ecosystem services that are provided by green infrastructure.

19.5 THE SANTO ANDRÉ GREEN INFRASTRUCTURE STUDY: HOW MUCH COULD GREEN INFRASTRUCTURE HELP WITH URBAN FLOOD MANAGEMENT IN A SÃO PAULO NEIGHBORHOOD?

The 45 ha Santo André sub-basin is located within the São Paulo metropolitan area. Flood control in this basin is provided by detention reservoirs that were built in 1991. Although the reservoirs have functioned well for their intended flood-control function to date, their effectiveness in a context of increased climate change–related precipitation increases, as discussed previously, is uncertain. Analysis of the water quality of the detention reservoirs revealed the presence of pollutants, including heavy metals and high concentrations of total coliform bacteria. In addition, the detention reservoirs have a bad odor and a general unpleasant aspect. Analysis also confirmed that the reservoir and stream pollution worsens with rainfall events, transporting a myriad of non-point source pollutants to accumulate in the reservoir basins. The limitations of the monofunctional flood control approach are becoming significant and recognized by the local population and by São Paulo city officials.

To explore green infrastructure–based flood-control alternatives for Santo André, multiple bio-retention and infiltration strategies were simulated and modeled for the neighborhood. The potential volume of storm water storage was simulated for all local streets inside the catchment area for the reservoirs. In the simulations, runoff was reduced by a proposed narrowing of the paved surface of the streets and using traffic-calming practices (Figures 19.4 and 19.5). To increase infiltration, simulations

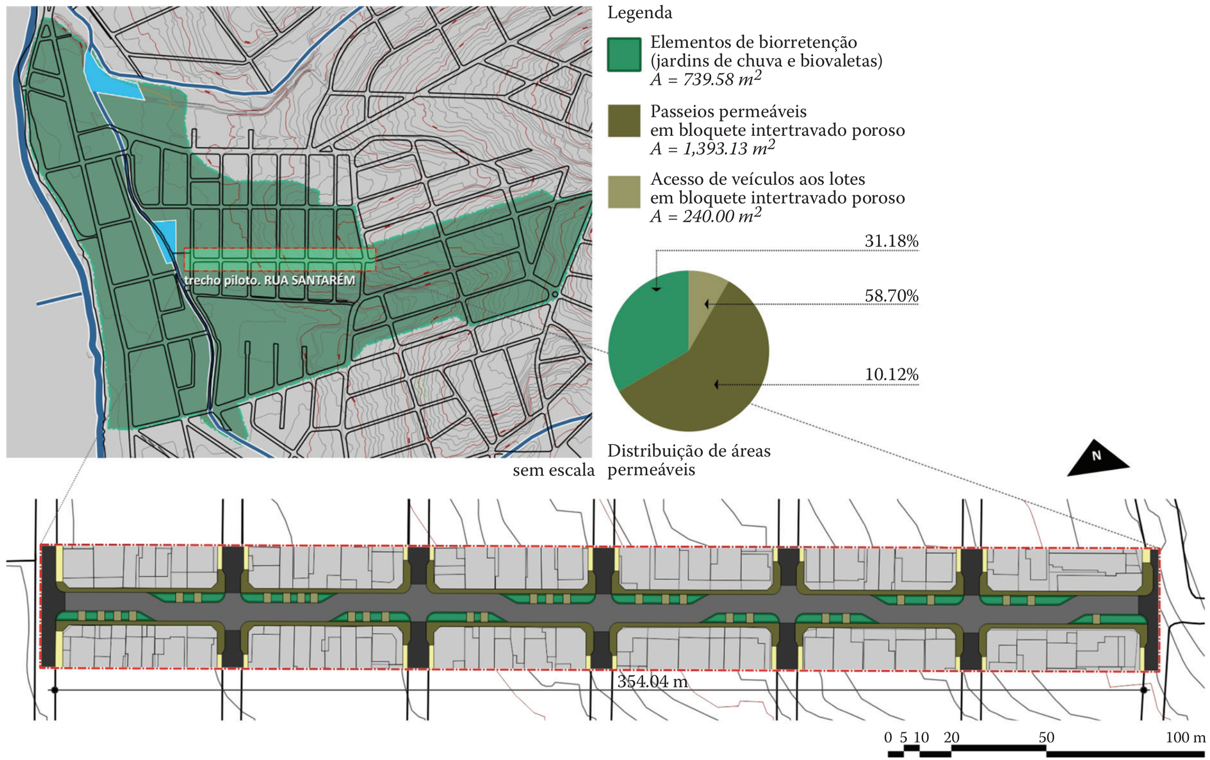

FIGURE 19.4 Proposed green infrastructure demonstrating the potential to introduce pervious green infrastructure to the neighborhood.

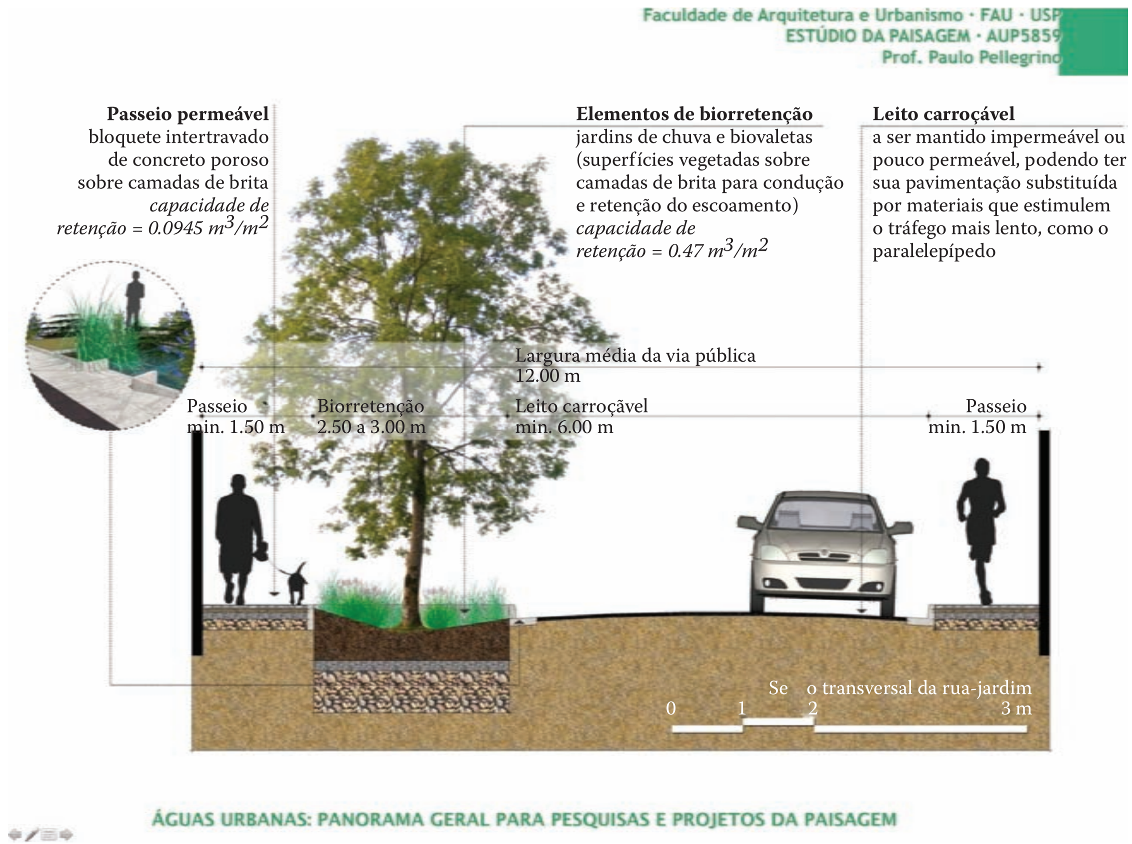

FIGURE 19.5 Proposed modifications for Rua Santarem to enhance infiltration and reduce runoff in the Santo André neighborhood, São Paulo.

were made for subsurface gravel, rain gardens, bio-swales, and permeable paving on sidewalks and building lots. The areas of these bio-retention and infiltration elements were summed, and the percentages identified were replicated for other streets through all the urban catchment area. The retention volume was calculated for each retention element and pavement construction. Even without taking into account the natural terrain infiltration and evapotranspiration and planting substrate to be held by the vegetation cover, the resulting volume of runoff that can be stored by this landscape infrastructure could add more than 42% to the capacity of the traditional detention reservoir techniques. In addition to the intended storm water management services, this landscape infrastructure would provide a broad suite of ecosystem services, including mitigating the urban heat island effect, providing wildlife habitat, and improving the aesthetic character of the neighborhood.

With the once-extraordinary climate events now occurring more frequently, it's becoming clear that cities need to prepare. One option is to use green infrastructure to clean water, defend from floods, cool the weather, enhance the ecosystems, and define neighborhood character. The challenge is to employ natural systems and processes for their ecosystem-services benefit and to integrate these natural processes with the urban fabric to make the urban landscape a sustainable and sheltering garden.

19.6 INTERDISCIPLINARY GREEN INFRASTRUCTURE FIELD EXPERIMENT, UNIVERSITY OF SÃO PAULO

A field test was designed and installed in 2012 at the University of São Paulo to test the performance of alternative rain garden/bio-retention plantings for water-quality retention and improvement. This test was part of a research collaboration between the programs of landscape and environment and hydraulic and environmental engineering at the University of São Paulo. The experiment was designed to address the specific climatic conditions in São Paulo to apply regionally familiar construction materials and practices and to examine the differential performance of native versus exotic plants in the rain garden (Dufek and Ambrizzi 2008; Moura et al. 2008). The experiment includes electronic, real-time, continuous monitoring of 21 water-quality parameters.

This test evaluated storm water runoff samples collected in its curb inlet and paired outlets to measure the efficiency of alternative treatments to improve water quality (Figure 19.6). The experiment consists of two hydrologically independent vegetated plots connected to the street gutter through a concrete channel. Each plot has its own spillway, where "outlet" samples are collected for laboratory analysis and compared to "input" street gutter runoff samples. During periods of high runoff, the surplus is directed to a drainage channel located immediately adjacent to the plots. The plots are installed in hydrologically sealed concrete basins and equally structured with 60 cm of crushed stone at the base, overlaid by 15 cm of gravel, geotextile fabric, then 5 cm of coarse sand, and, finally, 45 to 75 cm of planting substrate with side slopes (Figure 19.7). The soil surface is covered with an organic mulch. The identical substrates in each plot support two types of plantings:

FIGURE 19.6 Inlet to the University of São Paulo bio-retention experiment.

FIGURE 19.7 Paired bio-retention cells, University of São Paulo bio-retention experiment, mixed planting (M) on right and lawn (L) on left.

- Plot 1–mixed garden (M): ground covers with a predominance of native shrubs and herbaceous vegetation distributed in wetter (bottom) and drier (side slopes) zones. Diversification and proximity among species is aimed at stimulating competition, densification, biomass increase, and complete rooting throughout the planting substrate.

- Plot 2–lawn (L): covered only with emerald grass carpet (Zoysia japonica), which has been extensively used for lawns throughout Brazil. This planting followed the same shape as in the mixed garden with side slopes and bottom.

Three sets of samples were collected during precipitation events in the following sequence: gutter (G), mixed garden (M), and lawn (L). In each monitored rain event, an average of four to six samples for each point were collected with a total of 12 to 18 samples. The interval between collections and between each set of samples is the shortest possible, estimated at approximately five minutes due to the time required to fill and pack the set of sampling vials. One hundred sixteen samples have been collected during seven rain events from March 2012 to March 2013 (Tables 19.1 and 19.2).

Citation of Tables 19.1 and 19.2 were inserted here. Please check if okay.

TABLE 19.1

Water-Quality Results from Sampling at Gutter (G), Mixed-Planted Cell (M), and Lawn-Planted Cell (L), (March 27, 2012) Sets 1 and 2

		Set 1			Set 2		
Sample Collection Point		**G**	**M**	**L**	**G**	**M**	**L**
Water Quality Parameter	**Unit**	**16:05**	**16:15**	**16:25**	**17:05**	**17:12**	**17:19**
Total alkalinity	mg/L	13	61	112	15	65	107
pH		8.64	8.70	8.87	8.91	8.57	8.77
Conductivity	μS/cm	173.00	253.00	160.00	47.00	250.00	154.00
Hardness	mg/L	18.111	38.381	67.072	17.961	38.709	65.987
Calcium (Ca)	mg/L	5.04	11.51	20.53	5.05	11.54	20.09
Magnesium (Mg)	mg/L	1.59	2.78	4.56	1.54	2.85	4.56
Iron (Fe)	mg/L	10.42	0.321	0.331	10.02	0.198	0.393
Chrome (Cr)	mg/L	0.020	0.013	0.010	0.020	0.005	<0.006
Zinc (Zn)	mg/L	0.267	0.026	0.021	0.252	0.070	0.028
Copper (Cu)	mg/L	0.046	0.008	0.006	0.046	0.005	0.015
Cadmium (Cd)	mg/L	0.003	0.0002	0.0002	0.003	0.0003	0.0001
Chloride	mg/L	2.21	2.56	2.59	2.86	2.61	2.66
Sulfide	mg/L	0.047	0.032	0.012	0.038	0.040	0.018
Fluoride	mg/L	0.32	0.40	0.62	0.30	0.53	0.60
Biochemical oxygen demand	mg/L	10	<2	2	30	<2	<2
Nitrate (NO_3)	mg/L	0.65	<0.07	0.07	0.58	0.35	<0.07
Nitrite (NO_2)	mg/L	0.12	<0.02	<0.02	0.12	<0.02	<0.02
Total organic carbon	mg/L	18.10	2.10	2.90	28.40	2.70	2.80
Oils and greases	mg/L	8	<5	2	11	2	<5
Total suspended solids	mg/L	17	<5	18	17	2	7
Total dissolved solids	mg/L	104	152	96	28	150	92

Source: Operator Environment. Analysis Bulletin No. 4166/2012-1.0.

TABLE 19.2
Comparison of Results of Water-Quality Samples Showing Increases and Decreases in the Parameters Analyzed (G_0–M_f = gutter to mixed planting, G_0–L_f gutter to lawn planting) (March 27, 2012)

Indicator	G_0–M_f	G_0–L_f
Total alkalinity	415.385%[a]	707.692%[a]
pH	–3.009%[b]	–4.630%[b]
Biochemical oxygen demand	–90.000%[b]	–80.000%[b]
Total organic carbon	–86.740%[b]	–85.635%[b]
Nitrate (NO_3)	–89.231%[b]	–89.231%[b]
Nitrite (NO_2)	–83.333%[b]	–83.333%[b]
Oils and greases	–37.500%[b]	–25.000%[b]
Iron (Fe)	–97.466%[b]	–95.633%[b]
Chrome (Cr)	–85.000%[b]	–80.000%[b]
Zinc (Zn)	–91.386%[b]	–91.011%[b]
Copper (Cu)	–80.435%[b]	–73.913%[b]
Cadmium (Cd)	–43.333%[b]	–96.667%[b]
Conductivity	–10.405%[b]	46.821%[a]
Hardness	126.774%[a]	266.015%[a]
Calcium (Ca)	137.897%[a]	300.595%[a]
Magnesium (Mg)	101.887%[a]	188.050%[a]
Chloride	4.977%[a]	38.009%[a]
Sulfide	740.426%[a]	–59.574%[b]
Fluoride	65.625%[a]	87.500%[a]
Total suspended solids	–52.941%[b]	–94.118%[b]
Total dissolved solids	–10.577%[b]	46.154%[a]

[a] Increase.
[b] Decrease.

19.6.1 Discussion of the Water Quality Analysis

Both lawn (L) and mixed garden (M) treatments showed very significant reductions (mostly above 80%) in biochemical oxygen demand, total organic carbon, nitrate, nitrite, iron, chrome, zinc, and copper. This pattern of improvement in the quality of storm water runoff remained in the other monitored rain events, attesting to the efficiency of the best management practices (BMPs) under evaluation for most of the parameters. However, there were significant increases in total alkalinity, hardness, calcium, magnesium, and fluoride from both plots.

Considering the water-quality parameters selected, overall, the mixed garden (M) was more efficient than the lawn (L) in reducing the concentration of pollutants.

However, the lawn plot (L) was also effective in reducing pollution concentrations and outperformed the mixed garden (M) for reducing total suspended solids and sulfide.

As it is difficult to measure precisely the amount of pollutants from runoff, it is difficult to determine the effects of best management practices in the field. Most of the experiments and research on this issue have used laboratory-controlled environments. In the field experiment described here, the conditions of the urban realm are analyzed with no artificial interference. We can assume that similar positive findings would occur if the results of the experiment were adopted as a best management practice.

This experiment has provided scientific answers that demonstrate the effectiveness of the performance of both lawn and mixed vegetated surfaces to retain and treat storm water. With proper experimental design, this model could be routinely tested in green infrastructure projects as "designed experiments." This research should complement, not replace, conventional methods of urban drainage in local cities. Green infrastructure may be integrated with other types of infrastructure as illustrated in Figure 19.1, an urban infrastructure continuum. Changing the current storm water management paradigm in Brazilian urban areas demands a transdisciplinary alliance between private and public interests, scientists, engineers, and designers to test innovative practices of runoff retention and treatment. In a transdisciplinary approach, neighborhood residents and decision makers would be involved from the initial planning to the evaluations of alternative treatments to the detailed design decisions, importantly, to learn their impressions and opinions of the built projects over time. The collateral ecosystem services should also be monitored to learn if such green infrastructure provides multiple benefits, for example, urban biodiversity, local urban climate, and public preferences among alternatives.

In Brazil, national surface water-quality regulations only address point sources of pollution. Non-point sources from diverse sources of water pollution are not yet regulated but are known to cause substantial degradation of urban water quality. Recently published São Paulo storm water management manuals describe bio-retention typologies in isolation, focusing on their importance as elements of engineering but not of the urban landscape. For green infrastructure to be accepted as a practice to improve non-point urban water pollution as well as to provide other ecosystem services in São Paulo, it needs to be researched further with monitoring of its expected ecosystem services.

19.7 TOWARD AN ADAPTIVE DESIGN AND PLANNING RESEARCH AGENDA FOR GREEN INFRASTRUCTURE

This chapter has proposed an adaptive approach to planning and designing urban green infrastructure in which urban infrastructure, and "designed experiments" can be deployed to explore and measure its performance in public, visible locations under local ecological and climatic conditions. It argues for a redefinition of infrastructure as an emerging convergence of resources, processes, and ecosystem services that support 21st-century urbanization (Bélanger 2013). Water is the focus of much attention here because water is understood as an equally life-sustaining and erosive-hazardous force (Margolis and Robinson 2010). The acceptance of urban green infrastructure as an alternative system faces multiple challenges. The performance that green infrastructure claims to provide must be rigorously monitored over time. A culture of monitoring needs development as does an "ecosystem services assessment toolbox" with an appropriate set of indicators, methods, and monitoring protocols. Acceptance of green infrastructure depends on its provision of multiple ecosystem services, including public acceptance and aesthetic preference. To be sustainable, green infrastructure needs to provide humans with meaning, beauty, and delight (Meyer 2008). These goals warrant and deserve appropriate research methods and discussion. As economics is one of the three pillars of sustainability, so it must be included in measures of green infrastructure performance. The European Commission has adopted a strategy to promote green infrastructure citing its economic benefits as a justification (EU 2013). Adapted and new economic cost-benefits are needed to compare the lifetime costs of alternative infrastructure versus conventional. Green construction certification programs and professionally sponsored research are starting to address this challenge (Landscape Architecture Foundation 2014; Sustainable Sites Initiative 2009).

If there are other ways to equip cities, other kinds of open space design and open space networks that can somehow give rise to more resilient and pleasant cities, then we may be more inclined to ask what is so special about the existing infrastructure in our cities that cannot be a transition for a new one? Instead of a traditional centralized solid infrastructure, which is inherently fragile, can we now imagine something different, something that can synthesize nature and the city, ecology and design?

Because green infrastructure aspires to provide multiple ecosystem services, no single discipline can dominate it. A transdisciplinary approach is appropriate in which scientists, engineers, designers, planners, decision-makers, and local stakeholders are all involved, not only as consumers of knowledge, but as contributors and collaborators. Transdisciplinarity is arguably the appropriate modus operandi for sustainability but remains a rudimentary aspiration in most contemporary practice. The empirical field experiment in São Paulo presented here compared the performance of two green infrastructure options for removing specific contaminants from storm water runoff. Because the experiment was robust in its design, data collection, and analysis, the results are both useful and defensible but only for water-quality performance. Other experiments could be designed to measure and compare green infrastructure performance for economic cost-benefits, biodiversity support, climatic effects, or public preference. The São Paulo field experiment provides a model for interdisciplinary research on green infrastructure performance. To be truly transdisciplinary, green infrastructure experiments such as this should involve local stakeholders and public decision makers from the conception of what to measure, who to involve in the experiment, and how the results will be used—and by whom?

For the concept of green infrastructure itself to be sustainable, it will need to demonstrate and document its ecosystem service performance and economic value continuously and repeatedly—in every specific location that it is employed, including the cultural and social benefits associated with human use and aesthetic appreciation for the urban environment.

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