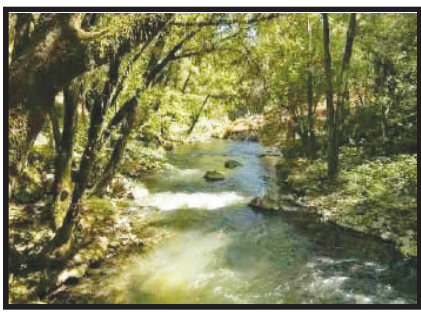
CABY Integrated Regional Water Management Plan
Proposition 84, Round 2 Implementation Grant



5 Wolf Creek Watershed: Restoration, Storm Water Source Control and Flood Management

ATTACHMENTS

5. Wolf Creek Watershed: Restoration, Stormwater Source Control, and Flood Management

The following attachments are provided in PDF form as supplemental materials to this proposal (unless otherwise noted):

- In the online package these documents are grouped into a single PDF uploaded as part of Attachment 7, entitled **Att7_IG2_TechJust_5WolfCkRefs_8of12.pdf**.
- In the hard copy package these documents are provided on DVD as separate PDFs in the folder entitled **"5 – Wolf Creek Project."**

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MAPS & CHARTS

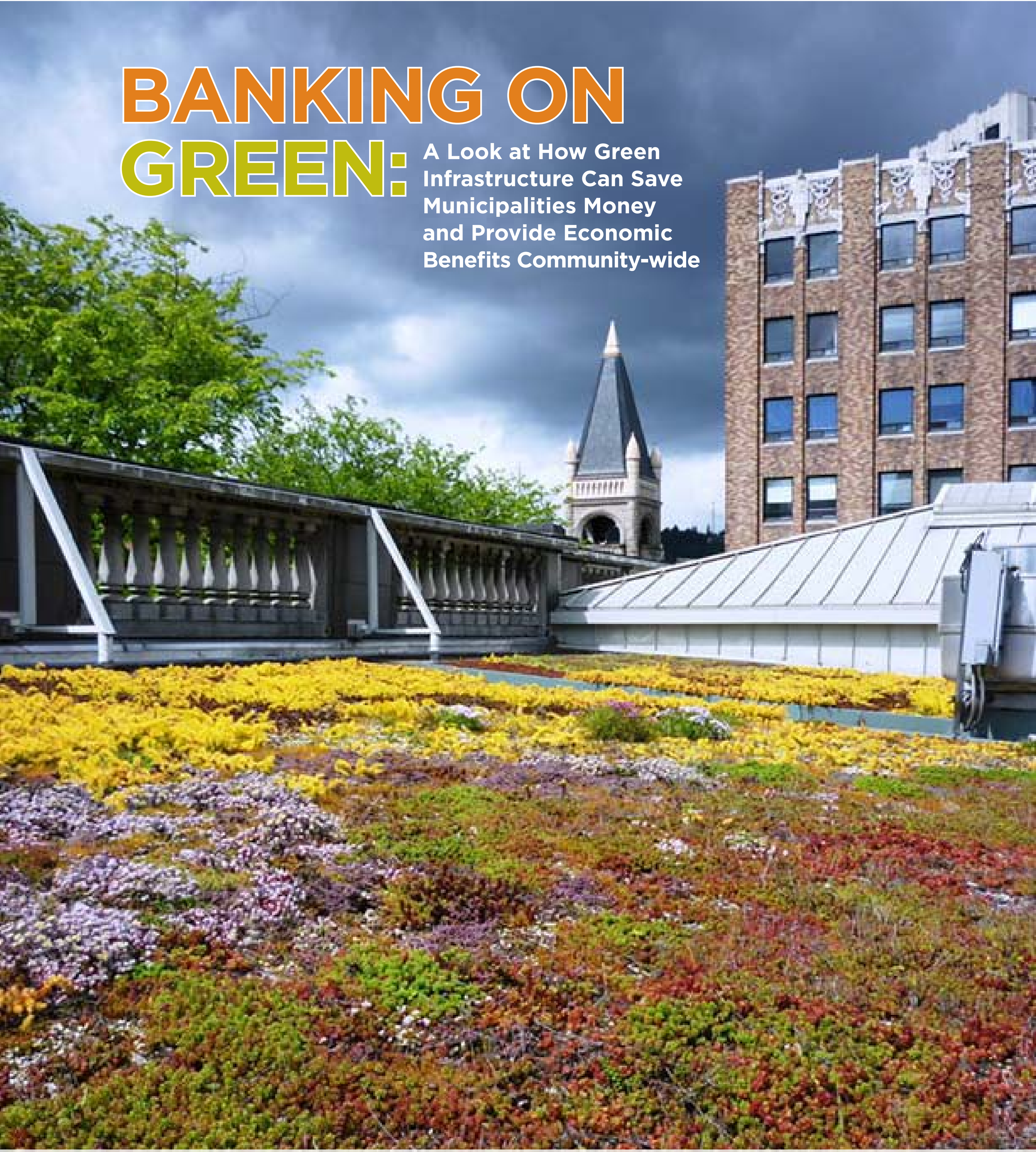
N. Project Map

O. Peabody Creek Floodplain Map

P. Project Flow Chart

BANKING ON GREEN:

A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-wide



A Joint Report by American Rivers, the Water Environment Federation, the American Society of Landscape Architects and ECONorthwest

April 2012

and maintenance expenses could be less particularly when combined with other efficiencies such as those corresponding to LEED certification. The reported cost savings over grey approaches were particularly substantial when large new equipment capacity would be otherwise necessary, or new conventional equipment would require more space than was available. In some cases planners combined grey and green components to find the most cost-effective option.

Green Infrastructure Can Be Less Costly

Examples of successfully implemented green infrastructure projects reveal the opportunities for cost-effective strategies to address stormwater and other water quality regulatory goals. Green infrastructure design and performance is generally more context-specific than grey infrastructure. This is true because these types of controls must be designed and built to suit the soil, terrain and hydrologic conditions of each individual site. As a result, however, they can be designed and implemented to address local concerns and values. Compared with the performance of grey infrastructure approaches, experiences with installed and functioning green infrastructure have revealed the following advantages:

- Reduced built capital (equipment, installation) costs
- Reduced land acquisition costs
- Reduced external costs (off-site costs imposed on others)
- Reduced operation costs
- Reduced repair and maintenance costs
- Reduced infrastructure replacement costs (potential for longer life of investment)

Many assessments of green infrastructure costs and benefits find that total benefits outweigh the total costs, particularly relative to grey infrastructure strategies and at comparable scales. For example, a 2007 U.S. EPA study found lower total costs for 11 of 12 green infrastructure projects when compared to equivalent grey infrastructure projects (Figure 1). The EPA study found the reliance on natural conveyance systems significantly reduced structural costs throughout the stormwater management chain. The opportunity to incorporate green infrastructure into other structures and landscaping also reduces the overall footprint of stormwater management infrastructure. Other categories of municipal costs, like flood control needs, can be reduced at the same time.

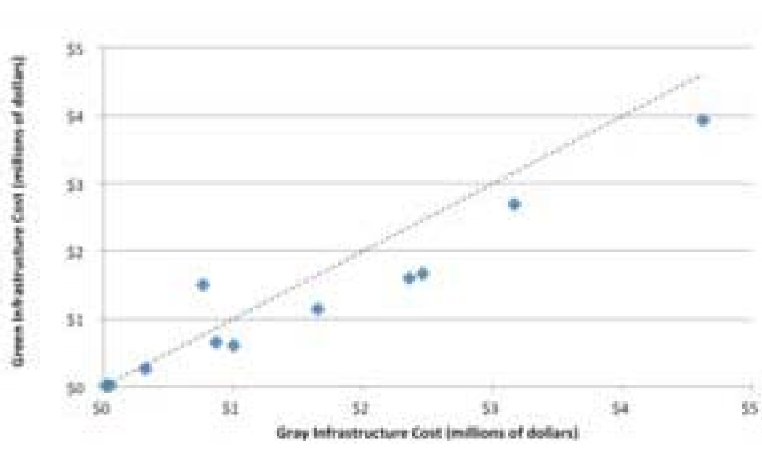


Figure 1. LID and Conventional Cost Comparison ($ Millions)

Green infrastructure project costs from EPA (2007) and equivalent grey infrastructure costs (n=12). Projects below the dotted line have lower green infrastructure costs than equivalent grey infrastructure costs. Only one project evaluated had higher green than grey costs. Source: U.S. EPA. 2007.

Green Infrastructure Practices Offer Cost-Effective Solutions

Saving Money with Green Infrastructure in Louisiana

Chad Danos, Duplantis Design Group, PC

For many years, Episcopal High School in Baton Rouge, Louisiana, was troubled with severe flooding in the school's quadrangle because of an inadequate and aging drainage system. Estimates for re-piping the site were approximately $500,000. In 2008, BROWN+DANOS landdesign, Inc. designed bioswales and a rain garden for the five-acre space to capture one inch of rainfall and slow down the impact to the storm drain system, costing about $110,000 for design and construction. Not only does this project represent cost savings in reduced capital costs, but two years following implementation of the project, the quadrangle has yet to experience any flooding.

http://www.asla.org/uploadedFiles/CMS/Advocacy/Federal_Government_Affairs/Stormwater_Case_Studies/Stormwater%20Case%20459%20Episcopal%20High%20School%20Stormwater%20Rain%20Garden,%20Baton%20Rouge,%20LA.pdf

Green Infrastructure Can Be More Cost-Effective

The cost-effectiveness of green infrastructure has also been demonstrated through many municipal programs and research studies. Cost-effectiveness means value in terms of relatively low costs for the benefits provided. Both costs and benefits are critical to valuing cost-effectiveness. Green infrastructure contributes to greater cost-effectiveness than grey infrastructure by:

- Increased water quality reliability in municipal drinking water supplies, which can lower treatment costs
- Increased predictability of water quality, which can reduce long-term capital costs
- Increased longevity of water quality investments through reduced wear on system components
- Increased development benefits through increased demand and pricing for "green" properties, as shown through premiums for structures employing green infrastructure, reduced non-stormwater expenses such as heating and cooling costs, and increased lots per area available
- Multiple benefits to the public good such as flood control and groundwater recharge

Stormwater Volume Control

Utilities, municipalities, and developers use stormwater controls to limit the volume of water that must be treated for pollutants and meet water quality and quantity regulations. By capturing, naturally treating, and infiltrating stormwater on site, these control costs are reduced or even avoided. The most straightforward assessment of green infrastructure cost-effectiveness then relies on cost comparisons to avoided grey infrastructure. The efforts in major cities across the U.S. demonstrate the potential cost savings and performance benefits. Green infrastructure approaches implemented in Chicago diverted over 70 million gallons of stormwater in 2009 from the CSO system.[15] New York City officials have

Conclusions

Green infrastructure approaches offer many opportunities for cost savings and cost-effectiveness, even though their costs and performance are somewhat more dependent on local conditions than grey infrastructure. As a result, green infrastructure practices are valuable and flexible tools to complement or decrease reliance on traditional stormwater technologies. The range of costs, benefits, and effectiveness of green infrastructure techniques allows local stormwater managers to tailor solutions that are more resilient and affordable then grey-only systems. Further, as plantings mature the effectiveness of green practices may improve over time compared to more traditional, grey infrastructure, likely with diminished O&M requirements. A few important considerations to remember when considering green infrastructure costs and cost-effectiveness are:

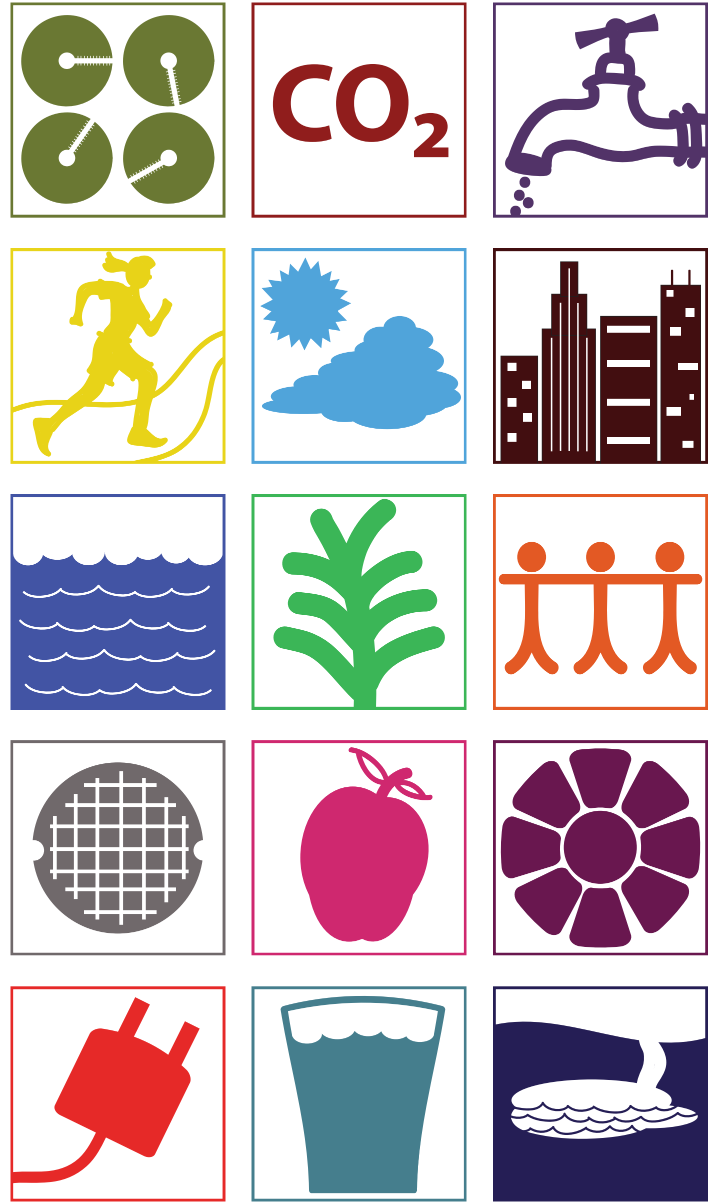
- ***Green infrastructure construction costs can be lower than conventional costs—***Some green infrastructure projects often allow elimination or reduction of costly material components of projects, such as curbs and drains, and stormwater conveyance pipes and tanks. Others, such as green roofs, may be more expensive than traditional counterparts, but provide life-cycle efficiencies that make them less expensive over time. And finally, some green infrastructure materials might currently be more expensive than conventional versions, but because they reduce overall stormwater management needs, the total project construction costs can be reduced.

- ***Green infrastructure may not require the same extent of ongoing costs of conventional infrastructure—***A variety of costs in the conveyance, storage, and operation of stormwater infrastructure can be avoided when functioning natural systems are used to manage stormwater, even though operation and maintenance expenses may be more regular or born by different workers. With appropriate maintenance, green infrastructure practices can regenerate and strengthen over time rather than wearing down and requiring replacements leading to lower overall life cycle costs.

- ***Green infrastructure benefits can extend beyond stormwater for total project cost-effectiveness—***Green infrastructure cost savings can combine with other benefits in terms of avoided costs for other aspects of a project, such as space requirements, landscape requirements, and maintenance efforts such as to address erosion, flooding, snow, and ice. As we learn more about putting green infrastructure into practice, we will likely learn far more about these cost advantages.

The Value of Green Infrastructure

A Guide to Recognizing Its Economic, Environmental and Social Benefits



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American Rivers
Thriving By Nature

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6. COMMUNITY LIVABILITY

Using green infrastructure for stormwater management can improve the quality of life in urban neighborhoods. In addition to the ecological and economic values described elsewhere in this handbook, the goods and services provided by urban vegetation and other green infrastructure practices carry socio-cultural values—aspects that are important to humans because of social norms and cultural traditions. This set of related benefits is grouped under the umbrella category of 'community livability' to describe the many ways in which increasing the use of green infrastructure can improve neighborhood quality of life. Community livability is classified into four categories:

- Aesthetics
- Recreation
- Reduced noise pollution
- Community cohesion

While all of these benefits carry significant value in communities, the literature regarding how to quantify their economic value is not extensive, widespread or well agreed upon at this time. Given the high levels of uncertainty involved in quantifying community livability benefits, this guide does not present methods and equations for quantification or valuation in this section. It does, however, points to ranges of benefit values that have been presented and proposed in various studies.

AESTHETICS

Increased greenery within urban areas increases the aesthetic value of neighborhoods. The positive impact of green infrastructure practices on aesthetics can be reflected in the well-observed relationship between urban greening and property value. People are willing to pay more to live in places with more greenery. To measure this value, various studies employ a Hedonic price method (calculating increases in property value adjacent to green features).

Several empirical studies have shown that property values increase when an urban neighborhood has trees and other greenery. For example, one study reported an increase in property value of 2–10 percent for properties with new street tree plantings in front (Wachter 2004; Wachter and Wong 2008). Another study done in Portland, Oregon, found that street trees add $8,870 to sale prices of residential properties and reduce time on market by 1.7 days (Donovan and Butry 2009). An extensive study on the benefits of green infrastructure in Philadelphia also explores the effect that these practices have on property values (Stratus 2009). While the authors conclude that property values are notably higher in areas with LID and proximity to trees and other vegetation, they also note the difficulty in isolating the effect of improved aesthetics and avoiding double-counting of benefits such as air quality, water quality, energy usage (often relating to heat stress) and flood control that also impact property values. In this study, a range of 0– 7 percent is presented as suggested in literature, and a mean increase of 3.5 percent is chosen (Status 2009). Ward et al. (2008) estimate property values in the range of 3.5–5.0 percent higher for LID adjacent properties in King County, Washington.

The Forest Service *Tree Guides*, referenced previously, provide estimates of the property value benefits trees provide in an urban setting. The property value benefit is found to be the second largest component of the total benefits derived from trees. Benefits are presented on a per tree basis, based on type and size of each tree as well its location.

Environmental Literacy IN AMERICA

What Ten Years of NEETF/Roper Research and Related Studies Say About Environmental Literacy in the U.S.

THE NATIONAL ENVIRONMENTAL EDUCATION & TRAINING FOUNDATION

Kevin Coyle

September 2005

pollution sources. Perhaps because of the power of these vivid images, or perhaps because industrial pollution formed the main focus of government and media attention at the time when most American adults were just learning about environmental pollution, a majority of study respondents are stuck in the mindset of environmental conditions of thirty years ago. They continue to believe, thirty years later, that large industrial facilities are the primary cause of pollution. The fact is, government regulation of such facilities in the intervening years, coupled with new and more difficult-to-control sources of pollution, have changed the relative rankings of pollution problems. For example:

A. The Main Form of Pollution of Rivers and Streams

Few Americans understand that precipitation running off from farm fields, roads, parking lots, and lawns (called "non-point source" pollution) is the leading cause of water pollution in America today. NEETF/Roper studies found that just 22% of Americans know that run-off is the most common form of pollution of streams, rivers, and oceans, while nearly half of Americans (47%) think the most common form is waste dumped by factories (NEETF & Roper, 1997 and 2001). Factories and municipalities remain a cause of water pollution and must continue their clean-up efforts, but they are no longer the leading cause as they were in the 1960s and 1970s. Many government programs acknowledge the importance of looking closely at run-off pollution and are focusing on land use management, improved farming and timber practices, and more. For these programs to be successful, however, there surely must be greater understanding of the run-off problem – how significant it is, where it comes from, and how to prevent it. Indeed, Americans routinely identify clean and safe water as a top priority, but they may be reluctant to accept that their own day-to-day actions and those of their neighbors have a substantial effect on water quality.

B. The Main Source of Oil into Rivers, Lakes, and Bays

It has been 16 years since the oil tanker Exxon Valdez ran aground in March 1989 in Prince William Sound in Alaska. The tanker released millions of gallons of crude oil into a pristine natural ecosystem. The image was vivid and public recognition of the accident is nearly universal. But, according to public agencies including the U.S. EPA and NASA, many millions of gallons of petroleum still find their way into rivers, lakes, bays, and the ocean each year through simple ignorance and thoughtlessness (NASA, 1992). There was a time, thirty years ago, when much of this petroleum pollution came from American industries. Today, individual vehicle users contribute the most to this pollution. The oil comes from people changing car oil and dumping it down a nearby storm drain or pouring it into the ground, or from poorly maintained automobiles. Estimates in the mid-1990s were that individual Americans dump more oil on a monthly basis than the entire amount of oil spilled by the Valdez (NASA, 1992). Just 16% of the American public knows this, while 40% believe that oil pollution comes primarily from ships and offshore oil well spills, and 17% think it comes mostly from coastal oil refinery discharges. As with the most common cause of water pollution, Americans continue to see larger industrial facilities as the main problem and may fail to consider the impacts of their own actions. Certainly steps must be taken by the petroleum industry to prevent oil spills and other pollution problems. But America's car owners would do well to understand they are now the number one oil pollution source.

Myth Process 2 – Persuasive, Powerful Consumer Campaigns

When the media picks up on an information campaign involving the potentially harmful effects of a consumer product, it can have a lasting impact on public knowledge. The NEETF/Roper studies indicate that even if a product is later rendered more environmentally benign, its initial damaged reputation will carry on. Moreover, sometimes a product is identified as *a* problem but through some subtle shift in mass perception, the product is redesignated as *the* problem. Here are some illustrations from the 1998 NEETF/Roper study.

Prepared by the
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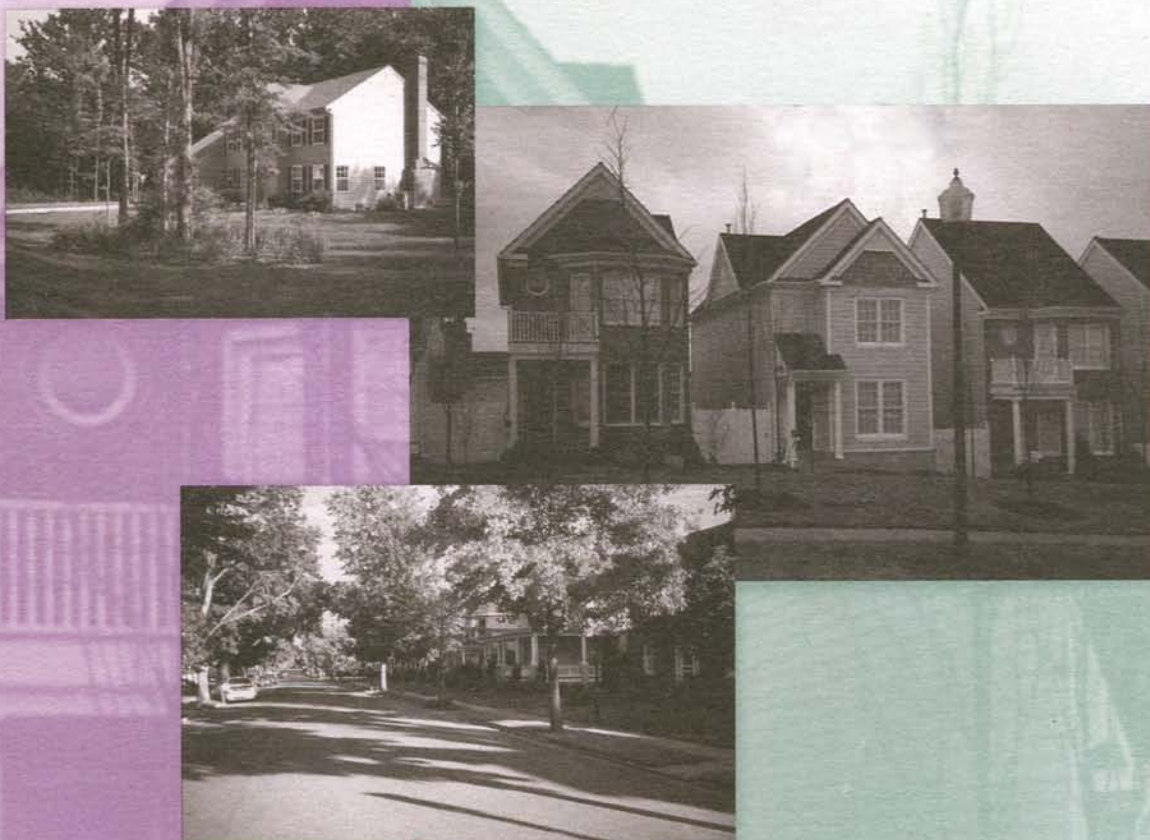
8390 Main Street Ellicott City, Maryland 21043

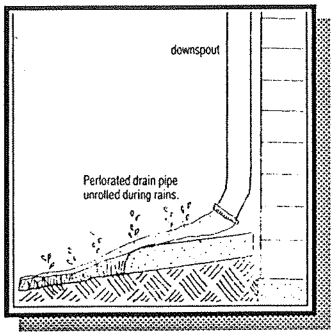
Prepared for the
Site Planning Roundtable



BETTER SITE DESIGN:
A Handbook for Changing Development Rules in Your Community

with assistance from
The Morris and Gwendolyn Cafritz Foundation
US EPA Office of Wetlands, Oceans, and Watersheds
Chesapeake Bay Trust
Turner Foundation
Chesapeake Bay Program

CENTER FOR WATERSHED PROTECTION



PRINCIPLE NO. 16

Direct rooftop runoff to pervious areas such as yards, open channels, or vegetated areas and avoid routing rooftop runoff to the roadway and the stormwater conveyance system.

CURRENT PRACTICE

Most subdivision codes require that yards have a minimum slope to ensure positive drainage away from the home (i.e. runoff moves away from the foundation of a home). A common code requirement is a minimum slope of 2.5% for all overland flow on yards or lawns and a minimum longitudinal gradient for swales, channels or ditches of 2.0%. In northern climates, codes may further specify that downspouts from rooftops to be directly connected to the stormwater conveyance system. These requirements stem, in part, from a desire to minimize nuisance ponding or puddling of water on private lots, and to prevent ice formation on driveways and sidewalks. Engineers are also accustomed to design criteria that mandates quick movement of stormwater through lots, ditches and roads. These code requirements discourage the storage and treatment of rooftop runoff on individual lots. Thus, a cost-effective opportunity for builders and homeowners to promote bioretention and infiltration is bypassed.

RECOMMENDED PRACTICE

Sending rooftop runoff over a pervious surface before it reaches an impervious surface can decrease the annual runoff volume from residential development sites by as much as 50% (Pitt, 1987). This grading technique can significantly can reduce the annual pollutant load and runoff volume being generated at a development site.

Perceptions about wet basements and/or soggy yards are legitimate concerns when it comes to rooftop runoff. Two recent publications, however, suggest that these concerns can be alleviated through careful design, construction inspection, and grading (see Table 16.1). The Low Impact Development Design Manual (PGDER, 1997) provides detailed guidance on methods to re-direct rooftop runoff to pervious surfaces. The Draft Maryland Stormwater Design Manual (MDE, 1997) also provides design criteria for rooftop runoff re-direction, and provides a stormwater management credit as a financial incentive.

Table 16.1 Design Elements for Re-Directing Rooftop Runoff to Pervious Areas

Low Impact Development Manual (Adapted from PGDER, 1997)	Draft Maryland Stormwater Design Manual (Adapted from MDE, 1997)
Encourage shallow sheet flow through vegetated areas. Use rock trenches to create level flow where necessary.	Rooftop runoff from certain land uses should not be re-directed over vegetated areas (e.g., industrial roofs).
Direct flow into BMPs specifically designed to receive rooftop runoff, such as, infiltration swales, infiltration trenches, and/or dry wells.	Limit the contributing path of stormwater flows off rooftops to a maximum length of 75 feet.
Direct flows from small drainage swales to stabilized vegetated areas.	Limit the contributing rooftop area to a maximum of 500 sq. ft. per downspout.
Divert runoff to on-lot swales and bioretention facilities.	The length of vegetated areas receiving runoff from the rooftop shall be equal or greater than the flow length of the contributing rooftop.
Provide wider drainage swales and/or swales with check dams.	Lot sizes must be greater than 6000 sq. ft. in area to receive a stormwater management reduction credit.
Direct rooftop runoff to depression storage areas.	The average slope of the vegetated area receiving rooftop runoff must be less than 5.0% for 75 ft.
	Downspouts must outlet flow at least 10 feet away from the nearest impervious surface.
	Flow from redirected downspouts must not contribute to basement seepage.

Perceptions and Realities about Re-directing Rooftop Runoff

While the benefits of re-directing rooftop runoff have been documented, concerns regarding wet basements and/or soggy yards remain. It is true that diverting runoff through yard areas may result in creating small erosion gullies or shallow soggy areas. Careful design criteria and construction inspection can minimize these conditions. Likewise, if rooftop runoff is diverted to a depression storage area specifically designed to receive these flows, such as a bioretention area or an infiltration area, soggy lawn areas will be minimized or eliminated altogether. Figure 16.1 illustrates an on-lot bioretention area.

Similarly, specific criteria regarding the discharge from downspouts away from building foundations or basements can minimize or eliminate seepage or foundation damage. Additional concerns and perceived impediments to implementation are presented in Table 16.2.

Figure 16.1: Residential On-Lot Bioretention Area (Adapted from Claytor and Schueler, 1996)

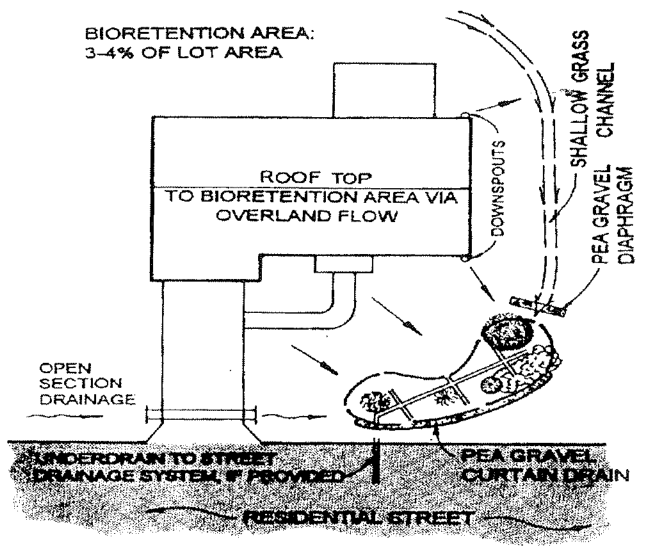
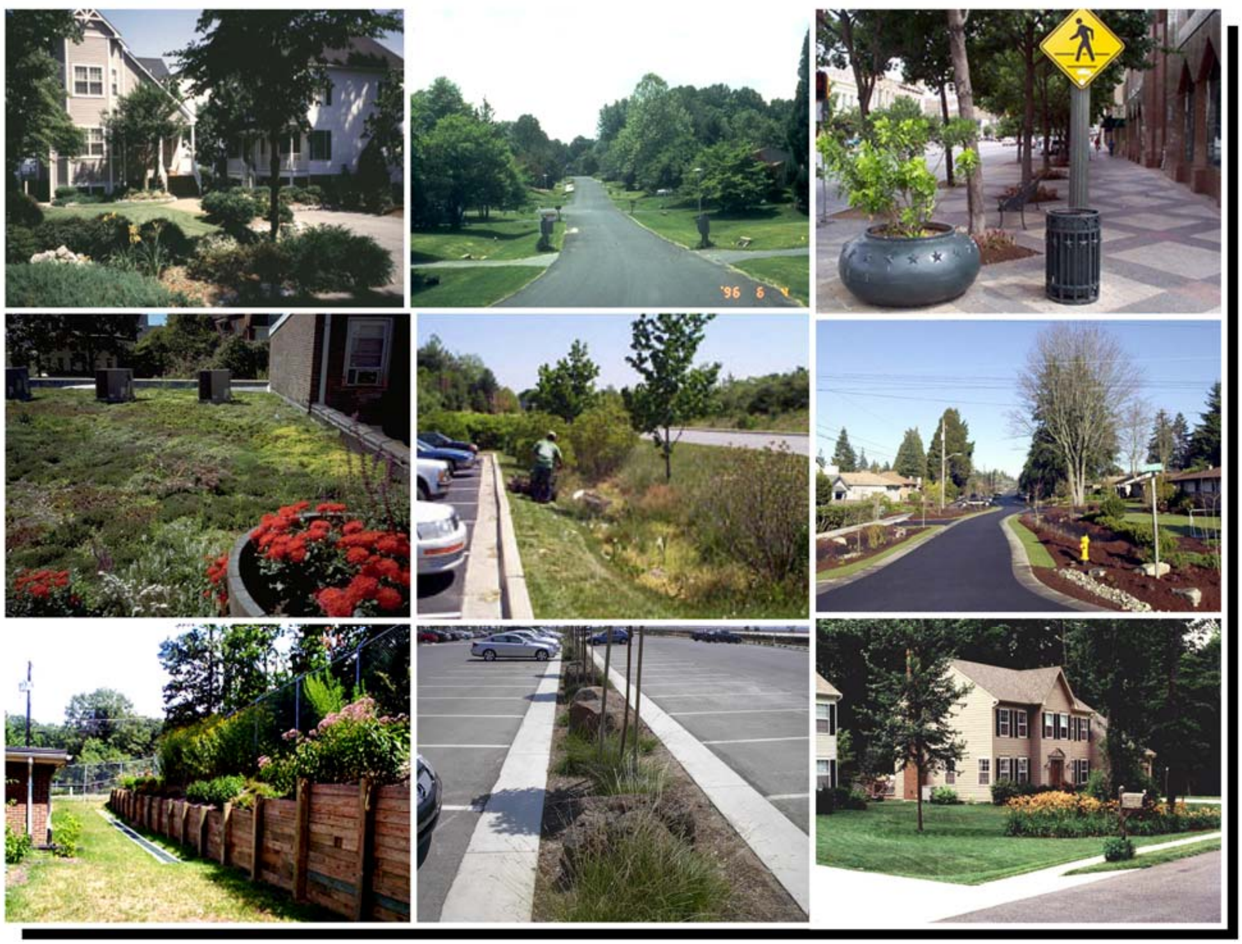


Table 16.2 Perceived Impediments to Re-Directing Rooftop Runoff

Perception	Facts, Case Studies, and Challenges	
1. Re-directed rooftop runoff may increase a property owner's maintenance burden.	FACT:	When designed properly, on-lot bioretention areas provide an attractive landscaping feature that does not require supplemental water.
2. Re-directed rooftop runoff can be directed onto impervious surfaces in the future.	CHALLENGE:	True, homeowners can always reconnect downspouts to the drainage system in the future. They are not likely to do so, however, unless they encounter problems due to poor grading or design.
3. Wet basements will result from re-directing rooftop runoff.	FACT:	These conditions can be minimized by setting specific criteria regarding the distance that downspouts must discharge from foundations, minimum adjacent slopes away for houses, and adequate construction inspection.
4. Local government codes and FHA lending criteria prohibit on-lot ponding and specify minimum slope requirements.	CHALLENGE:	Some local governments have grading ordinances which dictate minimum grades for lawns, yards, and drainage swales. These restrictions prohibit or discourage re-directing rooftop runoff. Developers must obtain waivers or exceptions to implement practices such as on-lot bioretention, water quality swales, or other flow attenuating BMPs.

Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices



The following discussion is organized into three categories: (1) environmental benefits, which include reductions in pollutants, protection of downstream water resources, ground water recharge, reductions in pollutant treatment costs, reductions in the frequency and severity of CSOs, and habitat improvements; (2) land value benefits, which include reductions in downstream flooding and property damage, increases in real estate value, increased parcel lot yield, increased aesthetic value, and improvement of quality of life by providing open space for recreation; and (3) compliance incentives.

Environmental Benefits

Pollution abatement. LID practices can reduce both the volume of runoff and the pollutant loadings discharged into receiving waters. LID practices result in pollutant removal through settling, filtration, adsorption, and biological uptake. Reductions in pollutant loadings to receiving waters, in turn, can improve habitat for aquatic and terrestrial wildlife and enhance recreational uses. Reducing pollutant loadings can also decrease stormwater and drinking water treatment costs by decreasing the need for regional stormwater management systems and expansions in drinking water treatment systems.

Protection of downstream water resources. The use of LID practices can help to prevent or reduce hydrologic impacts on receiving waters, reduce stream channel degradation from erosion and sedimentation, improve water quality, increase water supply, and enhance the recreational and aesthetic value of our natural resources. LID practices can be used to protect water resources that are downstream in the watershed. Other potential benefits include reduced incidence of illness from contact recreation activities such as swimming and wading, more robust and safer seafood supplies, and reduced medical treatment costs.

Ground water recharge. LID practices also can be used to infiltrate runoff to recharge ground water. Growing water shortages nationwide increasingly indicate the need for water resource management strategies designed to integrate stormwater, drinking water, and wastewater programs to maximize benefits and minimize costs. Development pressures typically result in increases in the amount of impervious surface and volume of runoff. Infiltration practices can be used to replenish ground water and increase stream baseflow. Adequate baseflow to streams during dry weather is important because low ground water levels can lead to greater fluctuations in stream depth, flows, and temperatures, all of which can be detrimental to aquatic life.

Water quality improvements/reduced treatment costs. It is almost always less expensive to keep water clean than it is to clean it up. The Trust for Public Land[5] noted Atlanta's tree cover has saved more than $883 million by preventing the need for stormwater retention facilities. A study of 27 water suppliers conducted by the Trust for Public Land and the American Water Works Association[6] found a direct relationship between forest cover in a watershed and water supply treatment costs. In other words, communities with higher percentages of forest cover had lower treatment costs. According to the study, approximately 50 to 55 percent of the variation in treatment costs can be explained by the percentage of forest cover in the source area. The researchers also found that for every 10 percent increase in forest cover in the source area, treatment and chemical costs decreased approximately 20 percent, up to about 60 percent forest cover.

Reduced incidence of CSOs. Many municipalities have problems with CSOs, especially in areas with aging infrastructure. Combined sewer systems discharge sanitary wastewater during storm events. LID techniques, by retaining and infiltrating runoff, reduce the frequency and amount of CSO discharges to receiving waters. Past management efforts typically have been concentrated on hard engineering approaches focused on treating the total volume of sanitary waste together with the runoff that is discharged to the combined system. Recently, communities like Portland (Oregon), Chicago, and Detroit have been experimenting with watershed approaches aimed at reducing the total volume of runoff generated that must be handled by the combined system. LID techniques have been the primary method with which they have experimented to reduce runoff. A Hudson Riverkeeper report concluded, based on a detailed technical analysis, that New York City could reduce its CSO's more cost-effectively with LID practices than with conventional, hard infrastructure CSO storage practices. [7]

Habitat improvements. Innovative stormwater management techniques like LID or conservation design can be used to improve natural resources and wildlife habitat, maintain or increase land value, or avoid expensive mitigation costs.

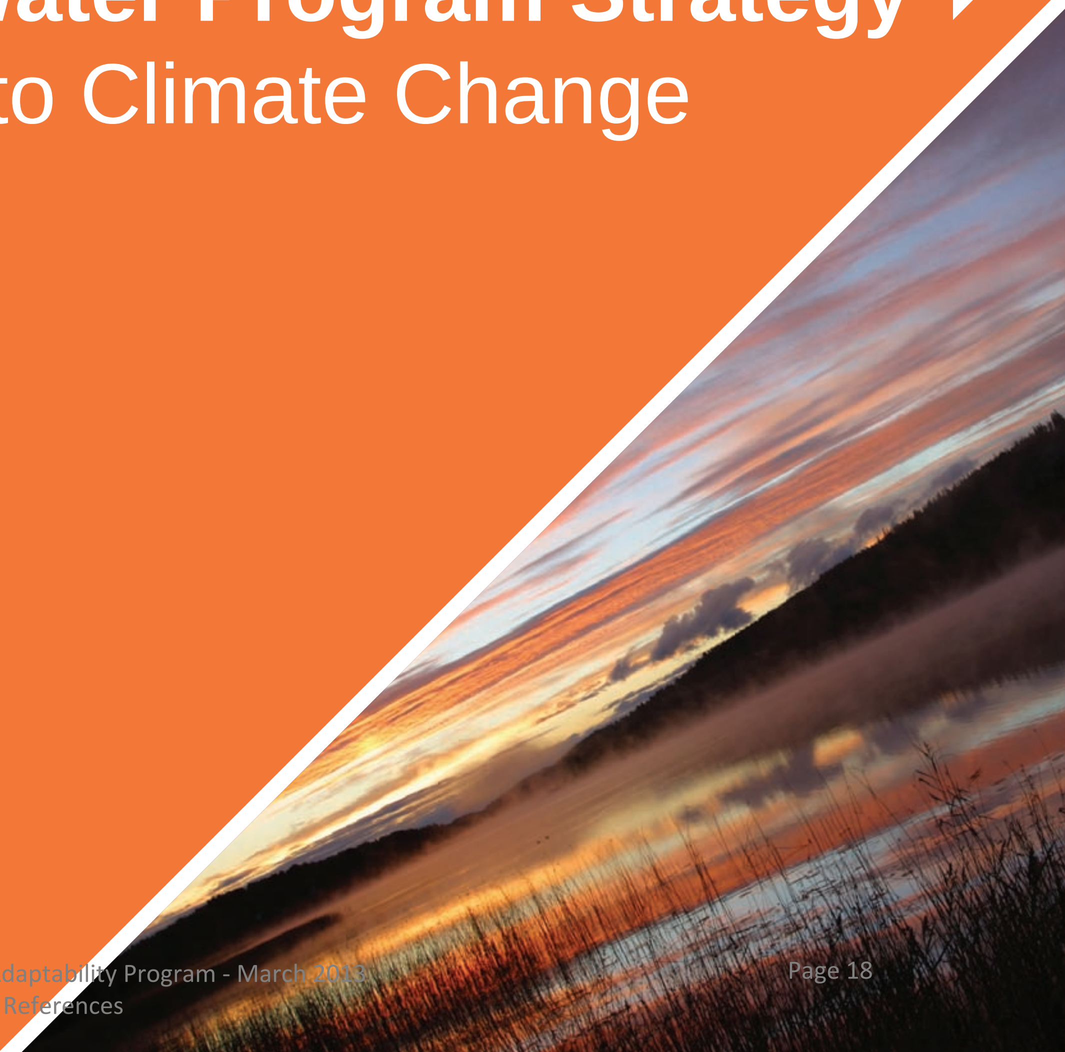
Land Value and Quality of Life Benefits

Reduced downstream flooding and property damage. LID practices can be used to reduce downstream flooding through the reduction of peak flows and the total amount or volume of runoff. Flood prevention reduces property damage and can reduce the initial capital costs and the operation and maintenance costs of stormwater infrastructure. Strategies designed to manage runoff on-site or as close as possible to its point of generation can reduce erosion and sediment transport as well as reduce flooding and downstream erosion. As a result, the costs for cleanups and streambank restoration can be reduced or avoided altogether. The use of LID techniques also can help protect or restore floodplains, which can be used as park space or wildlife habitat.[8]

Real estate value/property tax revenue. Homeowners and property owners are willing to pay a premium to be located next to or near aesthetically pleasing amenities like water features, open space, and trails. Some stormwater treatment systems can be beneficial to developers because they can serve as a "water" feature or other visual or recreational amenity that can be used to market the property. These designs should be visually attractive and safe for the residents and should be considered an integral part of planning the development. Various LID projects and smart growth studies have shown that people are willing to pay more for clustered homes than conventionally designed subdivisions. Clustered housing with open space appreciated at a higher rate than conventionally designed subdivisions. EPA's *Economic Benefits of Runoff Controls*[9] describes numerous examples where developers and subsequent homeowners have received premiums for proximity to attractive stormwater management practices.

Lot yield. LID practices typically do not require the large, contiguous areas of land that are usually necessary when traditional stormwater controls like ponds are used. In cases where LID practices are incorporated on individual house lots and along roadsides as part of the landscaping, land that would normally be dedicated for a stormwater pond or other large structural control can be developed with additional housing lots.

National Water Program Strategy
Response to Climate Change



B. Water Conservation

OBJECTIVE:
Promote water conservation to reduce energy use.

Water quantity and water quality are inextricably linked. Impacts on water resources due to climate change will make this connection more visible. For example, discharge of treated effluent assumes adequate flow for dilution and low flows require higher treatment to avoid impairments; shortages of precipitation and reduced snow melt result in increased competition between human uses and aquatic uses of in-stream flows; and shortages of surface water drive increases in groundwater pumping, which in turn affect recharge.

Water conservation through water use efficiency will be important not just to extend water supply, but also to reduce greenhouse gases. Reduced water consumption saves energy because less water needs to be pumped and treated. On the other side of the water/energy equation, when energy use is reduced, water is saved because less is needed to operate power plants. About half of the water gathered in the United States from surface and groundwater sources is used for power plant cooling (although most is returned) compared to 34 percent for irrigation and 11 percent for residential and commercial purposes (USGS 2004, pp. 6-7). On average, each kilowatt generated consumes approximately 0.2 to 0.3 gallons of water (EPA 2007o), which is based on cooling water consumption and annual electricity generation estimates from the Electric Power Research Institute (EPRI 2002, p. 6-3) and the Energy Information Administration (EIA 2004), respectively.

There are many opportunities for energy savings on the supply side, realized through better planning, maintenance, and operation of water delivery systems, as well as through the development of new technologies and processes. What is often overlooked is how demand-side management or conservation programs can effectively increase water and energy savings. For example, California's State Water Plan (California Department of Water Resources 2005) concluded in 2005 that the largest single new water supply available to meet their expected growth over the next 25 years will be water-use efficiency—made more critical in light of projected water shortages due to climate-related decreases in snow pack.

Residential and business customers use more energy to heat, cool, and otherwise use water than utilities spend treating and distributing it. For example, running a hot water faucet for five minutes is equivalent to running a 60-watt light bulb for 14 hours (Grumbles 2007 and EPA 2007o). By conserving water, less energy is used for these purposes.

For residential consumers, the opportunity to save both water and energy comes primarily from using water-efficient fixtures and appliances, including toilets, showerheads, faucets, clothes washers, dishwashers, and irrigation equipment. For example, an estimated 60 billion gallons and $650 million in energy costs (Grumbles 2007 and EPA 2007o) could be saved if every household also installed high-efficiency faucets or faucet aerators.

To promote water-efficiency and protect the future of our Nation's water supply, EPA launched the WaterSense program in 2007. The WaterSense label will help consumers and businesses identify products that meet the program's water-efficiency and performance criteria. The WaterSense program sets specifications for the labeling of products that are at least 20 percent more efficient than the current standards while performing as well or better than their less-efficient counterparts. Once a manufacturer's product is certified to meet EPA's WaterSense specification by an independent third party, they can use the label on their product. The WaterSense product specifications do not currently address energy consumption directly. However, all water savings realized through the use of WaterSense labeled products and services have a corresponding reduction in energy consumption. Both commercial and residential products and services will be addressed by WaterSense labeling efforts.

National Water Program 2012 Strategy: Response to Climate Change

United States
Environmental Protection
Agency

December 2012

CABY Headwaters Resilience and Adaptability Program - March 2013
Attachment 7 - Wolf Creek Project References

VII. Appendices

Appendix A: Principles for an Energy Water Future – The Foundation for a Sustainable America

Principles for an Energy Water Future

A Foundation for a Sustainable America

The nexus between energy and water is an increasingly important area for focus. There are significant societal and environmental benefits to be derived from improving coordination between the two sectors. Government should take a leadership role in this relationship and lead by example. EPA is proposing principles for government, service providers, and ratepayers to foster valuable collaboration in both the water and energy sectors to work together to meet our water and energy needs nationally and locally. The principles also serve as a reminder that rising water treatment costs or necessary tradeoffs such as stricter water treatment levels can be mitigated by efforts elsewhere such as reducing demand for energy and water.

Efficiency in the use of energy and water should form the foundation of how we develop, distribute, recover, and use energy and water. EPA supports:

- Encouraging energy and water efficiency by the ratepayer through the use of efficient products, like ENERGY STAR and WaterSense labeled products, supplemented by informed and wise use of resources.
- Improving system-level energy and water efficiency by water, wastewater, stormwater, and energy utilities and encouraging strategic investments in efficiency.
- Using full-cost rate structures while ensuring access to clean and safe water for low income households.
- Recognizing and reducing the embedded water and energy in manufactured and agricultural products.
- Relying on education and outreach, in collaboration with local communities, to be at the forefront of encouraging efficiency.

The exploration, production, transmission, and use of energy should have the smallest impact on water resources as possible, in terms of water quality and water quantity. EPA supports:

- Reducing consumption or use of water for producing energy and fuels: reduce, recover, reuse, and recycle.

THE VALUE OF GREEN INFRASTRUCTURE FOR URBAN CLIMATE ADAPTATION

The Center for Clean Air Policy
February 2011

Josh Foster
Ashley Lowe
Steve Winkelman

Center for Clean Air Policy
Dialogue. Insight. Solutions.

EXECUTIVE SUMMARY

In this paper CCAP provides information on the costs and benefits of "green" infrastructure solutions for bolstering local adaptation to climate change. Pioneering cities and counties have used green practices to increase community resilience by planning for, and adapting to, emerging climate change impacts. Generally, resilience means that communities can better withstand, cope with, manage, and rapidly recover their stability after a variety of crises. Practices such as green roofs, urban forestry, and water conservation are familiar to local governments as strategies to enhance sustainability and quality of life and they are increasingly being seen as best practices in climate adaptation. These solutions can help build adaptive capacity through planning, preparing, or reducing climate-related vulnerabilities, but the uncertainty involved in calculating their economic and social costs and benefits is a barrier to action for local governments. This report will evaluate the performance and benefits of a selection of green infrastructure solutions, using their range of technological, managerial, institutional, and financial innovations as a proxy for their value for climate adaptation.

Over the coming century, climate change scenarios project that urban regions will be managing extremes of precipitation and temperature, increased storm frequency and intensity, and sea-level rise. The problems with which urban areas are already coping may already be indicating–or at least mimicking – that climate change impacts have begun to occur and are likely to worsen in the future.

Often green approaches are combined with modifications to other traditional "hard" infrastructures such as expanding storm-sewers and streets or building storm-water storage tunnels. In recent thinking, portfolios of "green" infrastructure and technologies have been indentified as 'best practices' at the local level when combined with traditional "grey" infrastructure to achieve greater urban sustainability and resilience. In addition, green infrastructure is now being recognized for its value as a means for adapting to the emerging and irreversible impacts of climate change. Consequently, some local governments have adopted green infrastructure as a hedge against climate change risks, particularly if the strategies result in multiple other benefits. The discovery of the multiple benefits of green infrastructure has induced action regardless of the timing, extent, and rate of climate change impacts. Given the challenges of accurately calculating the incremental costs and benefits of climate adaptation policies, this report will use the costs, benefits, and performance of various green infrastructure practices as proxies for their value to climate adaptation across a range of technological, managerial, institutional, and financial innovations.

Green infrastructure approaches help to achieve sustainability and resilience goals over a range of outcomes in addition to climate adaptation. The climate adaptation benefits of green infrastructure are generally related to their ability to moderate the impacts of extreme precipitation or temperature. Benefits include better management of storm-water runoff, lowered incidents of combined storm and sewer overflows (CSOs), water capture and conservation, flood prevention, storm-surge protection, defense against sea-level rise,

California initiated the Cool Savings Program which provided rebates to building owners for installing roofing materials with high solar reflectivity and low thermal absorption. The California Energy Commission paid incentives of 15 to 25 cents per square foot of eligible roofing area. The program was so successful that California revised its Title 24 to make cool roofs on certain new or renovated buildings mandatory starting in 2005.

In the future, new mortgage products imitating PACE loans may incorporate the costs of adaptation into private property transactions. [106] Noted above, tax credits for green infrastructure implementation, reduced storm-water fees rewarding greater site permeability, or rebates for downspout disconnection are just a few examples of how to change price incentives by making some behaviors cheaper or more expensive. For example, starting in 2007, New York City aimed to support the installation of extensive green roofs by enacting a property tax abatement to offset 35% of the installation cost of a green roof. Keeping discount rates low also makes investing in green infrastructure that has longer-term benefits more valuable. As noted earlier, demonstrated increases in property values from green-infrastructure raising tax revenue, or lowering insurance premiums from greater site resilience also creates market incentives.

Conclusions: Implications for Policy, Research and Technical Assistance

Asking the Resilience Question

Green infrastructure is a means for simultaneously advancing environmental sustainability, smart growth, and now climate adaptation goals in urban settings with a goal of creating more resilient metropolitan communities. Although definitions of these concepts are at times vague and not entirely complementary they do overlap to a significant extent.[107] Sustainable development seeks goals of environmental protection, economic viability, and long-term resource continuity along with equity and social justice particularly for vulnerable populations. Smart growth uses the tools of planning and urban design to achieve resource efficiencies, building density, mixed land-uses, open space, public transit oriented development, and enhanced quality of life. More recently, climate adaptation policies and practices have sought to build the capacity of local communities and decision makers to better assess and manage risks, impacts, and opportunities from irreversible climate change and extreme weather (floods, droughts, wildfire, sea-level rise, and public health threats, etc.). Adaptation to climate change also is seen as having ecological, economic, and social dimensions.[108]

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[106]PACE: Property Assessed Clean Energy allows a local government to provide loans to homeowners for renewable energy and efficiency retrofits paying back via tax bills. However, PACE currently has been defined by the Federal government as an illegal lien on houses so the future of this mechanism is in question.
[107]Intergovernmental Panel on Climate Change (IPCC), 4th Assessment Report (2007): WG II Adaptation
[108] IPCC, AR4 (2007)

At the intersection of these three concepts is a desire for more resilient communities that are less vulnerable to natural and human induced hazards and disasters (See Figure 10). Generally, resilience means that they can better withstand, cope with, manage, and rapidly recover their stability after a variety of crises. However, there is considerable debate about what it means to achieve a resilient community in practice (operationally). For example, stability may not be a truly resilient trait if vulnerabilities are perpetuated in recovery to an original state (e.g., post-flood disaster rebuilding in a frequently inundated floodplain).

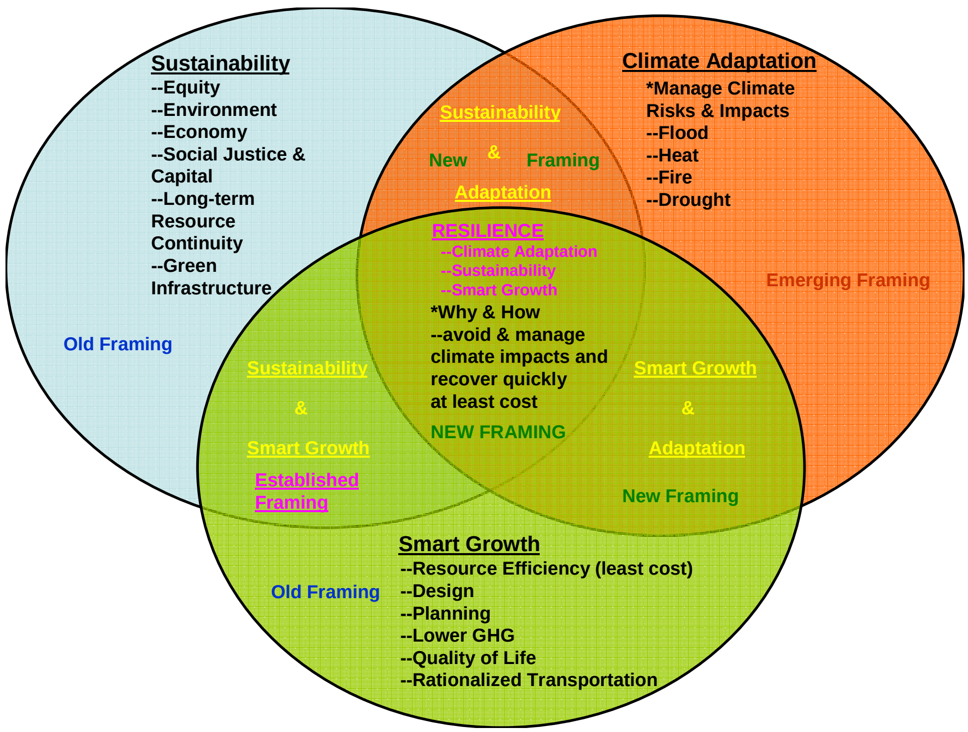

Figure 10: The Intersection of Sustainability, Smart Growth and Adaptation

Diversity, flexibility, sustainability, adaptability, self-organization, and the ability to evolve and learn are seen as key system attributes of community resilience as long as they do not lead to mal-adaptation in the process.[109] However, resilience generally is thought of in more reactive terms—akin to "autonomous adaptation" that responds as conditions change. In the face of climate change, adaptive capacity is seen as encompassing resilience as it more comprehensively focuses on planning, preparing, and implementing adaptive solutions drawing on a wide variety of technological, managerial, institutional (social), and market capabilities.[110] "Asking the resilience question"—means that local planning and building decisions need to incorporate how to prepare for and manage impacts from climate change and weather extremes—essentially "mainstreaming" resilience by enhancing adaptive capacity.

[109] Klein, Resilience (2003)
[110] Klein, Resilience (2003)

P R E P U B L I C A T I O N   C O P Y

Urban Stormwater Management in the United States

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Chapter 5
Stormwater Management Approaches

A fundamental component of the U.S. Environmental Protection Agency's (EPA) Stormwater Program, for municipalities as well as industries and construction, is the creation of stormwater pollution prevention plans. These plans invariably document the stormwater control measures that will be used to prevent the permittee's stormwater discharges from degrading local waterbodies. Thus, a consideration of these measures—their effectiveness in meeting different goals, their cost, and how they are coordinated with one another—is central to any evaluation of the Stormwater Program. This report uses the term stormwater control measure (SCM) instead of the term best management practice (BMP) because the latter is poorly defined and not specific to the field of stormwater.

The committee's statement of task asks for an evaluation of the relationship between different levels of stormwater pollution prevention plan implementation and in-stream water quality. As discussed in the last two chapters, the state of the science has yet to reveal the mechanistic links that would allow for a full assessment of that relationship. However, enough is known to design systems of SCMs, on a site scale or local watershed scale, to lessen many of the effects of urbanization. Also, for many regulated entities the current approach to stormwater management consists of choosing one or more SCMs from a preapproved list. Both of these facts argue for the more comprehensive discussion of SCMs found in this chapter, including information on their characteristics, applicability, goals, effectiveness, and cost. In addition, a multitude of case studies illustrate the use of SCMs in specific settings and demonstrate that a particular SCM can have a measurable positive effect on water quality or a biological metric. The discussion of SCMs is organized along the gradient from the rooftop to the stream. Thus, pollutant and runoff prevention are discussed first, followed by runoff reduction and finally pollutant reduction.

HISTORICAL PERSPECTIVE ON STORMWATER CONTROL MEASURES

Over the centuries, SCMs have met different needs for cities around the world. Cities in the Mesopotamian Empire during the second millennium BC had practices for flood control, to convey waste, and to store rain water for household and irrigation uses (Manor, 1966) (see Figure 5-1). Today, SCMs are considered a vital part of managing flooding and drainage problems in a city. What is relatively new is an emphasis on using the practices to remove pollutants from stormwater and selecting practices capable of providing groundwater recharge. These recent expectations for SCMs are not readily accepted and require an increased commitment to the proper design and maintenance of the practices.

With the help of a method for estimating peak flows (the Rational Method, see Chapter 4), the modern urban drainage system came into being soon after World War II. This generally consisted of a system of catch basins and pipes to prevent flooding and drainage problems by efficiently delivering runoff water to the nearest waterbody. However, it was soon realized that delivering the water too quickly caused severe downstream flooding and bank erosion in the receiving water. To prevent bank erosion and provide more space for flood waters, some stream channels were enlarged and lined with concrete (see Figure 5-2). But while hardening and

FIGURE 5-1 Cistern tank, Kamiros, Rhodes (ancient Greece, 7th century BC). SOURCE: Robert Pitt.

FIGURE 5-2 Concrete channel in Lincoln Creek, Milwaukee, Wisconsin. SOURCE: Roger Bannerman.

enlarging natural channels is a cost-effective solution to erosion and flooding, the modified channel increases downstream peak flows and it does not provide habitat to support a healthy aquatic ecosystem.

Some way was needed to control the quantity of water reaching the end of pipes during a runoff event, and on-site detention (Figure 5-3) became the standard for accomplishing this. Ordinances started appearing in the early 1970s, requiring developers to reduce the peaks of different size storms, such as the 10-year, 24-hour storm. The ordinances were usually intended to prevent future problems with peak flows by requiring the installation of flow control structures, such as detention basins, in new developments. Detention basins can control peak flows directly below the point of discharge and at the property boundary. However, when designed on a site-by-site basis without taking other basins into account, they can lead to downstream flooding problems because volume is not reduced (McCuen, 1979; Ferguson, 1991; Traver and Chadderton, 1992; EPA, 2005d). In addition, out of concerns for clogging, openings in the outlet structure of most basins are generally too large to hold back flows from smaller, more frequent storms. Furthermore, low-flow channels have been constructed or the basins have been graded to move the runoff through the structure without delay to prevent wet areas and to make it easier to mow and maintain the detention basin.

Because of the limitations of on-site detention, infiltration of urban runoff to control its volume has become a recent goal of stormwater management. Without stormwater infiltration, municipalities in wetter regions of the country can expect drops in local groundwater levels, declining stream base flows (Wang et al., 2003a), and flows diminished or stopped altogether from springs feeding wetlands and lakes (Leopold, 1968; Ferguson, 1994).

The need to provide volume control marked the beginning of low-impact development (LID) and conservation design (Arendt, 1996; Prince George's County, 2000), which were founded on the seminal work of landscape architect Ian McHarg and associates decades earlier (McHarg and Sutton, 1975; McHarg and Steiner, 1998). The goal of LID is to allow for development of a site while maintaining as much of its natural hydrology as possible, such as infiltration, frequency and volume of discharges, and groundwater recharge. This is accomplished with infiltration practices, functional grading, open channels, disconnection of

FIGURE 5-3 On-site detention. SOURCE: Tom Schueler.

impervious areas, and the use of fewer impervious surfaces. Much of the LID focus is to manage the stormwater as close as possible to its source—that is, on each individual lot rather than conveying the runoff to a larger regional SCM. Individual practices include rain gardens (see Figure 5-4), disconnected roof drains, porous pavement, narrower streets, and grass swales. In some cases, LID site plans still have to include a method for passing the larger storms safely, such as a regional infiltration or detention basin or by increasing the capacity of grass swales.

Infiltration has been practiced in a few scattered locations for a long time. For example, on Long Island, New York, infiltration basins were built starting in 1930 to reduce the need for a storm sewer system and to recharge the aquifer, which was the only source of drinking water (Ferguson, 1998). The Cities of Fresno, California, and El Paso, Texas, which faced rapidly dropping groundwater tables, began comprehensive infiltration efforts in the 1960s and 1970s. In the 1980s Maryland took the lead on the east coast by creating an ambitious statewide infiltration program. The number of states embracing elements of LID, especially infiltration, has increased during the 1990s and into the new century and includes California, Florida, Minnesota, New Jersey, Vermont, Washington, and Wisconsin.

FIGURE 5-4 Rain Garden in Madison, Wisconsin. SOURCE: Roger Bannerman.

Evidence gathered in the 1970s and 1980s suggested that pollutants be added to the list of things needing control in stormwater (EPA, 1983). Damages caused by elevated flows, such as stream habitat destruction and floods, were relatively easy to document with something as simple as photographs. Documentation of elevated concentrations of conventional pollutants and potentially toxic pollutants, however, required intensive collection of water quality samples during runoff events. Samples collected from storm sewer pipes and urban streams in the Menomonee River watershed in the late 1970s clearly showed the concentrations of many pollutants, such as heavy metals and sediment, were elevated in urban runoff (Bannerman et al., 1979). Levels of heavy metals were especially high in industrial-site runoff, and construction-site erosion was calculated to be a large source of sediment in the watershed. This study was followed by the National Urban Runoff Program, which added more evidence about the high levels of some pollutants found in urban runoff (Athayde et al., 1983; Bannerman et al., 1983).

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With new development rapidly adding to the environmental impacts of existing urban areas, the need to develop good stormwater management programs is more urgent than ever. For a variety of reasons, the greatest potential for stormwater management to reduce the footprint of urbanization is in the suburbs. These areas are experiencing the fastest rates of growth, they are more amenable to stormwater management because buildings and infrastructure are not yet in place, and costs for stormwater management can be borne by the developer rather than by taxpayers. Indeed, most structural SCMs are applied to new development rather than existing urban areas. Many of the most innovative stormwater programs around the country are found in the suburbs of large cities such as Seattle, Austin, and Washington, D.C. When stormwater management in ultra-urban areas is required, it entails the retrofitting of detention basins and other flow control structures or the introduction of innovative below-ground structures characterized by greater technical constraints and higher costs, most of which are charged to local taxpayers.

Current-day SCMs represent a radical departure from past practices, which focused on dealing with extreme flood events via large detention basins designed to reduce peak flows at the downstream property line. As defined in this chapter, SCMs now include practices intended to meet broad watershed goals of protecting the biology and geomorphology of receiving waters in addition to flood peak protection. The term encompasses such diverse actions as using more conventional practices like basins and wetland to installing stream buffers, reducing impervious surfaces, and educating the public.

REVIEW OF STORMWATER CONTROL MEASURES

Stormwater control measures refer to what is defined by EPA (1999) as "a technique, measure, or structural control that is used for a given set of conditions to manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner." SCMs are designed to mitigate the changes to both the quantity and quality of stormwater runoff that are caused by urbanization. Some SCMs are engineered or constructed facilities, such as a stormwater wetland or infiltration basin, that reduce pollutant loading and modify volumes and flow. Other SCMs are preventative, including such activities as education and better site design to limit the generation of stormwater runoff or pollutants.

Stormwater Management Goals

It is impossible to discuss SCMs without first considering the goals that they are expected to meet. A broadly stated goal for stormwater management is to reduce pollutant loads to waterbodies and maintain, as much as possible, the natural hydrology of a watershed. On a practical level, these goals must be made specific to the region of concern and embedded in the strategy for that region. Depending on the designated uses of the receiving waters, climate, geomorphology, and historical development, a given area may be more or less sensitive to both pollutants and hydrologic modifications. For example, goals for groundwater recharge might be higher in an area with sandy soils as compared to one with mostly clayey soils; watersheds in the coastal zone may not require hydrologic controls. Ideally, the goals of stormwater management should be linked to the water quality standards for a given state's receiving waters. However,

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because of the substantial knowledge gap about the effect of a particular stormwater discharge on a particular receiving water (see Chapter 3 conclusions), surrogate goals are often used by state stormwater programs in lieu of water quality standards. Examples include credit systems, mandating the use of specific SCMs, or achieving stormwater volume reduction. Credit systems might be used for practices that are known to be productive but are difficult to quantify, such as planting trees. Specific SCMs might be assumed to remove a percent of pollutants, for example 85 percent removal of total suspended solids (TSS) within a stormwater wetland. Reducing the volume of runoff from impervious surfaces (e.g., using an infiltration device) might be assumed to capture the first flush of pollutants during a storm event. Before discussing specific state goals, it is worth understanding the broader context in which goals are set.

Trade-offs Between Stormwater Control Goals and Costs

The potentially substantial costs of implementing SCMs raise a number of fundamental social choices concerning land-use decisions, designated uses, and priority setting for urban waters. To illustrate some of these choices, consider a hypothetical urban watershed with three possible land-cover scenarios: 25, 50, and 75 percent impervious surface. A number of different beneficial uses could be selected for the streams in this watershed. At a minimum, the goal may be to establish low-level standards to protect public health and safety. To achieve this, sufficient and appropriate SCMs might be applied to protect residents from flooding and achieve water quality conditions consistent with secondary human contact. Alternatively, the designated use could be to achieve the physical, chemical, and/or biological conditions sufficient to provide exceptional aquatic habitat (e.g., a high-quality recreational fishery). The physical, biological, and chemical conditions supportive of this use might be similar to a reference stream located in a much less disturbed watershed. Achieving this particular designated use would require substantially greater resources and effort than achieving a secondary human contact use. Intermediate designated uses could also be imagined, including improving ambient water quality conditions that would make the water safe for full-body emersion (primary human contact) or habitat conditions for more tolerant aquatic species.

Figure 5-5 sketches what the marginal (incremental) SCM costs (opportunity costs) might be to achieve different designated uses given different amounts of impervious surface in the watershed. The horizontal axis orders potential designated uses in terms of least difficult to most difficult to achieve. The three conceptual curves represent the SCM costs under three different impervious surface scenarios. The relative positions of the cost curves indicate that achieving any specific designated use will be more costly in situations with a higher percentage of the watershed in impervious cover. All cost curves are upward sloping, reflecting the fact that incremental improvements in designated uses will be increasingly costly to achieve. The cost curves are purely conceptual, but nonetheless might reasonably reflect the relative costs and direction of change associated with achieving specific designated uses in different watershed conditions.

The locations of the cost curves suggest that in certain circumstances not all designated uses can be achieved or can be achieved only at an extremely high cost. For example, the attainment of exceptional aquatic uses may be unachievable in areas with 50 percent impervious surface even with maximum application of SCMs. In this illustration, the cost of achieving even secondary human contact use is high for areas with 75 percent impervious surfaces. In such

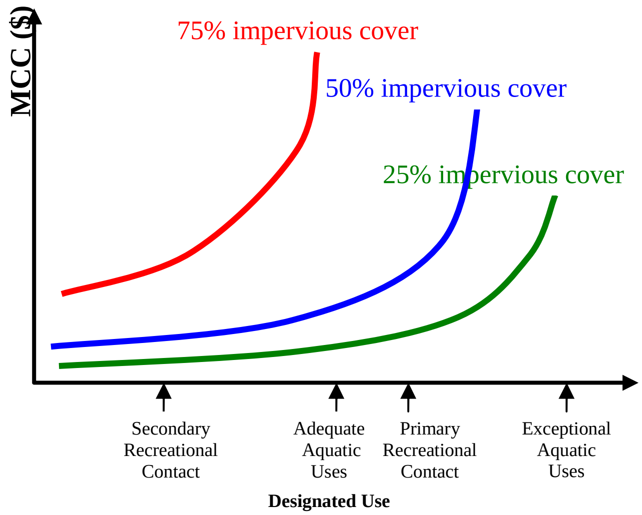

FIGURE 5-5 Cost of achieving designated uses in a hypothetical urban watershed. MCC is the marginal control cost, which represents the incremental costs to achieve successive expansion of designated uses through SCMs. The curves are constructed on the assumption that the lowest cost combination of SCMs would be implemented at each point on the curve.

highly urbanized settings, achievement of only adequate levels of aquatic uses could be exceedingly high and strain the limits of what is technically achievable. Finally, the existing and likely expected future land-use conditions have significant implications for what is achievable and at what cost. Clearly land-use decisions have an impact on the cost and whether a use can be achieved, and thus they need to be included in the decision process. The trade-off between costs and achieving specific designated uses can change substantially given different development patterns.

The purpose of Figure 5-5 is not to identify the precise location of the cost curves or to identify thresholds for achieving specific designated uses. Rather, these concepts are used to illustrate some fundamental trade-offs that confront public and private investment and regulatory decisions concerning stormwater management. The general relationships shown in Figure 5-5 suggest the need for establishing priorities for investments in stormwater management and controls, and connecting land usage and watershed goals. Setting overly ambitious or costly goals for urban streams may result in the perverse consequence of causing more waters to fail to meet designated uses. For example, consider efforts to secure ambitious designated uses in highly developed areas or in an area slated for future high-density development. Regulatory requirements and investments to limit stormwater quantity and quality through open-space requirements, areas set aside for infiltration and water detention, and strict application of maximum extent practicable controls have the effect of both increasing development costs and diminishing land available for residential and commercial properties. Policies designed to achieve exceedingly costly or infeasible designated uses in urban or urbanizing areas could have the net consequence of shifting development (and associated impervious surface) out into neighboring areas and watersheds. The end result might be minimal improvements in "within-watershed" ambient conditions but a decrease in designated uses (more impairments) elsewhere.

In such a case, it might be sound water quality policy to accept higher levels of impervious surface in targeted locations, more stormwater-related impacts, and less ambitious designated uses in urban watersheds in order to preserve and protect designated uses in other watersheds.

Setting unrealistic or unachievable water quality objectives in urban areas can also pose political risks for stormwater management. The cost and difficulty of achieving ambitious water quality standards for urban stream goals may be understood by program managers but pursued nonetheless in efforts to demonstrate public commitment to achieving high-quality urban waters. Yet, promising what cannot be realistically achieved may act to undermine public support for urban stormwater programs. Increasing costs without significant observable improvements in ambient water conditions or achievement of water quality standards could ultimately reduce public commitment to the program. Thus, there are risks of "setting the bar" too high, or not coordinating land use and designated stream uses.

The cost of setting the bar too low can also be significant. Stormwater requirements that result in ineffective stormwater management will not achieve or maintain the desired water uses and can result in impairments. Loss of property, degraded waters, and failed infrastructure are tangible costs to the public (Johnston et al., 2006). Streambank rehabilitation costs can be severe, and loss of confidence in the ability to meet stormwater goals can result.

The above should not be construed as an argument for or against devoting resources to SCMs; rather, such decisions should be made with an open and transparent acknowledgment and understanding of the costs and consequences involved in those decisions.

Common State Stormwater Goals

Most states do not and have never had an overriding water quality objective in their stormwater program, but rather have used engineering criteria for SCM performance to guide stormwater management. These criteria can be loosely categorized as

- Erosion and sedimentation control,
- Recharge/base flow,
- Water quality,
- Channel protection, and
- Flooding events.

The SCMs used to address these goals work by minimizing or eliminating increases in stormwater runoff volume, peak flows, and/or the pollutant load carried by stormwater.

The criteria chosen by any given state usually integrate state, federal, and regional laws and regulations. Areas of differing climates may emphasize one goal over another, and the levels of control may vary drastically. Contrast a desert region where rainwater harvesting is extremely important versus a coastal region subject to hurricanes. Some areas like Seattle have frequent smaller volume rainfalls—the direct opposite of Austin, Texas—such that small volume controls would be much more effective in Seattle than Austin. Regional geology (karst) or the presence of Brownfields may affect the chosen criteria as well.

The committee's survey of State Stormwater Programs (Appendix C) reflects a wide variation in program goals as reflected in the criteria found in their SCM manuals. Some states have no specific criteria because they do not produce SCM manuals, while others have manuals that address every category of criteria from flooding events to groundwater recharge. Some states rely upon EPA or other states' or transportation agencies' manuals. In general, soil and erosion control criteria are the most common and often exist in the absence of any other state criteria. This wide variation reflects the difficulties that states face in keeping up with rapidly changing information about SCM design and performance.

The criteria are ordered below (after the section on erosion and sediment control) according to the size of the storm they address, from smallest to most extreme. The criteria can be expressed in a variety of ways, from a simple requirement to control a certain volume of rainfall or runoff (expressed as a depth) to the size of a design storm to more esoteric requirements, such as limiting the time that flow can be above a certain threshold. The volumes of rainfall or runoff are based on statistics of a region's daily rainfall, and they approximate one another as the percentage of impervious cover increases. Design storms for larger events that address channel protection and flooding are usually based on extreme event statistics and tend to represent a temporal pattern of rainfall over a set period, usually a day. Finally, it should be noted that the categories are not mutually exclusive; for example, recharge of groundwater may enhance water quality via pollutant removal during the infiltration process.

Erosion and Sedimentation Control. This criterion refers to the prevention of erosion and sedimentation of sites during construction and is focused at the site level. Criteria usually include a barrier plan to prevent sedimentation from leaving the site (e.g., silt fences), practices to minimize the potential erosion (phased construction), and facilities to capture and remove sediment from the runoff (detention). Because these measures are considered temporary, smaller extreme events are designated as the design storm than what typically would be used if flood control were the goal.

Recharge/Base Flow. This criterion is focused on sustaining the preconstruction hydrology of a site as it relates to base flow and recharge of groundwater supplies. It may also include consideration of water usage of the property owners and return through septic tanks and tile fields. The criterion, expressed as a volume requirement, is usually to capture around 0.5 to 1.0 inch of runoff from impervious surfaces depending on the climate and soil type of the region. (For this range of rainfall, very little runoff occurs from grass or forested areas, which is why runoff from impervious surfaces is used as the criterion.)

Water Quality. Criteria for water quality are the most widespread, and are usually crafted as specific percent removal for pollutants in stormwater discharge. Generally, a water quality criterion is based on a set volume of stormwater being treated by the SCM. The size of the storm can run from the first inch of rainfall off impervious surfaces to the runoff from the one-year, 24-hour extreme storm event. It should be noted that the term "water quality" covers a wide range of groundwater and surface water pollutants, including water temperature and emerging contaminants.

Many of the water quality criteria are surrogates for more meaningful parameters that are difficult to quantify or cannot be quantified, or they reflect situations where the science is not developed enough to set more explicit goals. For example, the Wisconsin state requirement of an 80 percent reduction in TSS in stormwater discharge does not apply to receiving waters themselves. However, it presumes that there will be some water quality benefits in receiving waters; that is, phosphorus and fecal coliform might be captured by the TSS requirement. Similarly water quality criteria may be expressed as credits for good practices, such as using LID, street sweeping, or stream buffers.

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Channel Protection. This criterion refers to protecting channels from accelerated erosion during storm events due to the increased runoff. It is tied to either the presumed "channel-forming event"—what geomorphologists once believed was the storm size that created the channel due to erosion and deposition—or to the minimum flow that accomplishes any degree of sediment transport. It is generally defined as somewhere between the one- and five-year, 24-hour storm event or a discharge level typically exceeded once to several times per year. Some states require a reduction in runoff volume for these events to match preconstruction levels. Others may require that the average annual duration of flows that are large enough to erode the streambank be held the same on an annual basis under pre- and postdevelopment conditions.

It is not uncommon to find states where a channel protection goal will be written poorly, such that it does not actually prevent channel widening. For example, MacRae (1997) presented a review of the common "zero runoff increase" discharge criterion, which is commonly met by using ponds designed to detain the two-year, 24-hour storm. MacRae showed that stream bed and bank erosion occur during much lower events, namely mid-depth flows that generally occur more often than once a year, not just during bank-full conditions (approximated by the two-year event). This finding is entirely consistent with the well-established geomorphological literature (e.g., Pickup and Warner, 1976; Andrews, 1984; Carling, 1988; Sidle, 1988). During monitoring near Toronto, MacRae found that the duration of the geomorphically significant predevelopment mid-bankfull flows increased by more than four-fold after 34 percent of the basin had been urbanized. The channel had responded by increasing in cross-sectional area by as much as three times in some areas, and was still expanding.

Flooding Events. This criterion addresses public safety and the protection of property and is applicable to storm events that exceed the channel capacity. The 10- through the 100-year storm is generally used as the standard. Volume-reduction SCMs can aid or meet this criterion depending on the density of development, but usually assistance is needed in the form of detention SCMs. In some areas, it may be necessary to reduce the peak flow to below preconstruction levels in order to avoid the combined effects of increased volume, altered timing, and a changed hydrograph. It should be noted that some states do not consider the larger storms (100-year) to be a stormwater issue and have separate flood control requirements.

Each state develops a framework of goals, and the corresponding SCMs used to meet them, which will depend on the scale and focus of the stormwater management strategy. A few states have opted to express stormwater goals within the context of watershed plans for regions of the state. However, the setting of goals on a watershed basis is time-consuming and requires study of the watersheds in question. The more common approach has been to set generic or minimal controls for a region that are not based on a watershed plan. This has been done in Maryland, Wisconsin (see Box 5-1), and Pennsylvania (see Box 5-2). This strategy has the advantage of more rapid implementation of some SCMs because watershed management plans are not required. In order to be applicable to all watersheds in the state, the goals must target common pollutants or flow modification factors where the processes are well known. It must also be possible for these goals to be stated in National Pollutant Discharge Elimination System (NPDES) permits. Many states have selected TSS reduction, volume reduction, and peak flow control as generic goals. A generic goal is not usually based on potentially toxic pollutants, such as heavy metals, due to the complexity of their interaction in the environment, the dependence on

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HYDROLOGIC IMPACTS OF ALTERNATIVE APPROACHES TO STORM WATER MANAGEMENT AND LAND DEVELOPMENT[1]

Evan Shane Williams and William R. Wise[2]

ABSTRACT: Low impact development (LID) and other land development methods have been presented as alternatives to conventional storm water management and site design. Low impact development encourages land preservation and use of distributed, infiltration-based storm water management systems to minimize impacts on hydrology. Such systems can include shallow retention areas, akin to natural depression storage. Other approaches to land development may emphasize land preservation only. Herein, an analysis of four development alternatives is presented. The first was Traditional development with conventional pipe/pond storm water management and half-acre lots. The second alternative was Cluster development, in which implementation of the local cluster development ordnance was assumed, resulting in quarter-acre lots with a pipe/pond storm water management system and open space preservation. The "Partial" LID option used the same lot layout as the Traditional option, with a storm water management system emphasizing shallow depression storage. The "Full" LID used the Cluster site plan and the depression storage-based storm water management system. The alternatives were compared to the hydrologic response of existing site conditions. The analysis used two design storms and a continuous rainfall record. The combination of land preservation and infiltration-based storm water management yielded the hydrologic response closest to existing conditions, although ponds were required to control peak flows for the design storms.
(KEY TERMS: infiltration; urban hydrology; low impact development; cluster development; storm water management; runoff.)

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INTRODUCTION

This paper presents the results of a hydrologic analysis for alternative methods of land development and storm water management for a real site undergoing hypothetical residential development. If alternatives to current site design and storm water management practices are to be considered, some knowledge of the implications of implementing these practices must be anticipated. This work explores the hydrologic impact of preserving open space, implementing a distributed, infiltration-based storm water management system, and a combination of these two approaches. The goal was to quantify the anticipated impact of these alternatives as individual approaches (i.e., benefits of site planning versus engineered storm water management systems) and how site planning and engineered storm water management can work together. The combination of these two alternatives is consistent with the low impact development (LID) land development strategy developed by Prince Georges County, Maryland (Prince Georges County, 1999). The analysis was performed in the context of a large residential development project in Alachua County, Florida. The results of the analysis indicated that reduction of the development footprint and an infiltration-based, distributed storm water management system resulted in a hydrologic response closer to existing conditions. However, each development option required some conventional storm water management ponds.

The property analyzed for residential development was located in the Camp Blanding Wildlife Management Area that is part of the Camp Blanding Florida

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The modeling approach was based on lumped parameter assumptions, which may introduce theoretical error into the modeling process. Lumped parameter models, which are widely used, assume that individual subareas are homogenous. Therefore, parameters are averaged across the sub-area when there actually is spatial variation. A good example is the bioretention units that are accounted for as depression storage: the storage is applied to the entire subarea at a lower overall depth, but the storage is actually more localized in deeper storage cells. This also applies to indirectly connected impervious surfaces. These areas are also spatially distributed; however, the impact of these areas on subsurface storage and the runoff from these areas is distributed across the entire subarea. Zero storages resulting from IDCIAs were averaged with pervious areas, such as lawns and natural woodlands, which have positive storages. This is similar to the approach that would be used in a subarea with two different soil types or surface cover conditions where storage depths would be averaged. Again, a theoretical error may be introduced in the modeling process since the SMA infiltration/percolation equations are dependent on the ratio of storage filled in the upper contributing layer to the lower receiving layer. Percolation between one layer and the next lowest is greatest when the upper layer is full and the lower layer is empty (Bennett, 1998). Equivalent depths in two different storage layers with different total storage depths would yield slightly different infiltration/percolation results. Even with the concerns identified above, HEC-HMS is an effective tool to compare the anticipated hydrologic impacts of varying development strategies.

MODEL RESULTS AND DISCUSSION

The SMA model was calibrated using the collected rainfall and stream stage data. The results of the calibration are shown in Figure 4. The error in volume between the observed and calibrated data was under 2.5 percent of the rainfall for the study period. The time of peak flow tended to be earlier than was observed in the field data. This could be remedied by adjusting the subarea T_c. This was deemed unacceptable since the T_c results for the predictive models were computed, and consistency between methods for existing conditions and the alternatives was desired. The four alternatives were modeled for the design storms with and without storm water controls (depression storage or wet detention ponds). The continuous model was run only with all storm water controls implemented.

Peak Flow Impacts

Regulatory compliance required that the controlled peak flows for the design storms not exceed predevelopment levels. The two-stage pond outlet

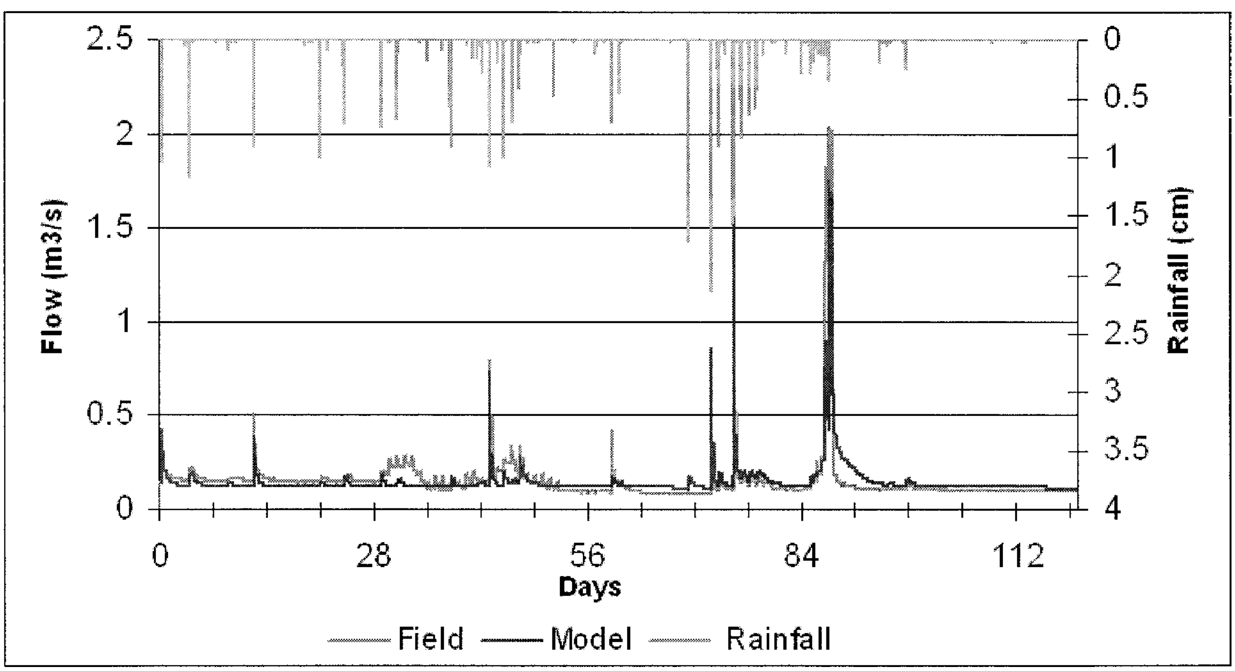

Figure 4. Results of Model Calibration.

structures were designed to meet this goal. The lower orifice also was designed for water quality residence time. The peak flows for the design storms when all storm water management controls are implemented are reported in Table 2. The two-year event peaks, from the conventional storm water management systems, are somewhat lower than the existing two-year peak. This is due to the design of the lower outlet for water quality (slow release of water quality storage). The peak timing change is small for the two-year event, but the delay for the 25-year design storm may cause unanticipated flooding problems downstream. The lack of a pronounced timing change was also evident in the uncontrolled model runs. This was likely due to the model calibration, where the subareas near the streams produced the most runoff and were little changed by development.

The LID designs could not meet peak flow control requirements with the final depression storage values. Dry detention ponds were added until the peak flow control requirements were met. These ponds are conceptual and not explicitly designed, although the resulting detention volume is probably quite accurate for the Full LID design since it was placed in a subarea where runoff would concentrate. The Partial LID design required more ponds. Three subareas were modeled with ponds before analysis was stopped. The reason analysis was stopped was because it became necessary to add a pond in a subarea where runoff did not concentrate based upon the site design and storm water transport system. Continuing this assumption would provide no further analytical benefit. It is notable that the large lot design would have required redesign of the storm sewer system to meet the regulatory requirement for the 25-year peak flow.

Runoff Volume Impacts

Table 2 also presents the flow volumes for the two design storms for both controlled and uncontrolled simulations. As expected, reducing the footprint of development (traditional versus cluster) reduced runoff volume. This reduction was greater when the storm water transport system was directly connected (no infiltration potential). Disconnecting the roads by providing grass swales for infiltration provided further volume reduction based on comparison of development options with the same footprint. For the controlled models with conventional storm water management, the only loss from a pond in the model is outflow through the outlet structure. Therefore any apparent volume reduction is due to detention of runoff. The volume distribution of the hydrographs was closest to the natural response for the LID designs, for all design storms, whereas the pond designs showed significant change during the 25-year event.

Continuous Model Results

The time period of the continuous model was from 2:00 p.m. on June 19, 2001, to 2:00 p.m. on October 17, 2001. This period corresponds to the time period that the watershed was gauged. Peak flow results for

TABLE 2. Model Results for Hypothetical Design Storms.

Alternative	Two-Year Peak (m^3/s)	Simulation Hour (military time)	25-Year Peak (m^3/s)	Simulation Hour (military time)	Two-Year Volume (mm)	25-Year Peak (mm)
Existing	3.3	1320	9.8	1330	33.8	101.4
Uncontrolled (no ponds or depression storage) Model Results						
Traditional	8.6	1320	23.3	1320	47.2	118.8
Cluster	5.6	1330	15.4	1330	43.4	114.5
Partial LID	5.7	1340	16.1	1340	41.0	111.3
Full LID	4.0	1340	11.1	1340	38.7	108.3
Controlled (all storm water management controls) Model Results						
Traditional	2.8	1300	9.8	1510	31.4	101.9
Cluster	2.9	1310	8.1	1540	31.4	100.5
Partial LID	3.3	1320	10.6	1320	30.2	98.8
Full LID	3.3	1320	9.7	1340	33.1	102.3

the continuous simulation showed little deviation from the existing flows. This not wholly unexpected since most convection generated runoff events only involved contribution from the areas immediately surrounding the streams, which were little changed through the development scenarios (due to a mandatory water resource buffer and site constraints). The LID designs tended to lower the convection storm peaks. This effect was more pronounced for the Partial LID where the sum of the assumed bioretention areas was larger. The exception, shown in Table 3, was a large peak flow associated with a tropical storm on September 14-15, where no design alternative adequately controlled the peak flow. It is notable that the LID options performed somewhat worse than the same development footprint with wet detention.

TABLE 3. Continuous Simulation Results: September 14-15 Event.

Alternative*	Peak (cms)	Date and Time
Existing	1.8	15 September 0940
Traditional	2.8	15 September 1000
Cluster	2.5	15 September 1000
Partial LID	3.0	15 September 0920
Full LID	2.8	15 September 0930

*All alternatives are controlled in this simulation.

Inspection of the model output for soil water storage indicated that the moisture conditions prior to the start of the tropical event were above the average conditions assumed for the design storms upon which the engineered storm water controls were based. It is possible that this condition would adversely impact the performance of the depression storage-based storm water system more than a pond-based system since the only means of recovery of volume is through infiltration, which could be inhibited by a rising water table. In addition, the depression storage-based option allows for runoff that would otherwise flow through storm sewers to be applied to pervious surfaces in addition to direct precipitation. This would, in effect, require the remaining pervious surfaces to infiltrate more runoff than normal.

Simulations were conducted on generic watersheds with identical area and timing parameters. The soil moisture model parameters were selected from one of the upland areas in the same general area of the site for the cluster and Full LID design options. The Full LID option was run with and without the additional depression storage results. It was apparent that the soil and the interflow ground water layer (first layer) drained more slowly in the Full LID alternative than in the cluster alternative. As a result, they fill faster so that by the time the worst portion of the tropical event arrived, the depression storage was filled.

In the case of the pond designs, the inability to control the peak flows for the tropical event may be the result of the design of the pond outlet structure. The orifices are designed to ensure an adequate residence time of the first flush. The second-stage weir controls the peak flow for the design storm events, which have larger peaks flows than the tropical event. The results raise the possibility that the weir designs allow a flow rate that is simply too large for a smaller event. Furthermore, pond systems can still be impacted by antecedent moisture conditions. This would be reflected by higher pond stage at the start of a rain event due to previous events.

Overall volume discharged through the simulation period increased 10 and 20 mm (0.39 and 0.79 in) for the pond system on the Cluster and Traditional developments, respectively, while the LID options were slightly lower, about 4.0 mm, than the existing conditions. Each design alternative resulted in slightly lower base flow; most likely due to a smaller area contributing ground water flow (the volume of ground water flow is routed through a linear reservoir to determine flow at any given point in time). Therefore, it appeared that any increase in total volume was due to increased surface runoff or interflow.

Flow Durations

Table 4 shows the percent of continuous model data points (17,280) that exceed a given flow. Each data point is 10 minutes. The LID alternatives are more reflective of the existing site conditions for flows below 0.5 m^3/s. Impacts on base flows are particularly apparent. Again, it is notable that above 0.5 m^3/s level the LID alternatives begin to perform worse than the alternatives with pond-based storm water management. Just as with the peak flows, this could be attributed to the tropical event occurring on September 14 and 15. Omitting this event from the flow duration calculation resulted in high flow durations close to the existing conditions across all alternatives. The tropical event had a double flow peak, and the underperformance of the LID alternatives was reflected in the first peak where the flows exceeded existing conditions for the LID alternatives, while the pond-based systems performed closer to the existing flow.

TABLE 4. Percent of Model Points Exceeding Flow.

Flow (CMS)	Existing	Full LID	Partial LID	Cluster	Traditional
0.1	99.95	93.65	81.42	63.41	51.38
0.15	17.96	18.86	19.74	23.67	26.36
0.2	7.18	11.16	11.87	12.65	15.02
0.3	2.86	2.75	2.68	6.33	7.38
0.4	1.90	1.98	1.88	2.45	2.77
0.5	1.42	1.67	1.58	1.66	1.68
0.6	1.15	1.46	1.39	1.41	1.42
0.7	0.82	1.27	1.20	1.15	1.11
0.8	0.60	1.05	0.96	0.79	0.78
0.9	0.41	0.94	0.88	0.64	0.64
1.0	0.36	0.88	0.83	0.49	0.49
1.5	0.10	0.48	0.46	0.31	0.31
2.0	0.00	0.21	0.22	0.14	0.16

Table 5 shows the impact of preserving natural open space on structural storm water management. The reduced lot designs all required less structural storm water management.

CONCLUSIONS

Application of an infiltration-based, distributed storm water management system should result in a developed watershed response that is closer to natural conditions, particularly if it is accompanied by a program of land preservation around stream corridors and upland high infiltration areas. Land preservation also should decrease reliance on storm water management control practices. However, infiltration-based storm water systems may perform worse than conventional pond systems when antecedent moisture conditions are above average because their means of recovery is lessened. This may need to be considered in the storm water system design or in the hydrologic modeling. The land preservation aspect of the Full LID alternative lessened this effect, but this design only performed about the same as the Traditional design for the September 14 and 15 event in terms of peak flows. The LID design options did not increase overall stream flow volume, compared to existing conditions, under continuous simulation, whereas the pipe/pond storm water management approach did increase volume.

The alternatives compared can be viewed as potential solutions in a solution space. Figure 5 represents this concept. Implementation of alternative methods of storm water management and site design may have a variety of feasible solutions as far as regulatory compliance is concerned. The results from this work also indicate that sole reliance on distributed depression storage controls may not be feasible. However, this is not inconsistent with the goals of LID as they were interpreted. A system could be designed where the infiltration controls are used to control runoff up to a critical event, beyond which detention ponds are used to control peak flows; this strategy would serve both runoff quality and quantity concerns well. Performance under high antecedent moisture conditions may also have to be considered in the design of the storm water management system.

The objective of this effort was to point out possible areas of hydrologic concern with various land development and storm water management practices. Field performance of alternative forms of land development and storm water management practices must still be analyzed to validate these results. This is particularly true for bioretention and other depression storage controls where performance under conditions that do not represent the average is of apparent concern.

TABLE 5. Final Volumes of Management Practices.

Alternative	Storage (m^3)	Average Per Lot (m^3)	Percent of Lot*	Total Pond Volume (m^3)**
Traditional	0	0	0	220,171
Cluster	0	0	0	157,122
Partial LID	32,059.11	44.59	15.6	29,576
Full LID	17,517.82	24.33	17.1	5,497

*Some storage was assumed to be provided in the roadside swales and would be in the right-of-way.
**Traditional and cluster designs utilize wet ponds with permanent pool while LID designs utilize dry detention ponds.

Modeling of LID storm water management is another area where research is needed. Models that account for water after it infiltrates, such as the SMA model used here, are useful when infiltration practices are considered. However, the potential limitations of current models should be addressed. Evolving distributed models should rectify many of the current limitations with widely used lumped hydrologic models.

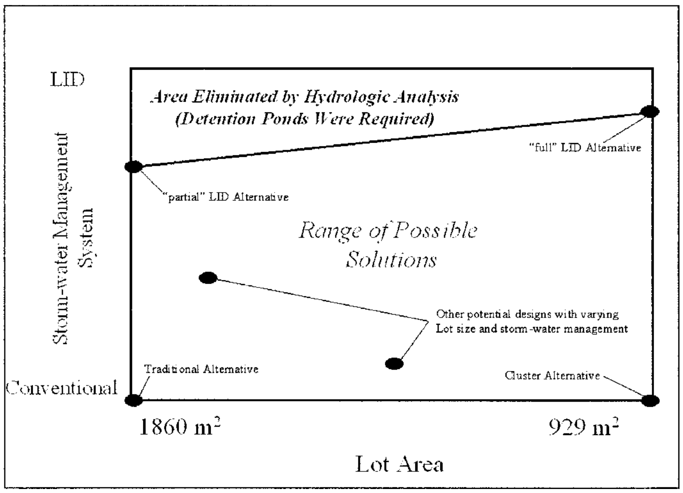

Figure 5. View of a Conceptual Solution Field.

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Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada

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Abstract

This study focuses on the differential hydrologic response of individual watersheds to climate warming within the Sierra Nevada mountain region of California. We describe climate warming models for 15 west-slope Sierra Nevada watersheds in California under unimpaired conditions using WEAP21, a weekly one-dimensional rainfall-runoff model. Incremental climate warming alternatives increase air temperature uniformly by 2°, 4°, and 6°C, but leave other climatic variables unchanged from observed values. Results are analyzed for changes in mean annual flow, peak runoff timing, and duration of low flow conditions to highlight which watersheds are most resilient to climate warming within a region, and how individual watersheds may be affected by changes to runoff quantity and timing. Results are compared with current water resources development and ecosystem services in each watershed to gain insight into how regional climate warming may affect water supply, hydropower generation, and montane ecosystems. Overall, watersheds in the northern Sierra Nevada are most vulnerable to decreased mean annual flow, southern-central watersheds are most susceptible to runoff timing changes, and the central portion of the range is most affected by longer periods with low flow conditions. Modeling results suggest the American and Mokelumne Rivers are most vulnerable to all three metrics, and the Kern River is the most resilient, in part from the high elevations of the watershed. Our research seeks to bridge information gaps between climate change modeling and regional management planning, helping to incorporate climate change into the development of regional adaptation strategies for Sierra Nevada watersheds.

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Introduction

General circulation models (GCMs) predict an increase in air temperature across California's Sierra Nevada mountain range, although predictions vary whether the region can expect more or less precipitation [1,2]. Most studies agree that decreases in mean annual flow, reduced snowpack, and more rapid snowmelt runoff are expected [3,4,5,6]. However, it is not well understood whether individual watersheds within a single region will respond differently to climate warming, how characteristics of the individual watersheds may temper future impacts, and how differential impacts relate to existing demands such as water storage capacity, hydropower generation, and ecosystem services.

In this paper, we analyze model results from 15 neighboring watersheds to examine differential watershed response within a larger region. We use results from a climate-forced rainfall-runoff model to explicitly simulate intra-basin hydrologic dynamics and understand localized sensitivity to climate warming. Insights presented here are intended to help guide local adaptation strategies by highlighting regional and basin-specific trends in the quantity and timing of water resources under regional climate warming, and to illustrate which basins are the most intrinsically vulnerable to climate warming.

Due to uncertainty regarding future precipitation change [1], we assume a historic hydrology and focus singularly on hydrologic response to climate warming. We analyze climate warming effects at the watershed scale for 15 west-slope watersheds of the Sierra Nevada mountain range. Model domain extends from the crest of the Sierra Nevada to the floor of California's Central Valley. Climate sensitivity analyses include basecase unimpaired conditions and uniform air temperature increases of 2°C, 4°C, and 6°C to bracket the range of likely outcomes for Sierra Nevada watersheds with climate warming. Other climate variables are unchanged from historic values. The modeled period, water years 1981–2001, covers a wide range of climatic variability including the wettest year on record (1983), the flood year of record (1997), and a prolonged drought (1988–1992). Predicting the frequency of extreme events due to climate warming is outside the scope of this study. Results are interpreted by focusing on potential impacts of changed water yield to water storage, runoff timing to hydropower generation, and extension of low flow duration to montane ecosystems, such as high elevation meadows, riparian areas, and aquatic habitats.

The Sierra Nevada mountain range is a water source for many of California's 38 million residents. The region has been extensively developed for water resources with reservoirs and conveyance facilities to enhance water supplies, hydropower, and flood control for downstream communities. Environmental minimum instream flows maintain habitat for aquatic and riparian ecosystems, and rivers and reservoirs are also used extensively for recreational purposes.

Climate warming will alter Sierra Nevada water resources in a number of ways, but direct impacts to water supply, hydropower

Appendix 3

Water-Harvesting Calculations

List of Equations and Other Information

Box A3.1. Abbreviations, Conversions, and Constants for English and Metric Measurement Units

Note: * items are approximate or rounded off

ABBREVIATIONS FOR ENGLISH UNITS
inches = in
feet = ft
square feet = ft^2
cubic feet = ft^3
gallons = gal
pounds = lb
pounds per square inch of pressure = psi

CONVERSIONS FOR ENGLISH UNITS
To convert cubic feet to gallons, multiply cubic feet by 7.48 gal/ft^3 *
To convert inches to feet, divide inches by 12 in/ft
To convert gallons of water to pounds of water, multiply gallons by 8.34 lb/gal *
To convert cubic feet of water to pounds, multiply cubic feet by 62.43 lb/ft^3 *

CONSTANTS
Pounds of pressure per square inch of water per foot of height = 0.43 psi/ft *
Ratio between a circle's diameter and its circumference is expressed as π = 3.14 *

ABBREVIATIONS FOR METRIC UNITS
millimeters = mm
centimeters = cm
meters = m
liters = l
kilograms = kg

CONVERSIONS FOR METRIC UNITS
1 liter of water weighs 1 kilogram
To convert cubic centimeters to liters, divide cubic centimeters by 1,000

CONVERTING BETWEEN ENGLISH UNITS AND METRIC UNITS
To convert inches to millimeters, multiply inches by 25.4 mm/in *
To convert inches to centimeters, multiply inches by 2.54 cm/in *
To convert feet to meters, multiply feet by 0.30 m/ft *
To convert gallons to liters, multiply gallons by 3.79 liter/gal *
To convert pounds to kilograms, multiply pounds by 0.45 kg/lb *

Best technique to measure rainfall: Buy a simple rain gauge for $10 or so from a hardware or feed store, plant and garden nursery, or a scientific supply house. A rain gauge that is tapered at the bottom makes reading small amounts of rainfall easier.

For resources documenting local rainfall rates and other climatic information, see appendix 6, section G.

Equation 1A.
Catchment Area of Rectangular Surface (English units)

length (ft) × width (ft) = catchment area (ft^2)

EXAMPLE:

A house that measures 47 feet long by 27 feet wide at the drip line of the roof. Note that it does not matter whether the roof is flat or peaked; the roof dimensions at the drip line are the same. It is the "footprint" of the roof's drip line that matters.

47 ft × 27 ft = 1,269 ft^2
1,269 ft^2 = catchment area

If the roof consists of two or more rectangles, calculate the area for each rectangle and add together. Again, take the view of a falling raindrop, and only look at the "footprint" of the roof's drip line. Roof pitch cannot be seen from above and does not matter. With conical, octagonal, or other non-standard roof shapes, again calculate the area based on the *drip line*.

Equation 1B.
Catchment Area of Rectangular Surface (metric units)

length (m) × width (m) = catchment area (m^2)

EXAMPLE:

15 m × 9 m = 135 m^2
135 m^2 = catchment area

Again, all the considerations in Equation 1A will apply.

Equation 2A.
Catchment Area of Triangular Surface (right triangle)

Multiply the lengths of the two shorter sides of the triangle then divide by 2 = catchment area

EXAMPLE:

A triangular section of roof measures 9 feet by 12 feet by 15 feet. This is a right triangle, with the 90-degree angle between the 9-foot and 12-foot sides. Taking the measurements of the two shorter sides:

(9 ft × 12 ft) ÷ 2 = catchment area (ft^2)
108 ft^2 ÷ 2 = 54 ft^2

54 ft^2 = catchment area

Equation 2B.
Catchment Area of Triangular Surface (standard math formula)

Multiply the triangle's base times its height then divide by 2 = catchment area
where the base can be any side, and the height is measured perpendicularly from the base to the opposite vertex.

EXAMPLE:

You want to know the area of a triangular section of patio. The length of the section in front of you is 20 feet (triangle base) and you measure 4 feet perpendicularly to the opposite vertex of the triangle.

(20 ft × 4 ft) ÷ 2 = catchment area (ft^2)
80 ft^2 ÷ 2 = 40 ft^2

40 ft^2 = catchment area

Equation 2C.
Catchment Area of Triangular Surface (Heron's formula)

This formula, attributed to Heron of Alexandria (first century A.D.), involves no trigonometry. It only needs the square root (sqrt) function found on most electronic or computer calculators. It may be useful when dealing with non-right triangles where you can measure (or know) all sides of the triangle.

Step 1: Determine the lengths of the sides of the triangle. These are a, b, c.

Step 2: Calculate s.
(a + b + c) ÷ 2 = s

Step 3: Calculate S, using:
s × (s – a) × (s – b) × (s – c) = S

Step 4: Calculate the catchment area, which is the square root of S.
sqrt S = catchment area

Equation 3.
Catchment Area of Circular Surface

$\pi \times r^2$ = catchment area
Note: r = radius of the circle. A circle's radius is half the circle's diameter.

EXAMPLE:

A circular roof has a 25 foot diameter. Divide the diameter by 2 to get the *radius* of 12.5 feet.

π × (12.5 ft × 12.5 ft) = catchment area (ft^2)
3.14 × 156.25 ft^2 = 490.62 ft^2

490.62 ft^2 = catchment area

Equation 4A.
Possible Volume of Runoff from a Roof or Other Impervious Catchment Area (English units)

catchment area (ft^2) × rainfall (ft) × 7.48 gal/ ft^3 = maximum runoff (gal)

Note: For a more realistic and conservative estimate see Equation 5.

EXAMPLE CALCULATING ANNUAL RUNOFF:

Calculate the gallons of rain running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. (In the example below, the roof dimensions at the drip line are included in the calculation; the catchment area is the same whether the roof is flat or peaked.) Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 = maximum runoff (gal)
(47 ft × 27 ft) × (10.5 in ÷ 12 in/ft) × 7.48 gal/ft^3 = maximum runoff (gal)
1,269 ft^2 × 0.875 ft × 7.48 gal/ft^3 = 8,306 gal

8,306 gal = runoff

EXAMPLE CALCULATING RUNOFF FROM A SINGLE RAIN EVENT:

Calculate the maximum gallons of rain running off the roof in a single rain event from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. It is not unusual for heavy storms in the example area to drop two inches of rain. To determine the runoff from such a rain event you will divide the 2 inches of rainfall by 12 inches of rainfall per foot to convert inches to feet for use in the equation. Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 = maximum runoff (gal)
(47 ft × 27 ft) × (2 in ÷ 12 in/ft) × 7.48 gal/ft^3 = maximum runoff (gal)
1,269 ft^2 × 0.167 ft × 7.48 gal/ft^3 = 1,585 gal

1,585 gal = maximum runoff

Equation 4B.
Possible Volume of Runoff from a Roof or Other Impervious Catchment Area (metric units)

catchment area (m^2) × rainfall (mm^2) = maximum runoff (liters)

Calculations for annual rainfall, a rainy season, or an event would be similar to those for English units.

Box A3.2. Estimating Rainfall Runoff Using Rules of Thumb

Rough rule of thumb for calculating rainfall runoff volume on a catchment surface (English units):
You can collect 600 gallons of water per inch of rain falling on 1,000 square feet of catchment surface.

On the really big scale:
You can collect 27,000 gallons of water per inch of rain falling on 1 acre of catchment surface.

Rule of thumb for calculating rainfall volume on a catchment surface (metric units):
You can collect 1,000 liters of water per each 10 millimeters of rain falling on 100 square meters of catchment surface.

On the really big scale:
You can collect 100,000 liters of water per 10 millimeters of rain falling on one hectacre of catchment surface.

Equation 5A. Estimated Net Runoff from a Catchment Surface Adjusted by its Runoff Coefficient (English units)

catchment area (ft^2) × rainfall (ft) × 7.48 gal/ft × runoff coefficient = net runoff (gal)

Impervious catchment surfaces such as roofs or non-porous pavement can lose 5% to 20% of the rain falling on them due to evaporation, and minor infiltration into the catchment surface itself. The more porous or rough your roof surface, the more likely it will retain or absorb rainwater. On average, pitched metal roofs lose 5% of rainfall, allowing 95% to flow to the cistern. Concrete or asphalt roofs retain around 10%, while builtup tar and gravel roofs can retain 15% to 20%. However, the percent of retention is a function of the size and intensity of the rain event, so more porous roof surfaces could absorb up to 100% of small, light rain events. To account for this potential loss, determine the runoff coefficient that is appropriate for your area and impervious catchment surface (0.80 to 0.95).

EXAMPLE CALCULATING NET ANNUAL RUNOFF FROM A ROOF:

Calculate the net gallons of rain running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Assume that the loss of water that occurs on the catchment surface is at the high end of the range so you get a conservative estimate of *net runoff*. This means you select a *runoff coefficient* of 80%, or 0.80. Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
(47 ft × 27 ft) × (10.5 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
1,269 ft^2 × 0.875 ft × 7.48 gal/ft^3 × 0.80 = 6,644 gal

6,644 gal = net runoff

Based on this, a realistic estimate of the volume of water that could be collected off the 47 foot by 27 foot example roof in an average year is 6,644 gallons.

Pervious surfaces such as earthen surfaces or vegetated landscapes can infiltrate up to 100% of the rain falling on them. Their runoff coefficient is greatly influenced by soil type and vegetation density. Large-grained porous sandy soils tend to have lower runoff coefficients while fine-grained clayey soils allow less water to infiltrate and therefore have higher runoff coefficients. Whatever the soil type, the more vegetation the lower the runoff coefficient since plants enable more water to infiltrate the soil. Below are some runoff coefficients for the southwestern U.S., although these are just rough estimates since runoff rates are also affected by rainfall intensity and duration. The more intense or the longer the rainfall the greater the runoff, since more rain is infiltrated in the soil before the soil becomes saturated. A very light rainfall may just evaporate, and not run off or infiltrate at all.

- Sonoran Desert uplands (healthy indigenous landscape): range 0.20–0.70, average 0.30–0.50
- Bare earth: range 0.20–0.75, average 0.35–0.55
- Grass/lawn: range 0.05–0.35, average 0.10–0.25
- For gravel use the coefficient of the ground below the gravel

EXAMPLE CALCULATING NET *ANNUAL* RUNOFF FROM A *BARE SECTION OF YARD*:

In an area receiving 18 inches of rain in an average year, you want to calculate the runoff from a 12 foot by 12 foot bare section of yard that drains to an adjoining infiltration basin. The soil is clayey and compacted, and you estimate its runoff coefficient to be 60% or 0.60.

catchment area (ft^2) × rainfall (ft) × 7.48 gal/ft × runoff coefficient = net runoff (gal)
12 ft × 12 ft × (18 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.60 = net runoff (gal)
144 ft^2 × 1.5 ft × 7.48 gal/ft^3 × 0.60= 969 gal

969 gal = net runoff

Based on this, a realistic estimate of the volume of runoff that could be collected off the 12 foot by 12 foot section of bare earth within the adjoining infiltration basin is 969 gallons in an average year.

EXAMPLE CALCULATING RUNOFF FROM A *SINGLE STORM EVENT* ON *ESTABLISHED LAWN* (*GRASS*):

The runoff coefficient for this established lawn is assumed to be 20% or 0.20, and the maximum storm event is 3 inches:

12 ft × 12 ft × (3 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.20 = net runoff (gal)
144 ft^2 × 0.25 ft × 7.48 gal/ft^3 = 54 gal

54 gal = net runoff

Equation 5B.
Estimated Net Runoff from an Impervious Catchment Surface Adjusted by its Runoff Coefficient (metric units)

catchment area (m^2) × rainfall (mm) × runoff coefficient = net runoff (liters)

EXAMPLE:

In an area receiving 304 millimeters of rain a year, you have a rooftop catchment surface that is 15 meters long and 9 meters wide, and you want to know how much rainfall can realistically be collected off that roof in an average year. You want a conservative estimate of annual *net runoff*, so you use a *runoff coefficient* of 80% or 0.80. (Since the roof is a rectangular area, use the following calculation for catchment area as in Equation 1B—catchment area (m^2) = length (m) × width (m)—which is figured into the calculation below.)

(length (m) × width (m)) × rainfall (mm) × 0.80 = net runoff (liters)
(15 m × 9 m) × 304 mm × 0.80 = net runoff (liters)
135 m^2 × 304 mm × 0.80 = 32,832 liters

32,832 liters = net runoff

A realistic estimate of the volume of water that could be collected off this 15 meter by 9 meter roof in a year of average rainfall is 32,832 liters.

Equation 6.
Cistern Capacity Needed to Harvest the Roof Runoff from a Large Storm Event

catchment area (ft^2) × rainfall expected in a local high volume storm (ft) × 7.48 gal/ft^2 × runoff coeficient = catchment runoff (gal)

EXAMPLE:

A water harvester with a 1,200 ft^2 roof lives in an area where a single storm (or two storms just a few days apart) can unleash 3 inches of rain.

1,200 ft^2 × (3 inches ÷ 12 inches) × 7.48 gal/ft^2 × 0.80 = catchment runoff (gal)
1,200 ft^2 × 0.25 ft × 7.48 gal/ft^2 × 0.80 = 1,795 gal

1,795 gal = catchment runoff

This is the *minimum cistern volume* needed to capture the roof runoff for this size storm.

Note: The above calculation is meant to give a rough estimate of a tank size that will reduce water loss to overflow from the tank and extend the availability of a lot of rainfall long after the rain event only—it is not based on estimated water needs. It is a quick and easy calculation for those simply wanting to supplement their water use with efficient rainwater tank storage. I often recommend beginner water harvesters start with a tank not exceeding a 1,500 gallon capacity. The system can always be expanded later. To start small you don't need to begin with a tank harvesting all the roof's runoff; rather begin by sizing a tank capturing water from just one section of the roof.

Equation 7.
Water Storage Capacity Needed for a Household Committing to Use Harvested Rainwater as the Primary Water Source (English units)

number of people × daily water consumption (gal/person/day) × longest drought period (days) = needed storage capacity (gal)

EXAMPLE:

If three people live in the household used in the above examples, each person consumes an average of about 50 gallons per day, and the typical dry season in their area lasts 140 days then:

3 people × 50 gal/person/day × 140 days = 21,000 gal

21,000 gal = needed water capacity

If the people in this household are planning to live primarily off rainwater at their current water consumption rate they would be wise to plan for at least 21,000 gallons of water collection and storage capacity to get them through up to 140 days of dry times.

If the needed water capacity (and needed catchment area) seems too large to be feasible, see how much you can realistically reduce your water consumption, then do the calculation again. For example, if the same household could reduce its daily water consumption to 20 gallons/person/day only 8,400 gallons of water collection and storage capacity would be needed.

Note: The above calculation will give a ballpark estimate of minimum tank capacity to meet dry season demand in expected drought. Sufficient catchment directing water to the tank is also needed to ensure the tank is full or close to full on day one of the dry season. See volume 3 of *Rainwater Harvesting for Drylands*, for additional calculations and considerations.

Equation 8. Potential Gravity-Fed Water Pressure from Your Tank (English units)

height of water above its destination (ft) × water pressure per foot of height (psi/ft) = passive water pressure (psi)

For every foot your source of water is above the elevation of the place where it will be used you develop 0.43 psi/ft of passive water pressure (gravity is the only force being used to create that pressure). The source of water may be in a tank, or a gutter and its associated downspout. The place you use the water may be a garden bed, a fruit tree basin, or any other location where supplemental water is needed.

EXAMPLE:

The folks with the new 8-foot-tall tank want to figure out how much passive water pressure will be available to deliver water from the tank to their squash plants placed in basins 6 inches (0.5 ft) below the surrounding land surface. The height of water in the 8-foot tank is 4 inches below the top of the tank due to the presence of an overflow pipe that allows excess rainwater to safely flow out of the tank during large storms. Based on this information the height of water above its destination is around 8.1 ft. Using Equation 8, calculate the passive water pressure as follows:

8.1 ft × 0.43 psi/ft = 3.48 psi

3.48 psi = passive water pressure

As the cistern water is used, the water pressure will drop with the dropping level of water (head) in the tank. Also, keep in mind that friction between water and the walls of a hose, pipe, or irrigation line will cut down on water pressure, so to maintain pressure try to use the water close to the tank, reducing the length of pipe or hose. For example, place a garden on the east side of your tank where the veggies will be shaded from the hot afternoon sun by the bulk of the tank, and you won't need a hose any longer than 25 feet (7.6m).

EXAMPLE:

I often place cisterns so their base is at least 2.5 feet above the garden or basin receiving the stored water. This guarantees me at least 1 psi of gravity-fed pressure even when the tank is nearly empty.

height of water above its destination (ft) × water pressure per foot of height (psi/ft) = passive water pressure (psi)
2.5 ft × 0.43 psi/ft = 1.08 psi

1.08 psi = passive water pressure

Equation 9A.
Storage Capacity of a Cylinder (Can Apply to Both a Cylindrical Cistern or a Length of First Flush Pipe) (English units)

$\pi \times (\text{cylinder radius (ft)})^2 \times \text{effective cylinder height* (ft)} \times 7.48\ \text{gal/ft}^3 = \text{capacity (gal)}$

Note: r = radius of the circle

*Effective height is the height of water you can get back out of the tank when it's full, as opposed to the total height of water in the tank, which includes several inches of water that can never be drained out due to an outflow pipe above the bottom of the tank.

EXAMPLE:

The householders above are considering using a cylindrical tank to store their rainwater. They want to determine the capacity of a tank with a diameter of 3 feet and a height of 8 feet. The radius of the tank is one half the diameter, so it is 1.5 feet. Since they realize the effective tank storage height is going to be reduced by 4 inches because of the raised outlet 4 inches from the bottom of the tank, and by another 5 inches because of the bottom of the tank overflow pipe being 5 inches below the top of the tank, the effective height is going to be 7.25 feet. Using Equation 9A, they calculate the usable capacity of the tank as follows:

$\pi \times (1.5\ \text{ft})^2 \times 7.25\ \text{ft} \times 7.48\ \text{gal/ft}^3 = \text{capacity (gal)}$
$3.14 \times 2.25\ \text{ft}^2 \times 7.25\ \text{ft} \times 7.48\ \text{gal/ft}^3 = 383\ \text{gal}$

383 gal = capacity

Equation 9B.
Storage Capacity of a Cylinder (Can Apply to Both a Cylindrical Cistern or a Length of First Flush Pipe) (metric units)

$\pi \times (\text{r (cm)})^2 \times$ effective cylinder height (cm) $\div$ 1,000 cm^3/liter = capacity (liters)

See notes for Equation 9A.

Equation 10A.
Storage Capacity of a Square or Rectangular Tank (English units)

length (ft) $\times$ width (ft) $\times$ effective height (ft) $\times$ 7.48 gal/ft^3 = capacity (gal)

EXAMPLE:

A household decides to install a rectangular tank that has interior dimensions: 8 feet tall, 6 feet long, and 4 feet wide. The tank outlet tap is located 4 inches above the bottom of the tank. The underside of the overflow pipe is located 5 inches below the top of the tank. They calculate the effective height of water as 7.25 ft, so the calculation is as follows:

6 ft $\times$ 4 ft $\times$ 7.25 ft $\times$ 7.48 gal/ ft^3 = 1,301 gal

1,301 gal = capacity

Equation 10B.
Storage Capacity of a Square or Rectangular Tank (metric units)

length (cm) $\times$ width (cm) $\times$ effective height (cm) $\div$ 1,000 cm^3/liter = capacity (liters)

See notes with Equation 10A.

Equation 11A.
Cistern's One-Time Dollar Price for Storage Capacity (English units)

price of cistern (dollars) $\div$ storage capacity (gal) = price of storage capacity (dollars/gal)

EXAMPLE:

The tank in Equation 9A holds 1,301 gallons of water, and would cost around \$850 to purchase and install:

\$850 $\div$ 1,301 gal = \$0.65/gal

\$0.65/gal = price of storage capacity

Equation 11B.
Cistern's One-Time Price for Storage Capacity (metric units)

price of cistern ÷ storage capacity (liters) = price of storage capacity (price/liter)

See notes with Equation 11A. For non-USA currencies, substitute the appropriate currency.

Equation 12A.
Weight of Stored Water (English units)

stored water (gal) × 8.34 lb/gal = weight of stored water (lb)

EXAMPLE:

A 55-gallon drum under a rainspout has filled to the very top with water and you need to figure out how much it weighs to decide whether you can move it.

55 gal × 8.34 lb/gal = 458.7 lb

458.7 lb = weight of stored water

Water is extremely heavy. Do not underestimate the force you are dealing with when you store it. Platforms supporting storage tanks must be able to hold the water's weight!

Equation 12B.
Weight of Stored Water (metric units)

1 liter of water weighs 1 kilogram

So:
stored water (liters) × 1 kg/liter = weight of stored water (kg)

CONCRETE PAVING Technology

AMERICAN CONCRETE PAVEMENT ASSOCIATION

Stormwater Management with Pervious Concrete Pavement

Pervious Concrete Pavement

Description

Pervious concrete pavement is a porous pavement, often with an underlying stone reservoir, that captures rainfall and stores runoff before it infiltrates into the subsoil. This pervious surface replaces traditional pavement, and allows stormwater to infiltrate directly into the ground, permitting a naturally occurring form of water treatment. Pervious concrete mixtures consist of specially formulated hydraulic cementitious materials, water, and uniform open-graded coarse aggregate (e.g., ASTM C33 Size Numbers 5, 56, 67, 8, and 89). When properly designed and installed, pervious concrete has a high percentage of void space (15% or more) to accommodate stormwater from significant storm events (see Figure 1).

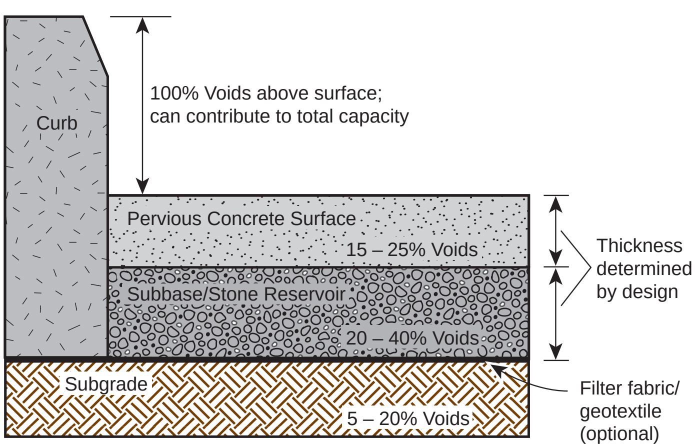

Figure 1. Typical cross-section of pervious concrete pavement. On level subgrades, stormwater storage is provided in the pervious concrete surface layer (15% to 25% voids), the subbase (20% to 40% voids), and above the surface to the height of the curb (100% voids). After: ACI 552R-06.

Application

Pervious concrete pavement is ideal around buildings (e.g., walkways, courtyards, etc.), as parking lots and as low-volume roadways. Pervious concrete pavement also has some application on highways, where it can be used in shoulder and median construction for stormwater runoff mitigation. It also may be used as a surface material to reduce hydroplaning, splash and spray, and mitigate tire-pavement noise.

Regional Applicability

Pervious concrete pavement can be applied in most regions of the country, but the practice has unique challenges in cold climates. Design of the system should ensure that washout from adjacent (soil) areas is not allowed to drain onto pervious concrete pavement surfaces. Care should be taken with regard to sand being applied to the pavement surface for deicing because the sand may become lodged in the pavement surface. This is not to imply that it is impossible to use pervious concrete pavement in cold climates. In fact, anecdotal evidence suggests that snow-covered pervious concrete pavement actually may clear more quickly than impervious surfaces, reducing the need for snow plowing. Additionally, melted snow and ice will drain through the pervious concrete pavement rather than ponding and refreezing at the surface, a common occurrence with traditional impervious pavements; this action alone may minimize the need to apply deicing materials to a pervious concrete pavement.

Another concern in cold climates is that infiltrating runoff below the pavement may cause frost heave, although design modifications that provide for an

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adequate subbase layer can reduce this risk. Pervious concrete pavement structures that incorporated frost-heave-reducing design features have been used successfully in Norway (Stenmark, 1995). Successful longer term installations of pervious concrete pavements in regions of cold weather also have been documented in North America (Delatte, et al, 2007; NRMCA, 2004; and Schaefer, et al, 2006).

ULTRA-URBAN AREAS

Ultra-urban areas are densely developed urban areas in which pervious and naturally draining surface area is reduced. Pervious concrete pavements are ideal design options in such areas because they allow for additional use of land by eliminating the need for stormwater retention systems.

STORMWATER HOT SPOTS

Stormwater hot spots are areas where land use or activities generate highly contaminated runoff, with concentrations of pollutants in excess of those typically found in stormwater. These areas may include commercial nurseries, auto recycle facilities, fueling stations, storage areas, industrial rooftops, marinas, outdoor container storage of liquids, outdoor loading/unloading facilities, public works storage areas, hazardous materials generators (if containers are exposed to rainfall), vehicle service and maintenance areas, and vehicle and equipment washing/steam cleaning facilities. Pervious concrete pavement should not be used as an infiltration practice on stormwater hot spots due to the potential for ground water contamination.

STORMWATER RETROFIT

A stormwater retrofit is a stormwater management practice (usually structural) put into place after development has occurred to improve water quality, protect downstream channels, reduce flooding, or meet other specific objectives. The best application of pervious concrete pavement for retrofits may be on individual projects where a parking lot or low-volume road is being reconstructed.

COLD WATER (TROUT) STREAMS

Pervious concrete pavement can help to reduce the increased runoff water temperature commonly associated with impervious cover (Dane County, 2007 and Hunt and Collins, 2008). Stormwater ponding on or around the surface of conventional pavement is subsequently heated by the sun and hot pavement surface. By allowing rainfall to rapidly infiltrate, pervious concrete pavement eliminates this problem, helping to mitigate the potential for "thermal shock" events caused by heated stormwater flowing into nearby streams and estuaries.

Siting and Design Considerations

Siting Considerations

Pervious concrete pavement has the same siting considerations as other infiltration practices. The site needs to meet the following criteria:

- When pervious concrete pavement systems are designed with a stone reservoir, the reservoir should be of sufficient depth to accommodate stormwater storage for the design storm event.
- Design options include installation of wells or drainage channels through the subgrade and/or underground storage chambers for below surface storage of stormwater.
- If used to treat off-site runoff, pervious concrete pavement should incorporate pretreatment, as with all structural management practices.
- Pervious concrete pavement should be sited at least 3 ft (1 m) above the seasonally high ground water table, and at least 100 ft (30 m) away from drinking water wells.

Design Considerations

Some basic features should be incorporated into all pervious concrete pavement designs. These design features can be divided into five categories: pretreatment, treatment, conveyance, maintenance reduction, and landscaping.

1. ***Pretreatment.*** The pervious concrete pavement acts as pretreatment to the stone reservoir below. Because the surface serves this purpose, periodic maintenance of the surface is an important factor in optimal performance.
2. ***Treatment.*** The stone reservoir directly below the pavement surface should be sized to attenuate

water flows from the design storm event. Typically, pervious concrete pavement is sized to treat a small event such as a water quality storm (i.e., the storm that will be treated for pollutant removal), which can range from 0.5 to 1.5 in. (13 to 25 mm). As with infiltration trenches, water can be stored in the void spaces of the stone reservoir.

3. ***Conveyance.*** Water is conveyed to the stone reservoir through the pavement surface where it then infiltrates into the ground. A geosynthetic liner should be placed below the stone reservoir to prevent preferential flow paths and to maintain a flat bottom. Designs also may incorporate some method to convey larger volumes of stormwater runoff to the storm drain system, such as the inclusion of drain pipes below the pavement, diverting stormwater flow to supplementary catchment areas for potential reuse, or other innovative devices.

4. ***Maintenance Reduction.*** One nonstructural component that can help ensure proper maintenance of pervious concrete pavement is the use of a carefully worded maintenance agreement that provides specific guidance, including how to conduct routine maintenance. Ideally, signs should be posted on the site identifying pervious concrete pavement areas. Vacuum (preferred) or pressure wash the surface annually, or more frequently if dictated by site specific conditions.

5. ***Landscaping.*** Reducing sediment loads entering the pavement can help prevent clogging. Thus, the most important landscaping feature is fully stabilized upland drainage.

Design Variations

SLOPING SURFACES

When the surface is not level, the depth of the pavement and subbase must be designed to meet the desired runoff goals, or more complex options for handling water flow may be used. Pervious concrete pavements have been placed successfully on slopes up to 16%. In such cases, trenches were dug across the slope, lined with 0.25 in. (6 mm) visqueen, and filled with rock (see Figure 2). Pipes extending from the

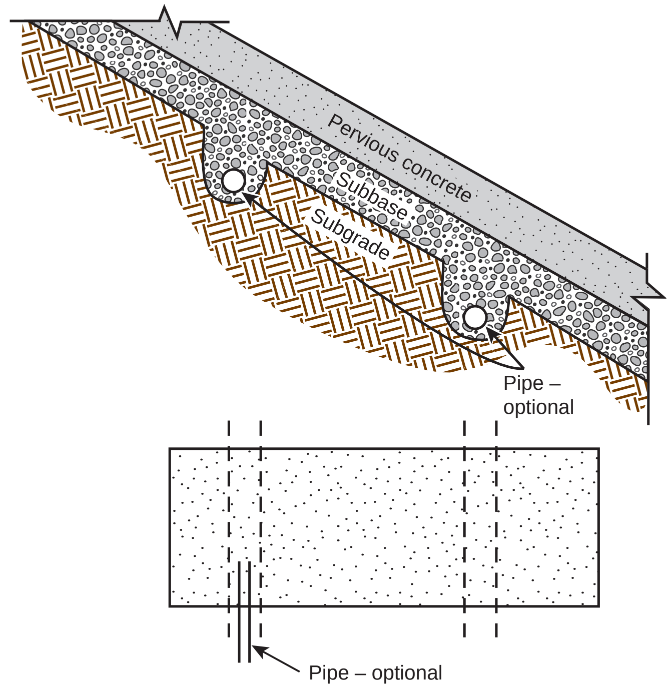

Figure 2. Elevation (top) and plan (bottom) views of a sloped installation. For sloped pervious concrete pavements, storage capacity calculations must consider the depth of pavement, infiltration rate of subbase, and desired runoff goals. Source: Tennis, et al, 2004.

trenches carry water traveling down the paved slope out to the adjacent hillside. Use of soil filter fabric also is recommended to prevent wash out of the subgrade (Tennis, et al, 2004).

REGIONAL ADAPTATIONS

In cold climates, the base of the stone reservoir should be below the frost line. This modification will help to reduce the risk of frost heave.

POORLY DRAINING SOILS

While more suitable for well-draining soils (minimum percolation rate of 0.5 in. [13 mm] per hour), pervious concrete pavement can be utilized in poorly draining soils, provided special design considerations such as those shown in Figure 3 are followed (Tennis, et al, 2004).

Limitations

Installation/construction procedures for pervious concrete pavement differ from those used for conventional concrete pavement. Care should be taken to pre-qualify suppliers and installers for pervious concrete pavement systems. Guidance on applications, specifications and installation techniques are continually evolving and being published (ACI 522.1-08, 2008; ACI 522-R06, 2006; NRMCA, 2006).

Maintenance Considerations

For a pervious concrete pavement to perform as designed, the required maintenance schedule must be followed. In addition to owners not being aware of the presence of pervious concrete pavement on a site, negligence of required maintenance activities and schedules is the chief reason for premature pervious concrete pavement failures. Typical maintenance requirements are shown in Table 1 on Page 5.

Effectiveness

Pervious concrete pavement can be used to substantially reduce the volume of runoff, to provide ground water recharge and to reduce pollutants in storm water runoff. Research suggests that pervious concrete pavement systems help up to 80% of the annual rainfall go towards ground water recharge (Clar, et al, 2004).

Studies conducted on long-term pollutant removal have shown that pervious concrete pavement is very effective in removal of pollutant load (Dierkes, et al, 1999), in some cases demonstrating greater than 80% efficacy in pollutant removal (Rushton, 2001).

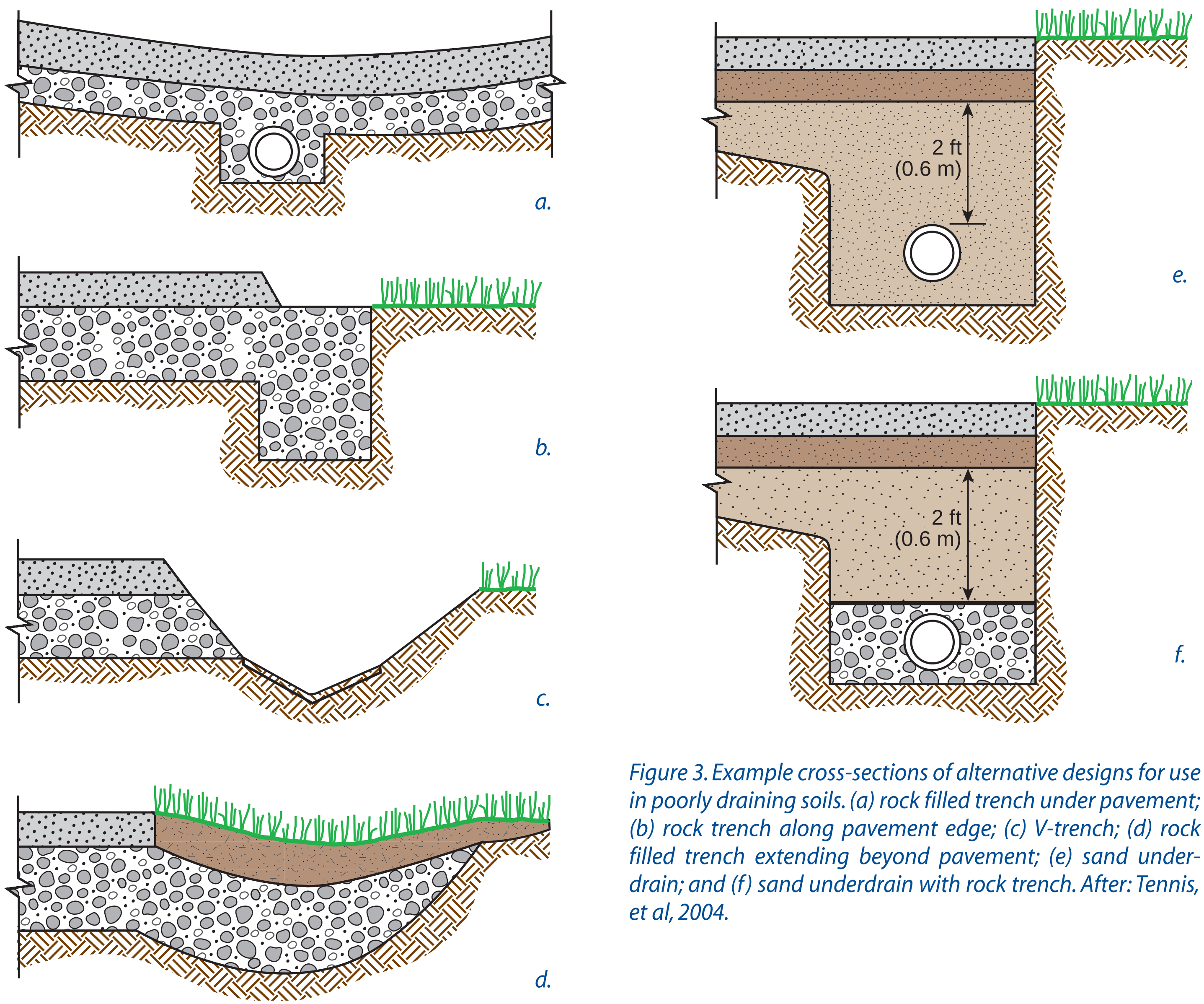

Figure 3. Example cross-sections of alternative designs for use in poorly draining soils. (a) rock filled trench under pavement; (b) rock trench along pavement edge; (c) V-trench; (d) rock filled trench extending beyond pavement; (e) sand underdrain; and (f) sand underdrain with rock trench. After: Tennis, et al, 2004.

Table 1. Typical Maintenance Requirements for Pervious Concrete Pavement (Source: WMI, 1997)

Activity	Schedule
• Avoid sealing or repaving with impervious materials.	N/A
• Ensure that the pavement area is clean of debris. • Ensure that the pavement dewaters between storms. • Ensure that the pavement area is clean of sediments.	As needed
• Mow upland and adjacent areas, and seed bare areas. • Vacuum/sweep the pavement surface to keep it free of sediment.	As needed
• Inspect the surface for deterioration or spalling.	Annually

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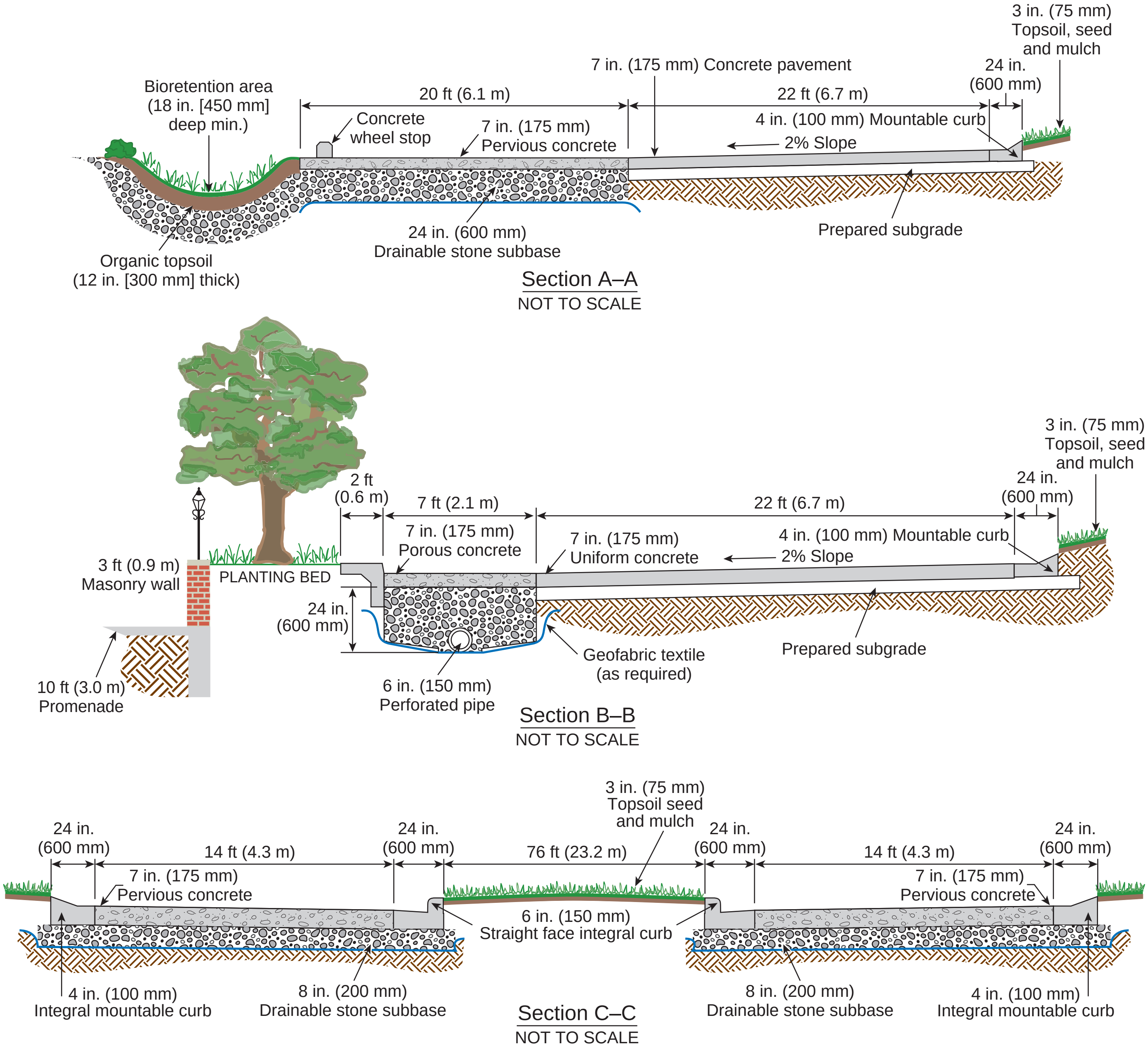

Figure 4. Illustrations from the Lost Peninsula Marina project in Erie Township, Michigan.

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