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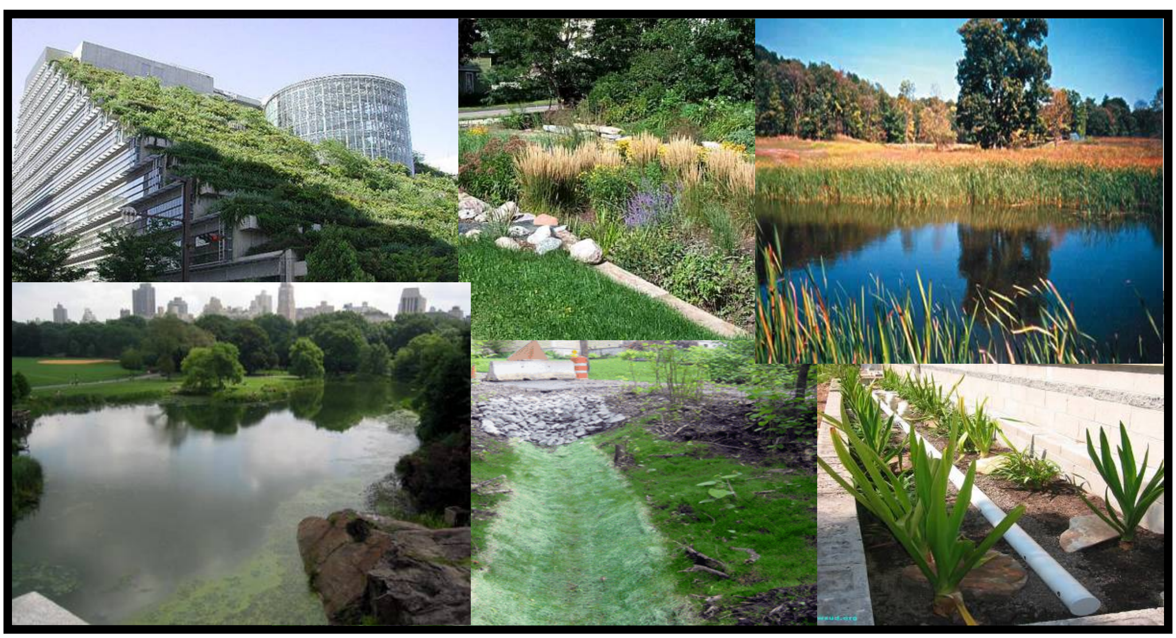
# Innovative Approaches for Urban Watershed Wet-Weather Flow Management and Control: State-of-the-Technology

# INTERIM REPORT



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# Innovative Approaches for Urban Watershed Wet-Weather Flow Management and Control: State-of-the-Technology

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By

Scott D. Struck, Ph.D., PWS
Tetra Tech, Inc.
350 Indiana St., Suite 500
Golden, CO 80401

A. Charles Rowney, Ph.D., P. Eng., D.WRE
ACR, LLC
184 Tollgate Branch
Longwood, FL 32750

and

Linda D. Pechacek, PE
LDP Consultants, Inc.
2115 Chantilly Lane
Houston, TX 77018

FOR

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

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# Abstract

This report documents initial efforts to identify innovative strategies for managing the effects of wet-weather flow in an urban setting. It served as a communication tool and a starting point for discussion with experts. As such, the document is a compilation of literature reviews from prior work and of content based on interviews with experts, but stops short of a definitive final analysis. Investigations of wet-weather flow treatment approaches through source control (and treatment at the source) make up its setting. Innovative systems that treat stormwater as a beneficial resource through reclamation and reuse are also explored. The effort focused on practices and technologies that can be implemented at the urban watershed management and infrastructure interface to combine cost-effective, integrated solutions. The result is a document containing urban watershed wet-weather flow management and control approaches from a national and international perspective.

Specific tasks included a global information search to identify wet-weather flow management approaches that represent the current state-of-the-technology. The topics were subjected to review by international experts who provided comment and feedback. This document is targeted for the user community of regulators, academics, consultants, and municipalities investigating options to control the high costs of water, wastewater, and stormwater management and treatment. Case examples are included along with conclusions and recommendations to guide future research, development, and demonstration initiatives.

# Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and natural systems. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a scientific knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce future environmental risks.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally C. Gutierrez, Director
National Risk Management Research Laboratory

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## Acronyms and Abbreviations

| | |
|---|---|
| ANN | Artificial Neural Network |
| ASCE | American Society of Civil Engineers |
| ASTM | American Standard Testing Methods |
| BMP | Best Management Practice |
| BSD | Better Site Design |
| BOD | Biochemical Oxygen Demand |
| COD | Chemical Oxygen Demand |
| CSO | Combined Sewer Overflow |
| CSS | Combined Sewer System |
| CWA | Clean Water Act |
| DWF | Dry-Weather Flow |
| EMC | Event Mean Concentration |
| EPA | U.S. Environmental Protection Agency |
| EU | European Union |
| I/I | Infiltration and Inflow |
| LEED | Leadership in Energy and Environmental Design |
| LID | Low Impact Development |
| NPDES | National Pollutant Discharge Elimination System |
| NTU | Nephelometric Turbidity Units |
| ORD | Office of Research and Development |
| PICP | Permeable Interlocking Concrete Pavement |
| POTW | Publicly Owned Treatment Works |
| RTC | Real-Time Control |
| SCADA | Supervisory Control and Data Acquisition |
| SM | Standard Methods |
| SS | Suspended Solids |
| SSC | Suspended Sediment Concentration |
| SSO | Sanitary Sewer Overflow |
| SSP | Stormwater Site Plan |
| SUDS | Sustainable Urban Drainage Systems |
| TMDL | Total Maximum Daily Load |
| TN | Total Nitrogen |
| TOC | Total Organic Carbon |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| TWM | Total Water Management |
| UK | United Kingdom |
| US | United States of America |
| UV | Ultra Violet |
| WWF | Wet-Weather Flow |
| WSUD | Water Sensitive Urban Design |

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An undertaking of this type requires the dedication and cooperation of a team. The technical direction and coordination for this project was provided by the technical project team of the Urban Watershed Management Branch, under the direction of Mr. Richard Field, PE, Task Order Manager. Special recognition is extended to Mr. Anthony Tafuri, PE, Branch Chief who provided critical editorial review and technical and managerial guidance at key points. Also acknowledged is the support during these investigations provided by Linda Pechacek, PE, who provided literature search, written content and critical review to the project, and by Christopher Rowney, who was a substantial help in tracking down references and remedying bugs in the text. Finally, the manifold contributions of the many authors and professionals who were contacted or cited in this work are acknowledged, as it is their efforts that underlay the discussion and advances contained in this report.

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# Chapter 1. Global Perspectives on Wet-Weather Technology

The intent of this project was to explore emerging topics in wet-weather control, those that have passed the point of being pure research, but have not yet reached the point of common practice. A starting point for this effort was in the form of an earlier report produced by Rowney *et al.* (2009) which addressed advanced technologies in water resources and which provided a foundation. Some of the content in this work borrows from that foundation where it is relevant, but the primary interest was to extend the thinking in that earlier work into new areas.

As the present work progressed, the authors found that the emerging topics do not provide an easy area to evaluate, because the zone of interest that lies between these two conditions is somewhat subjective in extent and is by definition a moving target. If a technology passes muster at a research level, and begins a shift towards common practice, it will if successful, eventually reach the point of prevailing practice and therefore move out of our zone of interest. Further, no objective benchmark as to what constitutes prevailing practice was found. Ultimately, it was concluded that discussions with prominent leaders in the industry coupled with an examination of the content emerging in global conference publications was a reasonable way to discover what might be termed leading edge notions in technology. Supported by reviews of the literature, including research journals, trade publications and internet searches, this examination gave rise to a number of instances where there are technologies or technical perspectives that seemed to be promising but that are new to prevailing industrial practice. Much of this search also focused on studies that contained cost information to provide comparisons of promising technologies. Time will tell whether or not these ideas become mainstream or simply fade, but in the mean time there are a number of intriguing notions as to alternative ways to approach wet-weather technology that have been selected for consideration.

New technology emerges in various ways, but as the authors went through this process a number of drivers or pressures that seem to have prompted new thinking surfaced. Climate change, population shifts and economic pressures all have the potential to affect control requirements, design considerations, and or solution opportunities. Increases in precipitation could lead to overflows where none existed. Increases in population could do the same. Economic pressures, however, could reduce the ability to implement potential solutions or could make less costly solutions (and perhaps less effective) preferable. The technologies to detect flows or predict them, and the ability to manage data and communicate information, are also changing. Taken together, this means that the water resources world is in a state of flux, and the strategies for mitigating the impacts of wet-weather runoff in an urban environment are numerous. They are so diverse, in fact, that common practices on a global scale are as yet not a reality even though professional society interactions make it clear that common interests abound[1]. Even a common vocabulary has yet to emerge. A recent attempt by a well-founded research program in France,

[1] The recent 11 International Conference on Urban Drainage, held in Edinburgh in September of 2008, underscored this point. Participants from all over the world were present, and the authors observed first hand the spirit of mutual interest and divergent methodologies that are discussed in this report.

intended to develop a simple multilingual (French, German, English, Spanish) thesaurus illustrated this, because it was found that about one third of the technical terms identified were in common use in one language had no definable translation into another[2]. The theoretical underpinnings may be common, as they are defined at their root by the physics of precipitation, hydraulics, chemistry and so on, but the realization of theory in practice is very divergent and seems to be a function of the chance effects of historical local needs and practices.

This divergence complicates a task already made challenging by the diversity in technical solutions that can be employed. Wet-weather control systems can range from a city-wide rainwater catchment and reuse system such as that employed in Knittlingen, Germany, (Smrcka, 2007) to a community-based organization implementing an incentive program to install ultra-low-flush toilets in East Los Angeles, United States (US) (Dickinson, 2003). Stormwater management is regionally specific and runs the gamut from city-wide technological updates to single-family residential renovations. Even the goals of these systems and programs can vary substantially from one point to another. One perspective is that water management is intended to make water resources more sustainable. Another goal is to simply remove flood water with some reasonable degree of certainty. Yet another goal is to provide potable water. The intent of water management is clearly regionally dependent.

Nevertheless, there are common underlying themes. Urban areas tend to increase imperviousness (at least, in unfrozen conditions) wherever the location, with numbers like 85% impervious coverage in commercial areas, 20% in residential areas (Novotny and Olem, 1994) typical, and imperviousness alters the natural flow regime of stormwater in predictable ways. Also predictable is the fact that during wet weather events, water becomes more polluted, increases in velocity, and cannot be slowly released into the ground before it reaches storm sewer systems and open waterways. These are issues that cross national and state boundaries and that do not change due to international political situations. Every country is faced with these issues. Whether they are priorities and how they express themselves depends on context, but the means of coping with them depends on physical principles. So translation of solutions from one point to another may be more a matter of inclination and prevailing practice than anything else. This means that solutions elsewhere may be new to the US and candidates for adoption here if they fit our regulatory, climatological and infrastructure needs. At the same time, it seems implicit in the above notions that developing countries focused on flood protection and water supply may have priorities that are not conducive to solutions of interest in the US, while those that are well developed may have a preoccupation with sustainability, habitat, aesthetics or other factors that are of material US potential. The detailed discussion in the following chapters probe this point further, but several examples of global priorities provide a useful backdrop.

The United Nations has a division for sustainable development whose mission statement promotes "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," (United Nations, 2008; The Economist, 2007).

Australia has in recent years had severe drought conditions with stormwater conservation developing out of necessity. This force has been strong enough that changes in behavior were prompted, including such simple social changes as altered practices in bathing, car washing, and other common activities. The result persists as a focus on conservation and resource management (Grubel, 2007).

In Europe, stormwater control initiatives are being championed as part of what is called Sustainable Urban Drainage Systems (SUDS), also known as Water Sensitive Urban Design (WSUD) (SUDSWP, 2007). Programs that use such technologies are only as strong as the partnerships forged to implement them. Scotland has recognized this as a necessity because there is no single organization with the control to implement successful SUDS (SUDSWP, 2007). A successful partnership between state and local

[2] Personal communication, Bernard Chocat, Groupe de Recherche Rhône Alpes sur les Infrastructures et l'Eau., November 6, 2008.

governments, non-governmental organizations, city planners, and developers is necessary to ensure that technologies are implemented effectively and consistently.

The United Kingdom (UK), especially, has seen climate change as its rallying cry for new technologies, including green infrastructure, to make its way into the mainstream of urban development (SUDSWP, 2007). The British government has made commitments to address the serious future water issues that will arise from the impacts of global climate change. These commitments include conservation of water to keep it sustainably within its replenishment cycle, addressing diffuse water pollution problems, and managing existing and future of flood risks (SUDSWP, 2007). Again, the onus is on policymakers and local organizers to develop partnerships to implement these programs.

More broadly, in the European Union (EU), these kinds of national efforts are backed by a broader program. The Water Framework Directive (2000) is a program beginning in 2002, and drives an integrated and far reaching approach to water management that is different from anything prevailing in US practice. This program alone is likely to drive research and evolution of practice in ways central to this research.

The directive has been taking steps legislatively in the UK since 2003 on measures to ensure the health of local ecologies, drinking water, and particular habitats (SUDSWP, 2007). URBACT is a European program whose goal is to "develop exchanges between towns, disseminate expert knowledge across Europe and design the urban policies of the future" (URBACT, 2008). Scotland, Wales, and Northern Ireland have championed the Sustainable Development Commission, which acts as their Government's watchdog on sustainable development (SDC, 2008).

The conclusion is that there are differences in practice internationally, but that water across the world is a major preoccupation not just in developing countries but in well-established nations as well. The changes in practice across the globe are extensive and continuing, and the need to track these changes and seek out lessons learned or practical solutions that may be of use in the US is clear not only now but as a part of any future program.

The following sections explore innovative approaches and design and operation of sewerage system that consider potential cost saving opportunities that have yet to be tried or proven or those that hold promise. Also included are opportunities for watershed management strategies that improve wet-weather flow (WWF) management in a cost-effective manner. Exploration of technologies will apply to new development, redevelopment and retrofit situations in US and International locations including reviews of case studies.

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# Chapter 2. Integrated Water Management

In recent years, it has become increasingly evident that the water problems of a country can no longer be resolved by the water professionals and/or the water agencies alone. The water problems are becoming increasingly more interconnected with other development-related issues and also with social, economic, environmental, legal, and political factors at local and national levels and sometimes at regional and even international levels. Already, many of the water problems have become far too complex, interconnected and large to be handled by any one single institution, irrespective of the authority and resources given to it, technical expertise and management capacity available, level of political support, and all the good intentions.

The current and the foreseeable trends indicate that water problems of the future will continue to become increasingly more complex, and will become more intertwined with other development sectors like agriculture, energy, industry, transportation, and communication, and with social sectors like education, environment, health, and rural or regional development. The time is fast approaching when water can no longer be viewed in isolation by one institution or any one group of professionals without explicit and simultaneous consideration of other related sectors and issues and vice versa. In fact, it can be argued that the time has already come when water policies and major water-related issues should be assessed, analyzed, reviewed, and resolved within an overall societal and development context; otherwise the main objectives of water management, such as improved standards and quality of life of the people, poverty alleviation, regional and equitable income distribution, and environmental conservation cannot be achieved. One of the main questions facing the water profession is how this challenge can be successfully answered in a socially-acceptable and economically-efficient manner.

In the 1990s, many in the profession began to appreciate that water problems have become multi-dimensional, multi-sectorial, and multi-regional and filled with multi-interests, multi-agendas, and multi-caused. Also, the 1990s brought in the introduction of ‘watershed-based’ approaches and ‘low impact development (LID)’. Both of these issues require proper multi-institutional and multi-stakeholder coordination. The issue at present then, is how can this be achieved in the real world in a timely and a cost-effective manner? Often these approaches are defined through Integrated Water Resource Management or Total Water Management (TWM).

The definition that is most often quoted at present for TWM is “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.”

The definition of TWM is an important consideration. When the definitional problem can be successfully resolved in an operational manner, it may be possible to translate it into measurable criteria, which can then be used to assess the degree to which the concept of integration has been applied in a specific case, and also the overall relevance and usefulness of the concept.

In addition, a fundamental question for which there is no clear-cut answer at the present state of knowledge is what are the parameters that need to be monitored to indicate that a water resources system is functioning in a TWM manner? In the absence of both an operational definition and measurable criteria, it is difficult to identify what constitutes an integrated water resources management at present, or how should water be managed so that the system remains inherently integrated on a long-term basis.

Depending upon the viewpoint, TWM can mean the integration of:

- Objectives that are not mutually exclusive (economic efficiency, regional income redistribution, environmental quality, and social welfare);
- Water supply and water demand;
- Surface water and groundwater;
- Water quantity and water quality;
- Water and land related issues;
- Different types of water uses: domestic, industrial, agricultural, navigational, recreational, environmental, and hydropower generation;
- Rivers, aquifers, estuaries, and coastal waters;
- Water, environment, and ecosystems;
- Water supply and wastewater collection, treatment, and disposal;
- Macro, meso and micro water projects and programs;
- Urban and rural water issues;
- Water-related institutions at national, regional, municipal, and local levels;
- Public and private sectors;
- Government and non-government organizations;
- Timing of water release from the reservoirs to meet domestic, industrial, agricultural, navigational, environmental, and hydropower generation needs;
- All legal and regulatory frameworks relating to water, not only directly from the water sector, but also from other sectors that have implications on the water sector;
- All economic instruments that can be used for water management;
- Upstream and downstream issues and interests;
- Interests of all different stakeholders;
- National, regional, and international issues;
- Water projects, programs, and policies;
- Policies of all different sectors that have implications for water, both in terms of quantity and quality, and also direct and indirect (sectors include agriculture, industry, energy, transportation, health, environment, education, gender, etc.);
- Intra-state, interstate, and international rivers;
- Bottom-up and top-down approaches;
- Centralization and decentralization;
- National, state, and municipal water policies;
- National and international water policies;
- Timings of water release for municipal, hydropower, agricultural, navigational, recreational, and environmental water uses;
- Climatic, physical, biological, human, and environmental impacts;
- All social groups, rich and poor;
- Beneficiaries of the projects and those who pay the costs;
- Present and future generations;
- All gender-related issues;
- Present and future technologies; and
- Water development and regional development.

The above list, which is by no means comprehensive, identifies many sets or combinations that should be integrated under the aegis of TWM. Even at a conceptual level, all of these issues simply cannot be achieved. Therefore fundamental to future research would be a prioritization where the greatest potential for integration on a social, environmental, and economic level can be achieved.

## Water and Energy

Consider the issue of water and energy interrelationships. The water profession in the past has ignored energy for the most part, even though in many ways water and energy are closely interlinked. For example, water not only produces energy (hydropower), but also the water sector is a prodigious user of energy. Accordingly, in a country like India, hydropower accounts for slightly over 20 % of electricity generated, but the water sector in turn "consumes" a similar amount of India's electricity. Furthermore, no large-scale electricity production, be it thermal, nuclear, or hydro, is possible without water. In countries like France, the biggest user of water is not agriculture, but the energy industry. Thus, it simply is not possible to consider water resources management in an integrative manner without reference to energy, or integrated energy resources management without considering water.

## Challenges of Total Water Management

In the real world, integrated water resources management, even in a limited sense, becomes difficult to achieve because of extensive turf wars, bureaucratic infighting, and legal regimes (like national laws and constitutions) even within the management process of a single resource like water, let alone in any combined institution covering two or more ministries which have been historic rivals. In addition, the merger of such institutions produce an enormous organization that is neither easy to manage nor control. It should also be noted that water has linkages to all development sectors and social issues like poverty alleviation and regional income redistribution. It is simply unthinkable and totally impractical to bring them under one roof in the guise of integration, irrespective of how it is defined. Such integrations are most likely to compound the complexities of the problems, instead of solving them.

## Technological Innovation

Technology and adaptation of technologies are key components of many efforts within water sectors. At the conceptual level technologies such as models and forecasting systems are being improved, particularly as a result of advances in computer technology, to allow better predictions of temporal and spatial variations in the quantity and quality of available water resources. This may help to reduce uncertainties and risks in the use and management of the resources. Water saving technologies in irrigation (e.g., drip irrigation), improved and cost-effective methods for the treatment and reuse of wastewater in industries and domestic systems, aquifer recharge technologies, human waste disposal systems that require no or extremely small quantities of water, and cheap but effective water purification systems for villages are other examples of promising innovations which can promote the sustainability of future water resources.

## One Approach - Water Balance

The water balance approach promotes and facilitates sustainable approaches to water use, land use and water resource management at all levels – from the region to the household; and in all sectors – from domestic, resource, industrial and commercial, to recreational and ecosystem support uses. The water accounting methodology is based on an accounting or pre-development versus post-development water distribution weighed with other water resource needs. Water balances consider inflows and outflows from basins, sub-basins, and service and use levels

Conceptually, the water balance approach is straightforward but may require a change in perception from stormwater management (waste product) to rainwater management (source of water resource) (Figure 1). Often though, some of the components of the water balance concept can be difficult to estimate or are not available. For example, groundwater inflows and outflows to and from an area of interest may be difficult to measure.

## Stormwater Management to Rainwater Management

| From Traditional | to | Integrated TWM |
|---|---|---|
| Drainage Systems | ⇨ | Ecosystems` |
| Reactive (Solve Problems) | ⇨ | Proactive (Prevent Problems) |
| Engineer-Driven | ⇨ | Interdisciplinary Team-Driven |
| Protect Property | ⇨ | Protect Property and Habitat |
| Pipe and Convey | ⇨ | Mimic Natural Processes |
| Limited Consultation | ⇨ | Extensive Consultation |
| Local Government Ownership | ⇨ | Partnership with Others |
| Extreme Storm Focus | ⇨ | Rainwater Integrated with Land Use |
| Peak Flow Thinking | ⇨ | Volume-Based Thinking |

**Figure 1. A schematic of transitioning from stormwater only management to total integrated water management.**

# Chapter 3. Framing the Challenges Ahead

The foregoing chapters present potential opportunities for future research to innovatively manage urban WWF flows. To advance the body of knowledge and to communicate a consensus to the expert community to be polled in this project, it was necessary to go beyond a simple recitation of the literature, much of which is known to those experts, and establish a series of perspectives and questions that would guide a further and more forward-thinking discussion. This section provides a summary of the notions developed during this part of the process. The content of this section closely follows the form and sequence of a white paper that was developed for delivery at a forum of experts scheduled as a part of this project. These notions are then followed by the key findings from a technological perspective and a summary of workshop outcomes from participating experts.

## Notion 1: Prediction of the Future Needs More than Records of the Past

An underlying need in water resource management is to predict the future and assess the consequences of change (for example to some developed condition). The literature reviewed made it clear that most analyses consider hydrologic systems to be statistically stationary. Changes to a watershed or drainage system are almost universally depicted in terms of changes in conveyance capacity, infiltration capacity and so on. The precipitation in the future, however, is assumed to be the same as has been experienced for decades, as are temperature, evaporation and so on. The literature describes in detail the various approaches for the interpretation of rainfall, flow and other records as a basis for projections of the future. We estimate such things as flood frequencies, geomorphic drivers and habitat characteristics on this basis. Yet it is now generally accepted that for some things, notably including water resources engineering, the past is becoming a poor predictor of the future. Changes in our climate are upon us, and a scan of the projections over the last decade makes it tempting to suggest that the predictions of our future are changing faster than the reality.

The question that is therefore reasonable to explore is to probe whether or not current predictive methods are useful. If changes are going to affect the way precipitation is received, but precipitation is uncertain, what is the value of the simulation? On the other hand, if forecasting is to be eliminated, where does that leave us? What should we do instead? And if we do, how do we defend ourselves in a legal system wedded to the idea of precedents? Even if we get all that right, what do we do to predict the human response to the massive impacts we will experience, the movement of populations to high ground or cooler climates or some other preferred region?

## Notion 2: Water Quality is Not an Adequate Basis for Evaluating Impacts and Solutions

The preponderance of the literature shows that climate change, for whatever reason, is upon us. Less obvious in discussions, but just as clear, is the implication that major changes in our ecosystems coming (a prospect that a moment's reflection on recent reports on the polar ice cap underscores). A large part of our effort is targeted at preserving native species and the conditions that gave rise to them. It is generally assumed that such an ecosystem will be protected if water quality and quantity are preserved. If massive changes in climate or other factors are on their way, the question of water quality and quantity could become moot. So a position could be taken that water quality standards cannot truly be targeted at anything we are certain will come to pass. They then become abstract ideals, no longer reflective of value propositions based on habitat. That being the case, should we ensure that we invest our limited resources in pursuit of something more determinate, such as flood protection perhaps coupled with epidemiology, and limit our pursuit of wider objectives to truly gross pollutant capture?

## Notion 3: Regional Planning is Not Always the Best Basis for Decisions.

For years it has been accepted that the more globally we plan and build drainage solutions, the better chance we will have to develop a generally optimum solution. The idea has been that by looking at interactions at a large scale, decisions can be better made at a small scale. Opportunities of scale are the essence of this idea. It seems reasonable, for example, to set recharge and runoff requirements for a small parcel based not on its local impact, but on the net effect of many such choices. It is also reasonable to question if this is always true, however. In some cases, it probably is. If one is considering major infrastructure elements that are only replaced or altered with difficulty, such as highways, regional planning may be essential. But in smaller scale problems it may not be. If the future is driven by indeterminate needs, where the population is mobile and solutions are evolving, then drainage requirements are inherently uncertain. In such a case, what is really accomplished with regional planning practices if we can not predict regional behavior? Add to that the recognition that meaningful regional planning implies solutions of regional extent, and we encounter the implication we will invest in advance of need, possibly far in advance. Do we then end up with structures and practices either undersized or never used? Should we push for local solutions locally planned and built, and recognize they not only can but must change in the future?

## Notion 4: Planning for the Long Term is Not Always the Best Choice.

The above notions also directly raise the question of just how far ahead we should attempt to plan. If a system will change over a scale of years, what is the benefit of planning building for conditions anticipated to be operative over a scale of decades? Given that we are in a time of significantly changing needs and horizons, how can we justify major planning studies, and how do we make a convincing case for long term investments? A balance seems to be the point, here. Planning ahead makes sense. Planning beyond what we can predict is questionable. There is a need to explore the actuarial realities of working with long-term designs that have high risk of obsolescence. It may be that we should be thinking in terms of short-term solutions on the expectation that that they will be superseded, and plan and build accordingly.

## Notion 5: The Control Technologies are Not All Proven.

As noted in the literature review (Appendix A), there is a range of physical devices currently popular, including such things as porous paving, green rooftops, hydraulic controls, and all manner of devices or methods intended to remove undesirable materials from effluents either at the point of discharge or somewhere in the catchment. Yet, at the same time, as we are building these things, we are still doing research on how they work and in some cases if they work. The question must be asked whether or not we truly know how these devices will work, and whether we are working largely based on assumptions. Results from the National BMP database (www.bmpdatabase.org) in particular make this a relevant question, because the evidence in that program is not persuasive that the BMPs we are installing are all effective. A look at long-term empirical evidence of BMP performance does not present a compelling case that we can predict how these various things will perform. An examination of the literature shows that we are still at odds when it comes to fundamentals as basic as indicator organisms, their meaning and the way they are affected by BMPs. Should we therefore reconsider our design approaches, and build solutions with the expectation of immediate failure a central design principle? Rather than trying for designs that are robust, should we just make them easy to remove and re-build when we finally figure out how well they work?

## Notion 6: The Ultimate Problem is Broader than Engineering.

Civil engineers are well equipped to plan, design and build a pipe network, or indeed any physical expression of a drainage infrastructure. It is uncertain that they possess all the skills necessary to deal with the wide range of biological, physical and institutional problems that are also part of the solution. Some industries with different skill sets are only marginally involved in planning and solution but might offer value if engaged in the solution process. As an example, control systems are increasingly evident in water resources practice, and these inherently involve information technology, something not always included on BMP planning teams. As another example, industrial engineers think in terms of facility life cycles as a start point, not a collateral factor, and this might be a useful mind set in the future planning problem. It may be that progress might be found outside the bounds of traditional engineering as applied to this problem.

## Notion 7: Owner/Operators May Not be Able to Handle the Solutions That are Needed.

It is reasonable to question if the future solutions, those that are adaptive, are truly value-centric and an expression of what is known about stormwater imply service demands beyond the ability of those responsible for managing them. The day-to-day labor force may not have what it takes to manage the results. Will new solutions be hampered by the inability of regulators, constructors and managers to respond to new realities? Can we change our practices meaningfully if our pace of progress is limited by the adaptability of our service population?

## Notion 8: Our Analytical Capability is Less Than What is Needed.

Delivering sustainable solutions truly requires the integration of widely varied technical considerations. To date, however, our sector has been marked by a mix of detailed assessments of compartments of the problem, and only cursory examinations of behavior in an integrated form. There are currently efforts under way to remedy this, notably in such things as the EU efforts embodied by the Water Framework Directive, but despite such examples, the problem still is approached piece meal. We offer for example the gulf between the groundwater and surface-water communities, physically two sides of the same coin but often isolated from each other on projects.

The above questions are quite specific, but consideration of them leads to several points that need to be answered. These points, were to be addressed in an expert workshop and presented in the following questions:

- What are the criteria by which new solutions should be judged?
- What solutions are emerging?
- Of the emerging solutions, which ones seem best positioned to fulfill the criteria?

The results of these discussions are presented in the next section.

# Workshop Results: Innovative Approaches for Urban Watershed Wet-Weather Flow Management and Control: State-of-the-Technology

## Overview

The overall project objective is to document a range of innovative and emerging technology and management strategies for dealing with urban watershed management control and failing infrastructure from within and outside of the US. The intent is to establish areas where external information can benefit EPA research. This includes gaining an understanding on developing priorities, research breakthroughs elsewhere, potential overlaps or duplications, and common needs. Specific technologies and topics that can be implemented or researched for implementation in the US are targeted.

The proposed approach for obtaining this information included: a worldwide search and review of the literature, the convening of an (or multiple) international forum to supplement the literature and provide additional case examples, and provide a report of forum results and findings that consider the state-of-the-technology literature and case studies.

Interest from the international community in the project was high. Sessions designed to elicit information from experts in the field were well attended. There was unforeseen synergy with other agencies, and matching funding was applied to this work by European sources (see below). The work is still under way, but findings of value have emerged and will be consolidated and documented over the next months. As well as research reports, journal papers in association with several European entities are planned.

## Key Findings to Date

Researchers and practitioners in the field contacted to date have shown a pervasive interest in revisiting some of the principles of planning and design now applied in water resources engineering. A finer granularity for decision making, adaptable solutions and technologies, new targets (shifting away from chemical parameters to ecosystem based evaluations) and methods that address the inherent uncertainty of predictions in an evolving multivariate context are all high priority items.

Specific technologies that have emerged as areas of interest include:

- **Intelligent materials** – pipes and tanks with built-in sensing and communications links that enable auto-detection of leaks or other conditions of interest so as to support proactive and timely management.
- **Virtual management systems** – software visualization and manipulation tools that enable managers and operators to make better founded decisions in real time, by facilitating the retrieval and manipulation of data in a more comprehensible way, including such things as 3D visualization and virtual manipulation of system components.
- **IT/IM data and decision systems** – technologies that enable secure and reliable storage, retrieval and manipulation of data, including and real-time prediction of intervention scenarios, so that response lags and data degradation are minimized and management functions improved.
- **Emerging detection and response systems** – technologies that enable real-time monitoring of water quality constituents and/or surrogate parameter measurement rapidly and accurately enough to enable real-time control based on ambient conditions.
- **Control algorithms suitable for uncertainty analysis in a water system** – mathematical methods and associated software that enable decision making in real-world systems where

conditions, targets and system responses are only approximately known, improving on existing predominantly used pseudo-deterministic methods that are only weakly able to deal with uncertain systems.

## Methods and Outcomes

The approach used in this work has been to i) build on earlier EPA ORD Advanced Topics research (which among other things evaluated emerging needs with a focus on CSOs), ii) complete a literature review to establish a body of knowledge that contains state-of-technologies that have associated data from outside and within the US, and iii) conduct workshops to enable focused review that is beyond day-to-day preoccupations. Two workshops have been held, with a total attendance of 89 international experts. One workshop was held in Edinburgh, Scotland and one in Lyon, France in September and November of 2008, respectively. Discussed below are pre-workshop ideas that were used to spark debate in these forums, and synopses of the outcomes of each. The sequence was such that the results of the Edinburgh workshop were made available to participants in the Lyon workshop.

The two-day Lyon Workshop was well attended by notable engineers and researchers, government directors, planners, architects, sociologists and water operators from France, the UK and other European representatives, as well as many experts from the US. To facilitate a focused discourse on emerging evolutions of urban water management at the Lyon workshop, a document detailing new concepts in sustainable urban water management was provided to the participants. Workshop objectives focused on identifying a clear vision of the stakes and difficulties in surmounting probable evolutions of urban water management. Reflections from workshop discussions focused on eight proposals to enhance successful implementation of water sustainability strategies. These proposals included:

- Restoring water visibility in the city
- Designing adaptable and time-sliding planning procedures
- Integrating solutions' diversity, redundancy and adaptability
- Analyzing, understanding and integrating individual and collective behaviors
- Defining new multi-objective and multi-criteria assessment tools
- Taking into account the global cost of economic assessment
- Taking advantage of the cultural and urban related opportunities

One prominent theme woven throughout the workshop was the acknowledgement that future planning is predicated on an analysis of the past. This planning process is typically rigid and straightforward, and does not allow for adaptable solutions, which are needed to meet present challenges, such as predicting climate change for long term implementation of stormwater and wastewater systems. Feedback mechanisms were proposed within the planning process that integrated uncertainty in planning procedures, allowing for structured review as knowledge and forecasting abilities evolved. Rather than precisely defining the works to be constructed, it was proposed that the planning process be more strategic in nature, whereby solutions are designed that enable the time required for implementation of solution(s) to be shortened. Solutions could include a shorter life span or diversified solutions that include redundancy and a higher exchange of information, thereby facilitating adaptability.

Another underlying concept related to 'adapting the organizations' whereby multidisciplinary project teams or simultaneous engineering groups are the norm, as opposed to the current partitioning of technical services. Such a notion integrates new indicators or systems of reference. Such evaluation criteria would be measurable in a continuous manner (cyclic or regular) to assess the relevance and efficacy of the strategy implemented. The real costs of solutions could be better assessed if such elements as investment, operation and amortization as a function of effective service life were integrated into a cost evaluation system. In addition, developing new uses of existing assets should be considered. Real time management tools offer new horizons in this topic. Time will be needed to shift from the current planning process system toward the development of dynamic management systems. Transition management strategies are needed so that the system functions appropriately in the intermediate period.

Results of the workshops were positive. Interaction and engagement by both assembled communities was forward thinking, intense and substantial. In both cases, interest in follow-up discussions was substantial. Two sponsors expressed interest in this kind of follow-up, including the Pennine Water Group in the UK, and GRAIE in France, with the France workshop to become a reality. It is a significant indicator of the value of this initiative that was perceived by other agencies to commit to matched funding. This was made possible for the Lyon effort by the French Water Agency, INSA of Lyon, the Rhone-Alps Region, and GRAIE. A multiplier effect on EPA ORD funds was therefore achieved.

The outcome of this effort is still being assembled, but some of the early findings are that there is a very substantial need for improvements in practice in a number of areas and for implementation or application of existing technologies on other areas. These include a listing of change agents likely to affect practice in water engineering:

- Regional impacts of climate change
- Changing demographics and their impact on service infrastructure needs
- New control technologies
- New control targets (those beyond quality and quality, such as ecosystem sustainability and other factors)
- Prevailing infrastructure development competencies (construction capability, maintenance limitations, service industry preparedness etc.)
- Granularity (the appropriate size of planning, design and operating units)
- Materials technology (intelligent materials, alternative materials etc.)
- Information technology (control systems, predictive systems, sensing technology etc.)

Specific findings from the groups involved included:

- Reconsider our basic approach to setting targets: We desire minimization of costs and ecosystem impacts, but focus on surrogate water quality indicators that may not safeguard these things.
- Climate change provides stormwater practice with a most important possibility for new targets and procedures: For example, heat island effects and green buildings/infrastructure ideas are increasingly important. We should consider a microclimate focus as we set objectives for control.
- Reintroduce planners and architects to natural ecosystems: We need a systematic way to move forward that incorporates these ideas in our thinking.
- Incorporate redundancy: We are currently forced to design without building in redundancy. Our approach to optimizing the design results in a bare minimum standard without redundancy provided in the system.
- Introduce urban sociology into the curriculum: The success and failure of solutions can depend on social reactions that engineers are not well equipped to motivate and manage, so specialist skills in this area may be valuable.

- Aesthetics: Should these be a part of the criteria, as the outcomes clearly have an aesthetic impact? Ugly parking lot 'holes in the ground' as opposed to water features with intrinsic aesthetic value were cited, as was the impact of perceived value on outcomes.
- Economic Equilibrium. As change is pursued, it should be guided by economic equilibrium, so that a balance is achieved.
- Tailored solutions: There is no one-size-fits-all solution in water management. Solutions need to be developed and designed against local requirements as opposed to some sweeping set of national criteria.
- Some specific technical development opportunities were also elicited.
- Pipe as indicator as well as network element: It may be possible to incorporate intelligent materials and sensing systems in pipe networks so that they have a dynamic ability to sense and control flows. Implementing this might be different in retrofit and new systems, but it would in principle be possible either way.
- Capitalize on available IT and model capabilities: Instead of building a pipe network system and letting it sit statically, with uniform operating capabilities, move to individual operations. This could happen all through the treatment train. Some of this is known to be possible, but not widely adopted; for example real-time control. It was voiced that the idea might have relevance in agricultural contexts as well as urban drainage systems. RTC scalability was discussed– Micro vs. small vs. integrated systems approaches are possible, but not often considered in the urban context. It might be possible to tailor the size to the application (intelligent house with IT linked solar elements as an example).
- Emerging contaminants (bioactive components): These may be detectable in stormwater, but are not always addressed. Germany and Switzerland were said to be leading on the issue and have developed most of the data to date. Research is being conducted in water and wastewater; there seems to be no data collection counterpart or detection process for stormwater.
- Multi-functional strategies are important: Consider more than a single control approach, but mesh treatment, re-use and optimization. There remain questions in performance and design, for example with biofilters and infiltration. Available computer simulation models to deal with these problems were questioned. The need to address solutions over wider scales was noted. The implication of wider temporal and spatial scales that would accompany this shift was acknowledged.
- Virtual asset management/materials repository: The technology exists to build virtual management systems that provide an expanded ability for managers to 'see' the system as a whole and make better informed decisions. This is completely possible with present technologies and applications, but not in the forefront of our thinking. We still tend to build systems and manage them at the inlet and outlet, with little consideration of what lies between. This could be updated and changed if pursued.
- Innovative detection technologies. It was noted that intelligent materials are harder to deploy than might meet the eye because of the challenge of getting an electric signal from a monitoring point to a point where it can be processed and interpreted. It may be, however, that alternative means of detecting problems could be used. Resonance techniques have been used, for example, to detect pipe fractures or irregularities remotely.
- Water balance: It was suggested that technologists use a local water balance approach as a basis for design. Linkage between surface and groundwater was also noted as an important element of the problem that is at present poorly addressed.

General ‘blank slate’ options for development, we might do when there is no old infrastructure (i.e., new development) to contend with were also brought up for discussion. In some cases, this could also include areas where wholesale changes in infrastructure were a possibility. Points of discussion included:

- Volume as a criterion: Consider shifting the paradigm from looking at flow rate to focus on volume, as this can better relate to quantity and loading, instead of only the flow rate paradigm.
- Elimination of the network: It was questioned why we think in terms of containment and why have a system, when other options may be available.
- Seek beneficial urbanization: Urbanize in a way that solves not just drainage and stormwater, but other problems. Seek ways to develop that consider contributions to energy, the food cycle, drinking water, and results in reduced footprint in all of these areas.
- A water neutral city: This is a concept that focuses on water balance. It also enables an overall balance instead of a point to point balance, for example it might be prudent or environmentally best if one can choose to degrade one location in order to preserve another and thereby achieve larger benefits over all.

The next challenge is to shift from the very broad considerations that the collective experts developed, towards a more focused set of actionable technologies and advances. This will be done in the next project stages.

# Appendix A - Literature Review

## Section 1:  CSO Technology Development - Design and Operation of Sewerage Systems

There is an increasing pressure on municipalities, emerging from National policy related to water quality management, to reduce discharges of contaminants to receiving waters.  This is a costly direction to take, although a crucial element of environmental management, because it touches on infrastructure nation-wide.  The systems that are now in place to collect and convey wastewater and combined flows is intimately associated with the municipal system, and it is disruptive and expensive to undertake major revisions of the constituent pipes, tunnels and tanks of which the system is comprised.   In order to establish a basis for exploring the cost-effectiveness and environmental consequences of this area of activity, a review of these situations is necessary.  It may be that truly meeting the newer discharge goals, total maximum daily loads (TMDLs) and other requirements can only be achieved with holistic system changes in collection and treatment approaches.  If that is the case, there is a significant benefit to identifying treatment technologies that can accomplish what is needed more readily or with potential use and maintenance of older infrastructure components.  This raises the question as to what alternatives should be considered in this research, and in particular what experience elsewhere might shed light on this question.  As noted in Chapter 1, this work focuses on those technologies that are not in common practice but are beyond the point of basic research.  This does not immediately imply that wholly new technologies are the only candidates for incorporation in this work.  In some cases, the context of application may be considered to fit this area of interest.  For example, BMPs are well established in the stormwater field, and have been applied in combined sewer systems (CSS), but it may be that there are techniques in the stormwater arena that can be re-purposed to positive effect in achieving combined sewer overflow (CSO) control.

It did not prove to be a simple matter to find truly new ideas or applications in the area of CSO control. Much of the published literature seemed to echo ideas that had been in the literature for some time, with refinements case by case but not in fundamental approach.  Perhaps this is because the fundamental technologies have been used for years, promoted by the fundamental problems they address.  Such things as source controls, inflow controls, optimization methods (real-time control, storing combined sewage in existing sewers, or revision to facility operations), improved treatment technologies, and in-situ remediation such as may be accomplished by aeration and flow augmentation are well known and provide proven approaches.  Each technology has differing potential for success when considered from the perspectives of regulatory compliance, cost-effectiveness, remedial efficacy, public acceptance, collateral impact, and other factors, but these are the outcome of the circumstances of the situation, not perhaps of novel thinking.  The authors sought to find in the literature new or innovative ways of applying old technologies, such as storage of WWF as it accumulates, and bleeding it back into either treatment plants or other advanced facilities.  High-rate treatment methods offered another possible area of investigation, and other avenues were sought.  What was discovered is that the grey literature, containing claims of effectiveness that are sensitive to the case at hand or are of unproven or uncertain merit, makes it difficult to determine with confidence whether or not an innovative re-purposing of technology truly has merit. A recent systematic review of options in this area is not available, and this literature is difficult to apply in balance as a result. A review of practice, in terms of what has been accomplished, particularly outside the US, is presented. Given the recent experiences of the EU and the massive effort into analysis on watershed management options in that area, it was found that this topic was of particular interest and requires further exploration.

## CSO Technology Alternatives

It is useful to provide a context from which to evaluate the potential application areas of candidate technologies. Four key principles are presented in CSO Policy to ensure controls are cost-effective and meet the objectives of the CWA (33 U.S.C. § 1251 et seq.). These principles include:

1. clear levels of control that would be presumed to meet objectives;
2. flexibility to consider the site-specific nature of CSOs and to determine the most cost-effective means to reduce pollutants and meet CWA requirements;
3. allowance for a phased approach given a community's financial capability; and
4. review and revision of water quality standards and implementation procedures when developing CSO control plans to reflect the site-specific wet weather impacts of CSOs.

Suggestions for evaluating control option alternatives include performance-based options, such as setting a maximum allowance of overflow episodes permitted per year, providing controls that achieve a designated capture rate, or expansion of the POTW secondary and primary capacity.

Given that the final long-term CSO plan will become the basis for NPDES permit limits and requirements, the selected controls should be sufficient to meet CWA requirements. Examples such as enlarging a sewer trunk line or adding storage tanks would be an acceptable CSO control alternative. Both alternatives increase the storage capacity of the sewer system, thereby decreasing the sanitary and stormwater flow volume that could otherwise overflow prior to discharging into the treatment plant.

Several EPA documents on CSOs have summarized characteristics of these complex systems, including impacts and a description of the resources spent and technologies used by municipalities to reduce impacts. It establishes a baseline of related data concerning sewerage management and describes typical technologies and operational practices to reduce CSO impacts. Summaries of major discussion topics follow.

### Collection System Controls

Collection system controls maximize the capacity of the sewer system to store or transport wastewater through hydraulic control point adjustments to maximize system storage capacity while minimizing the volume of infiltration and inflow (I/I) into the system undergoing treatment. The controls may include maximizing flow delivered to the plant for treatment, disconnecting stormwater discharges into the collection system, developing a more effective system using real-time controls to monitor flow rates and more effectively manage the system's storage capacity while maximizing the flow volume directed to the plant during WWF, and sewer system rehabilitation.

## Storage Facilities

In-line or off-line storage options provide additional capacity when a sewer system is unable to transport or provide full treatment for WWF. In-line storage of WWF is provided within the sewer system and includes the use of flow regulators, in-line tanks or basins and parallel relief sewers. DWFs pass directly through these facilities. Flow regulators allow for in-line storage by adjusting the flow into or out of the facility during wet weather. In-line storage capacity can be supplemented by the installation of parallel relief sewers or replacing older pipes with larger diameter pipes. Field *et al.*, (2004) note that areas of mild slopes provide the best opportunity for in-line storage facilities, while observing that this method can potentially increase wastewater basement back-up and street flooding. The mild slope may also promote sedimentation and debris accumulation within the sewer. The traditional solution to prevent solids deposition within the collection system is to have design wastewater flow velocities high enough to flush sediments and prevent solids accumulations within the pipe.

Off-line storage facilities store WWF in near-surface tanks and basins or deep tunnel locations. Off-line facilities can be adapted to numerous site-specific designs and settings relating to basin volume, inlet and outlet structure, and disinfection process. Flows are routed around the off-line facility during dry weather, whereas during wet weather, wastewater discharges are pumped and/or flow by gravity into the storage facility. Overflows can arise if capacity is exceeded. The primary utility of the facility is storage of WWF discharges and treatment by solids settling when stormflow volume exceeds storage capacity.

On-site storage at the wastewater treatment plant can also be used as a control where the capacity of the wastewater collection system exceeds that of the treatment facility. The two most common types of on-site storage are flow equalization basins and the conversion of abandoned treatment units, such as clarifiers or lagoons.

In areas where in-line storage is not attainable or unavailable, the cost of creating off-line storage may be very high. The costs associated with on-site storage are typically lower than the construction of near surface off-line facilities because the on-site storage facility is typically located on land already owned by the facility. Expanding conveyance capacity is usually the most expensive storage development option.

## Treatment Technologies

In those collection systems where WWF exceeds the sewer conveyance and treatment facility capacity, end-of-pipe controls may be used in lieu of storing excess flows. Different pollutants, such as solids, bacteria or floatables, use specific treatment technologies. The disinfection of excess WWF is used as an end-of-pipe treatment for microorganism removal, whereas vortex separators are used for solids removal. Given the assumption that dry-weather flows are treated at the wastewater treatment facility, these technologies are assumed to operate only during wet weather or storage dewatering conditions.

### *Supplemental Treatment*

These technologies supplement treatment during wet weather conditions. An example of such a supplement would be the installation of a parallel treatment process at a wastewater treatment plant that is only operated during wet weather conditions. Potential supplemental treatment technology options for excess WWF include ballasted flocculation and/or chemical flocculation to accelerate the settling of solids, deep-bed filtration using anthracite and sand, and microscreens. These technologies must be dependable and able to respond to intermittent and variable flow regimes and influent pollutant concentrations.

### *Plant Modifications*

Plant modifications to existing treatment process configurations or process operations can increase the facility's ability to handle and treat WWF. Such examples include providing an even flow distribution between process treatment units (blending), baffle installation to prevent hydraulic surges in clarifiers, adding flocculants to accelerate suspended solids removal, switching a portion of flow delivery from the primary to bypass the secondary units, and switching from series operation during dry weather to a parallel operation of unit processes during wet weather. Performance evaluations are necessary to confirm whether additional treatment capacity developed for WWF blending may adversely impact the pollutant removal and treatment process for dry-weather flow.

#### *Disinfection*

The application of a disinfection process to CSO discharges has been limited, when compared to the disinfection unit process used in wastewater treatment plants. High flow rates and partially treated wastewater may adversely impact the disinfection process if the exposure of the disinfection agent to the wastewater undergoing treatment is reduced. Chlorine disinfection is the method most often used to disinfect WWF. Toxic residual chlorine and disinfection byproducts limit the usefulness of chlorine disinfection in those areas that have high organic solids in their effluent. It is suggested that UV light may be an alternative disinfection method as long as WWF receives some secondary treatment (to remove larger particulate matter) beyond settling that occurs during primary treatment.

#### *Vortex Separators*

Vortex separators are designed to separate and concentrate solids and floatables from the flow undergoing treatment. The separated effluent with floatables and with some solids removed can then undergo further treatment or discharged to the receiving stream. These separators have limited capability to reduce small and light particles and dissolved contaminants and should not be placed in a treatment train downstream of other units that provide the same or a higher level of pollutant removal.

#### *Low Impact Development Techniques*

Low Impact Development (LID) techniques can be used to attenuate stormwater runoff discharging into the sewer collection system, thereby potentially reducing the volume or occurrences of CSO events and capacity of downstream control facilities. LID controls provide runoff volume storage opportunities and include technologies such as porous pavement, bioretention facilities, rain gardens, green roofs and water conservation practices. Incorporating LID controls into the footprint of urban developments decrease the storage volume capacity required in sewer collection and CSO control. More of this technology will be covered later in this report.

### Technology Combinations

Some technologies work well when applied together. Some of the combinations that have been suggested by Field *et al.*, (2004) are:

#### *LID Designs Coupled with Structural Controls*

Both controls reduce the peak flow rate and quantity of runoff that enters the sewer collection system. The runoff volume and peak flow reductions allow for the size of downstream storage control structures to be reduced or eliminated. Again, see later chapter on Total Water Management (TWM).

#### *Disinfection Coupled with Solids Removal*

Numerous pollutants in wastewater discharges can interfere with and reduce the effectiveness of disinfection processes. These pollutants include high concentrations of $BOD_5$, ammonia, and iron, which consume or prevent the disinfectant from interacting with the microorganisms. Larger solid particles can shield microorganisms located in the particle's interior from the effect of all disinfectants, including chlorine, ozone, chlorine dioxide, and UV.

Solids removal enhances disinfection by settling out and removing shielding particles and the clad pathogens, and reduces chlorine demand. Using effective solids removal controls can improve the performance of disinfection process units treating CSO discharges. Off-line storage facilities, vortex separators and supplemental treatment facilities have demonstrated additional benefit at removing solids out of the wastewater stream.

***Sewer Rehabilitation Coupled with Sewer Cleaning***

Sewer cleaning techniques should be conducted or at least considered before scheduling the rehabilitation of the sewer collection and retrofitting CSO control facility systems; so that needless and expensive infrastructure replacement is not implemented when simple maintenance and cleaning are all that is necessary.

***Real-Time Control (RTC) Coupled with In-line and Off-line Storage Tanks***

RTC technology is used to maximize flow to the treatment plant and storage within the sewer. Both outcomes serve to reduce the volume and frequency of untreated overflows. RTC uses operating rules, monitoring data, software (SCADA systems) to dynamically operate system components to optimize wastewater routing, treatment and storage. System components include weirs, gates, pumps, valves and dams. RTC is most often employed in sewers that have considerable in-line storage using large pipes designed for excess WWF. Off-line storage facilities, such as tunnels or basins, can also be operated by RTC. The dynamic operation resulting from RTC features optimizes the sewer storage volume available for excess WWF.

## References

Field, R., Sullivan, D. and Tafuri, A.N., editors, (2004) Management of Combined Sewer Overflows, CRC Press LLC, Lewis Publishers (ISBN 0-56670-636-X)

## Section 2: CSO Control – Real-Time Control and Storage Approaches

In principle, real-time control (RTC) and storage options provide a promising way to resolve CSO overflow problems. This is dependant, however, on a well developed capability to model the system, and that in turn depends on an equally well developed understanding of the mechanics that govern that system. A useful review of progress on modeling and the mechanics of in-line retention as a means of combating CSO releases that exceed regulated limits was recently provided by Ashley *et al.* (2002). As a part of this, they identified models suitable to represent the range of phenomena, but they concluded that no truly comprehensive model existed. They also evaluated solids buildup and behavior in the line and flushing effects at the plant, along with a number of other consequences of grit and material build up and removal along the length of the system. It was not concluded that the systems involved are fully understood. Nevertheless, it is clear from this work that a significant knowledge base exists and that modeling and control approaches might have merit as avenues of continued development.

### Real-Time Control

One approach to RTC is to directly predict the ability of a plant to provide treatment adequate for a particular event, and to adjust flows to meet that need or otherwise cope with it. Recent work by Seggelke *et al.* (2008) introduced an integrated control approach. The intent is to reduce CSOs and collect early information on the plant's critical process conditions. In their method, treatment processes are continuously monitored and models are used to predict the treatment capacity of a plant in contrast with the materials that need to be controlled. A controller is used to adapt the plant's inflow rate according to that assessment. The intervention is rule-based. This means that the system is evaluated in detail, and responses to stimuli are determined *a priori*. Such a system uses the input conditions to determine the appropriate response based on the rules developed this way. In their particular application, Seggelke *et al.* (2008) determined that a fixed value of the maximum wastewater treatment plant (WWTP) inflow does not provide the best use of treatment capacity at the plant, which lends support to the need for RTC methods.

Another hydraulics based effort that approaches the problem on a wider scale is being pursued by Guillon *et al.* (2008). Their work involves numerous on-line tanks in the HAUT-de-Seine sewer system, and the author explained[3] that the project had been based on independent pre-determined rule curves. Guillon *et al.* also indicated that those responsible were only recently considering movement to a more global approach to discharge management that involved comprehensive system-wide operations methods. She noted that a difficulty was in finding simulation and/or predictive tools that had the needed capabilities for this. A conclusion of this observation is that the benefits of system-wide operation are recognized and sought, but that there remains a need to further develop the necessary predictive and intervention systems.

A more complex approach is to have the system 'learn' from experience what the best possible operating mode may be in order to control a particular event. This provides an ability of the control system to adjust dynamically over time on the basis of known sequences of events and their outcomes. Kurth *et al.* (2008) described an Artificial Neural Network (ANN) to predict the hydraulic characteristics of CSO discharges. In order to predict hydraulic performance, they developed a comprehensive (monitoring, modeling and operational strategy were all incorporated) system. Their system uses input from weather radar to predict hydraulic performance of CSO assets. System data in three UK drainage areas were used to train, validate, and test what was described as a hidden layer feed-forward multilayer perception. The

[3] Personal communication, Lyon, France, November 5, 2008.

approach was hydraulically oriented. They used local rainfall data and predict consequences on water depth and weir crest elevation. Given the much more intractable nature of the problem of constituent prediction, this seems like a reasonable surrogate for performance evaluation. It may eventually be possible to distinguish between causes of observed water patterns such that discrimination of input conditions can lead to effective determination of responses. At the time of publication, prediction over a time horizon of 15 minutes was reported as being effective.

This kind of predictive approach may, in due course, be amended to incorporate constituents other than hydraulic, and this may be an avenue for further exploration. Hydraulic behavior brings with it quality impacts, and controlling the degree of quantity overflow has an impact on the degree of quality overflow so this is a useful step to take. However, it seems reasonable to consider the option of quality control as a direct effect instead of an implicit result of an intermediary phenomenon such as quantity.

There has been work which does step towards direct use of water quality simulation to determine operating conditions. Blumensaat *et al.* (2008) evaluated the implications of on-line quarter quality data on the reduction of model uncertainty. They applied water quality modeling and applied simulation results to explore system optimization options. The researchers concluded in part that water quality constituents associated with sediments were significant, and that long-term conclusions made without incorporating this effect were limited.

The elements of the problem are therefore all in place to enable predictive approaches as an integral part of RTC based on quality constituents. RTC of CSO discharges is not new, but there are elements of the problem that are certainly feasible, but not yet in common practice. The work currently being reported suggests that there is an opportunity in the extension of RTC to include quality constituents, in the development of predictive tools, and in the integration of RTC at a system-wide level.

## Tanks and In-line Storage

A tried and tested component of CSO management is the use of storage to buffer flows and minimize overflows. This storage can be on-line or off-line, and the best approach depends on the context. These have a significant history but are nevertheless relatively recent on the CSO scene. As noted by Brombach *et al.* (2008) pretreatment of excess WWF not flowing to the treatment works was introduced in the 1970s and consists of a combination of detention, sedimentation, and floatable debris removal. These are a popular solution, and it is noted by Brombach *et al.* (2008) that more than 30,000 decentralized CSO tanks are in operation in Germany. Even so, knowledge about the efficiency of the tanks is imperfect and research is need in this area, particularly as regards sedimentation and resuspension of sewer sediments. Practice continues to evolve. In the 1970s tanks were designed for first flush, but recently retention treatment basins have accepted as CSO treatment structures. This section examines the current state of this evolution.

On-line facilities, commonly accomplished by in-sewer storage and oversizing pipe but also possible through ‘point’ volumes, is provided within the sewer system. Since they are on-line, DWFs (undiluted sewage) passes through them. Simple geometry suggests that these facilities are readily implemented in flat areas. Unfortunately, this together with the flows during dry weather means that sedimentation and buildup are potentially problematic. Further, the intimate association with the conveyance system may predispose such a system to backups or other problems during extreme events. Some of this can be countered with careful design, for example by maintaining velocities such that scouring minimizes deposition.

Off-line storage facilities store WWF in volumes connected to the conveyance system but not in a way that requires flow to pass through them on a continuing basis. Instead, the larger events only are captured. They may be placed by using near-surface tanks and basins or deep tunnel locations. They are designed so that they drain back into the system, or are pumped back into the system, when the event has passed. Because they are situated off the main system, they can be cheaper and easier to retrofit than an on-line system, and are often used in that context as a result.

Shepherd *et al.* (2008) provide a full history of settling basin design. It is noted that according to classic theory, for an ideal rectangular basin, the selection of volume implies a surfaced overflow rate that is a driver for removal under steady conditions. Sediment removal under dynamic conditions has also been addressed by the EPA.[4]

Shepherd *et al.* (2008) also noted that about half the inflow is routed into storage tanks, and the rest is treated at the plant. Flows beyond what the tanks can manage are discharged to the receiving water. Flows diverted to the tanks are sent back to the plant when conditions moderate and capacity for this is recovered. The main benefit of the tank, therefore, is to hold volume that would otherwise be simply discharged so that it can be treated when conditions moderate. Since some materials settle out in the tanks, the depth and other characteristics have an impact on how much material is re-suspended and flushed into the receiving stream when overflow events are occurring.

Although the principles of storage tanks and CSO systems are universal, standards in implementation differ in various jurisdictions. It is interesting to note that UK design practices are stated in terms of volume only, with aspect ratio characteristics not specified, and that this means design characteristics that would tend to promote or minimize re-suspension are left up to the knowledge and judgment of the particular team managing the particular case. As noted by Shepherd *et al.* (2008), flows entering European facilities are limited to six times the mean DWF, and CSOs function above that level, at the entrance to the treatment works. This compares to typical US practice, which operates at a lower level. Other elements also vary. For example, Germany specifies a surface loading rate of 10 m/h and a 2 to 1 length to width ratio for sizing a rectangular tank. In the US, the specified loading rates range from 0.5 m/h for small populations (US Army Corps of Engineers, 1984) to 5 m/h (Tchobonoglous, *et al*. 2003) for larger populations.

## In-pipe Sediment Processes

Temporary storage methods commonly concentrate on managing volume and minimizing overflow as a result, but are not designed to actively treat the volumes that are captured. This may provide an opportunity for future enhancements.

The processes that affect WWF quality in the system are complex. Materials can fall out, or be resuspended, and biologically active materials can be transformed as well. These processes are imperfectly understood, even though some elements of solids in sewer systems have been under investigation by US and European researchers for over the past four decades (see for example Ashley *et al.* 2003). Some aspects of research are targeted at maintaining the hydraulic capacity of the system, which can be impaired by deposition. In more recent cases, European researchers target fluid-solids interactions as processes that lead to water quality changes during storm events. (Ashley, 2005).

Some results speak to the nature of these transformations. McIllhatton *et al.* (2002) reported that much of the observed suspended load originates from solids eroding from the sewer solids bed. They recognized that large changes in water quality result from the re-entrainment of materials during an event and could propagate to cause releases to the receiving waters accepting discharges from the facility. Other research supports the notion that in-pipe effects on quality can have an impact on system performance. Using

[4] Currently available at http://www.epa.gov/ednnrmrl/publications/reports/epa440587001/index.htm

physical models, Leung *et al.* (2005) concluded that solids originating from resuspended bed material exhibited higher bacterial activity than the solids originally present in the sewage stream, implying that the sediments can concentrate materials and/or are active. It has been suggested by Schellart *et al.* (2005) that microbial activity can have an impact on the release of in-pipe sewer sediments. Banasiak *et al.* (2005) reports results which add to this notion, in that biological processes were seen to weaken the strength of sediments, and in which it was suggested that weakened shear strength may be a contributor to the foul flush. Biggs *et al.* (2005) provided results that suggest that temperature may also be a factor in concentration and possibly sediment erodability. With a substantial data base (turbidity, conductivity and flow for one year at two sites at one minute intervals in a Paris CSS) Lacour *et al.* (2008) found it was not possible to develop a relationship between hydraulic flow dynamics and turbidity. On the other hand, Abda *et al.* (2008) was able to show good agreement for velocity, water height and suspended solid concentrations, which suggest that given the right conditions, the problem may not be intractable.

Although this may suggest that the problem of prediction may be more challenging than is immediately apparent, an implication of this work is that it may be better to simulate or measure and act on quality parameters than quantity parameters. Taken together, the evidence is persuasive that sediments are indeed active, and that prediction of their mobility will require substantial and complex analytical tools. Given the importance of sediment mobility on water quality, this would seem to be a promising area for further research, but given the limited practical ability to use these results in real-world applications, it may be that this area offers little benefit for the present project.

Some progress has been made in measuring build-up that may have value in real-time or at least operating contexts. Bertrand-Krajewski *et al.* (2008) described a marine sonar unit with an attached laser meter on a floating frame was successfully tested for measuring sediment profiles in a large sewer. Sections were measureable in a time scale of seconds and to a resolution of 1 cm, and telemetry made the results immediately available. This suggests that the ability to implement operating decisions based on real-time sediment build-up behavior may be possible.

There is also research that explores some of the smaller scale and more local effects of structural elements of the system on sediment buildup and disturbance. Campisano *et al.* (2007) simulated the sediment re-suspension effect of flushing waves produced by hydraulic flushing gates and developed insights into the design and positioning of the flushing gates. Williams (2008) investigated the cause of sediment deposition when using a generic flow control device, and suggested that sediment load affects the deposit formed. He also explored the relationship of a flushing device to sediment size, noting that finer sediments may be more easily removed by such a device.

## Tank Processes

Research is actively pursuing the implications of storage volumes on CSO behavior. As noted above, Guillon *et al.* (2008) evaluated on-line tanks in the HAUT-de-Seine sewer network to reduce CSOs to the River Seine. This is reported to be a large system, with 100 CSO points of which 22 have been outfitted with automatic gates to regulate flow. The overflows with automatic gates are independently operated, in real time, manage on-line storage. The remainder of the gates (fixed) are being considered for replacement with automatic gates. The main criterion for control was annual overflow volume, and the remaining storage capacity of the whole network was a decision factor as well. In this case, the location of the first overflow and of the onset of flooding was identified. Other factors important in establishing a plan included smaller pipes or steeper slopes that made them unsuitable for control of this type.

Numerical methods are sometimes used to size tanks. Paoletti *et al.* (2008) used numerical simulation to assess the filling and emptying of cycles for off-line CSO storage tanks associated with combined sewers using different operating rules. The results were expressed as multiple regression relationships between intercepted volume, mean annual overflows, and numbers of filling-emptying cycles of tanks. It was noted that the simulation was limited by available rainfall data. Schroeder *et al.* (2008) reported on the early stages of a long-term program to manage a system, in which numerical modeling was used to size a CSO tank. It is intended in this system to place the storage tanks within a river, and it is an interesting aspect of this that the surfaces of the tanks are to be developed as platforms by implementing designs that enable this. As a part of this, factors considered included peak inflows, average number of annual filling/emptying cycles, average and maximum duration of empty tanks, and duration of CSOs staying in the tank.

There is also current research into overflow hydraulic design as a performance factor. The hydraulic designs of clarifier-type CSO tanks was evaluated by Brombach *et al.* (2008) They examined tank geometry and surface loadings. It was noted that as well as a regular overflow, an emergency overflow is needed to bypass flows exceeding acceptable clarifier hydraulic limits, and that improper selection of the overflow weir can cause excessive through flow and re-suspend settled solids.

There is some effort being devoted to evaluation of receiving-water effects as a direct element of CSO management through RTC. Achleitner and Rauch (2007), in a program consistent with the EU's Water Framework Directive for basin-wide improvement approaches, used a RTC system to examine costs (including direct costs, energy and spilled water) associated with adjusting receiving-water baseflows to meet the dilution needs of upstream CSO discharges. In some ways this seems to be a dilution approach comparable to methods abandoned in North America, and it does little if anything to manage loads, but it does demonstrate the option to manage the receiving water concurrent with the CSO system.

Not all modeling approaches are detailed and/or complex. Simplified probabilistic methods have also been used in the CSO context. Balistrocchi *et al.* (2008) assessed the long-term efficiency of CSO capture tanks as represented by first flush mass reduction. The tanks were represented as buried with an overflow device. In this effort a new probabilistic rainfall model was calibrated using five sets of continuous simulation time series data. Reasonable agreement on runoff results was achieved when this approach was tested on an urban catchment.

Solids have also been evaluated in the suspended phase, in some detail, and that research suggests that this aspect, too, is imperfectly understood. Maus (2008) examined the effectiveness of settling velocity of suspended solids in the WWF context. This included testing of sedimentation tanks, separation efficiency, and real-time particle size distribution measurement using a submersible field instrument. The research demonstrated that sizing differed between the inlet and outlet, which implies a removal process that is sensitive to size. It was suggested that lighter organic materials are transported differently from denser inorganic materials. It was also noted that sample storage had an impact on results. Over all, this work exemplifies efforts to better understand removal processes in the treatment system.

Some basic research is being done to provide insights into the effects of various design conditions on deviations from ideal mixing conditions. Shepherd *et al.* (2008) describe full-scale and lab-scale physical models that were used to look at the difference between actual residence times and theoretical ideal residence times. It was noted that the fifty-percentile residence times are always less than the theoretical residence times. This can have implications on design because it implies that tanks designed without this effect accounted for will tend to be under-designed.

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# Section 3: Watershed Management Strategies - The US Baseline

A synthesis of practice in the US was not a target of this research, but it was useful to provide a synopsis for communication with the international community that was assembled as a part of this project. The following pages provide a brief outline of what was assembled for this purpose.

## Historical Approach and Legacy

WWFs in the US have historically been mitigated to ensure flood control, property protection and public safety. The mid-20th century initiated an era of rapid conveyance of stormwater through hardened structures, such as curbs, gutters, pipes, and concrete-lined channels. Flood control was achieved using stormwater detention practices, particularly wet and dry detention ponds. Standards were written to control peak stormwater flows from new developments without consideration of the changes in volume, timing, or duration of flows from the site.

This type of development led to water body degradation, particularly stream channel alteration, due to both hydrologic changes that altered stream geomorphology and from pollutant impacts. Increased regulation resulting from the CWA, shifted the focus of wet-weather management from flood control to water quality and water resource protection. Initial efforts focused on pollutant control with less emphasis on stormwater flow control. In the 1990s, research began in earnest to identify a new approach for stormwater management. The terms Low Impact Development (LID), as coined by Prince George's County, Maryland, and Better Site Design (BSD), coined by the Center for Watershed Protection, emerged to describe two similar approaches that focused on maintaining and restoring the natural function of a development site.

Most of the existing infrastructure in the US as it exists today is based on the flood protection, rapid removal approach. In older areas of the country, particularly in the Eastern and Midwestern US, drainage infrastructure was not built with adequate capacity for today's flows, and the condition of the infrastructure itself has deteriorated as a result of inadequate attention to maintenance and replacement.

Current regulations focus on new development controls, which in many heavily developed areas do little to address the impacts from decades of prior development and degradation. Some communities have embraced retrofitting of existing infrastructure to improve water quality and flow control performance. Policy approaches include incorporating water quality features into municipal maintenance and right-of-way projects, requiring additional stormwater management for redevelopment projects, and incorporating water quality and flow retrofits into maintenance and repair activities. However, most communities are not pursuing retrofits due to the lack of requirements to do so, and because retrofits can be difficult and costly to implement.

For developing areas where new development regulations are appropriate for addressing current and future stormwater impacts, there are a wide range of performance standards ranging from the basic flood-control, peak flow mitigation approach of the mid-20th century to more innovative requirements that strive to mimic a site's natural, pre-development hydrology (i.e., LID). This variability in policies can be attributed to a number of factors, including the extent to which the state or federal government imposes regulations on the community to control WWFs, the amount of funding available for stormwater research and program implementation at the local level, and the general attitude of the populace or government officials toward developing more sustainable communities.

Research sponsored by the Water Environment Research Foundation (2008) showed that the primary regulatory drivers for strong local wet weather and stormwater management programs were the National

Pollutant Discharge Elimination System (NPDES) municipal stormwater management requirements (http://www.epa.gov/npdes/stormwater), the need to reduce or eliminate CSOs (http://www.epa.gov/npdes/cso), and a general desire by citizens and municipal leaders to promote a sustainable, “green” ethic, which includes sustainable stormwater management.

## Emerging Trends in US Practice

Perhaps the most notable broad thrust in the US at present is denoted by the LID approach that has become a strong element of practice in the water resources community. LID is a stormwater management strategy that has been adopted in many localities across the country in the past several years (EPA, 2007). It is not really new, in the sense that the principles involved have been well understood for decades, but it represents a consensus understanding in the community and to that extent is a significant development. LID is a stormwater management approach and set of practices that can be used to reduce runoff and pollutant loadings by managing the runoff as close to its source(s) as possible. A set or system of small-scale practices, linked together on the site, is often used. LID approaches can be used to reduce the impacts of development and redevelopment activities on water resources. In the case of new development, LID is typically used to achieve or pursue the goal of maintaining or closely replicating the predevelopment hydrology of the site. In areas where development has already occurred, LID can be used as a retrofit practice to reduce runoff volumes, pollutant loadings, and the overall impacts of existing development on the affected receiving waters.

In general, implementing integrated LID practices can result in enhanced environmental performance while at the same time reducing development costs when compared to traditional stormwater management approaches. LID techniques promote the use of natural systems, which can effectively remove nutrients, Indicator bacteria, and metals from stormwater. Cost savings are typically seen in reduced infrastructure because the total volume of runoff to be managed is minimized through soil infiltration and evapotranspiration. By working to mimic the natural water cycle, LID practices protect downstream resources from adverse pollutant and hydrologic impacts that can degrade stream channels and harm aquatic life.

It is important to note that typical, real-world LID designs usually incorporate more than one type of practice or technique to provide integrated treatment of runoff from a site. For example, in lieu of a treatment pond serving a new subdivision, planners might incorporate a bioretention area in each yard, disconnect downspouts from driveway surfaces, remove curbs, and install grassed swales in common areas. Integrating small practices throughout a site instead of using extended detention wet ponds to control runoff from a subdivision is the basis of the LID approach.

When conducting cost analyses of these practices, examples of projects where actual practice-by-practice costs were considered separately were found to be rare because material and labor costs are typically calculated for an entire site rather than for each element within a larger system. Similarly, it is difficult to calculate the economic benefits of individual LID practices on the basis of their effectiveness in reducing runoff volume and rates or in treating pollutants targeted for best management practice performance monitoring.

The following is a summary of the different categories of LID practices, using US terminology, including a brief description and examples of each type of practice.

### Conservation Design

Conservation designs can be used to minimize the generation of runoff by preserving open space. Such designs can reduce the amount of impervious surface, which can cause increased runoff volumes. Open space can also be used to treat the increased runoff from the built environment through infiltration or evapotranspiration. For example, developers can use conservation designs to preserve important features on the site such as wetland and riparian areas, natural vegetation, forested tracts, and areas of porous soils.

Development plans that outline the smallest site disturbance area can minimize the stripping of topsoil and compaction of subsoil that result from grading and equipment use. By preserving natural areas and not clearing and grading the entire site, less total runoff is generated on the development parcel. Such simplistic, nonstructural methods can reduce the need to build large structural runoff controls such as retention ponds and stormwater conveyance systems and thereby decrease the overall infrastructure costs of the project. Reducing the total area of impervious surface by limiting road widths, parking area, and sidewalks can also reduce the volume of runoff. Residential developments that incorporate conservation design principles also can benefit residents and their quality of life due to increased access and proximity to communal open space, a greater sense of community, and expanded recreational opportunities.

## Infiltration

Infiltration practices are engineered structures or landscape features designed to capture and infiltrate runoff. They can be used to reduce both the volume of runoff discharged from the site and the infrastructure needed to convey, treat, or control runoff. Infiltration practices can also be used to recharge ground water. This benefit is especially important in areas where maintaining drinking water supplies and stream baseflow is of concern because of limited precipitation or a high ratio of withdrawal to recharge rates. Infiltration of runoff can also help to maintain stream temperatures because the infiltrated water that moves laterally to replenish stream baseflow typically has a lower temperature than overland flows, which might be subject to solar radiation. Another advantage of infiltration practices is that they can be integrated into landscape features in a site-dispersed manner. This feature can result in aesthetic benefits and, in some cases, recreational opportunities; for example, some infiltration areas can be used as playing fields during dry periods.

## Runoff Storage

Impervious surfaces are a central part of the built environment, but runoff from such surfaces can be captured and stored for reuse or gradually infiltrated, evaporated, or used to irrigate plants. Using runoff storage practices has several benefits. They can reduce the volume of runoff discharged to surface waters, lower the peak flow hydrograph to protect streams from the erosive forces of high flows, irrigate landscaping, and provide aesthetic benefits such as landscape islands, tree boxes, and rain gardens. Designers can take advantage of the void space beneath paved areas like parking lots and sidewalks to provide additional storage. For example, underground vaults can be used to store runoff in both urban and rural areas.

## Runoff Conveyance

Large storm events can make it difficult to retain all the runoff generated on-site by using infiltration and storage practices. In these situations, conveyance systems are typically used to route excess runoff through and off the site. In LID, conveyance systems can be used to slow flow velocities, lengthen the runoff time of concentration, and delay peak flows that are discharged off-site. LID conveyance practices can be used as an alternative to curb-and-gutter systems, and from a water quality perspective they have advantages over conventional approaches designed to rapidly convey runoff off-site and alleviate on-site flooding. LID conveyance practices often have rough surfaces, which slow runoff and increase evaporation and settling and removal of solids. They are typically permeable and vegetated, which promotes infiltration, filtration, and some biological uptake of pollutants. LID conveyance practices also can perform functions similar to those of conventional curbs, channels, and gutters. For example, they can be used to reduce flooding around structures by routing runoff to landscaped areas for treatment, infiltration, and evapotranspiration.

### Filtration

Filtration practices are used to treat runoff by filtering it through media that are designed to capture pollutants through the processes of physical filtration of solids and/or cation exchange of dissolved pollutants. Filtration practices offer many of the same benefits as infiltration, such as reductions in the volume of runoff transported off-site, ground water recharge, increased stream baseflow, and reductions in thermal impacts to receiving waters. Filtration practices also have the added advantage of providing increased pollutant removal benefits. Although pollutant build-up and removal may be of concern, pollutants are typically captured in the upper soil horizon and can be removed by replacing the topsoil.

### Low Impact Landscaping

Selection and distribution of plants must be carefully planned when designing a functional landscape. Aesthetics are a primary concern, but it is also important to consider long-term maintenance goals to reduce the amount of labor, water, and chemicals needed. Properly preparing soils and selecting species adapted to the microclimates of a site greatly increases the success of plant establishment and growth, thereby stabilizing soils and allowing for biological uptake of pollutants. Dense, healthy plant growth offers such benefits as pest resistance (reducing the need for pesticides) and improved soil infiltration from root growth. Of particular importance is the avoidance of heavy earth-moving equipment and soil compaction during construction thus enabling post-construction soil-infiltration to occur in an uninhibited manner. Low impact landscaping can thus reduce impervious surfaces, improve infiltration potential, and improve the aesthetic quality of the site.

## Recent US Policy Developments

With the drafting of the *Managing Wet-weather with Green Infrastructure—Action Strategy 2008* (http://www.epa.gov/npdes/pubs/gi_action_strategy.pdf), the US formalized a collaborative effort to consider development with water management issues in mind (EPA, 2008). The stated purpose of the action strategy is to coordinate the efforts of several organizations to "promote the benefits of using green infrastructure in mitigating overflows from combined and separate sewers and reducing runoff, by encouraging the use of green infrastructure as prominent components of CSO and sanitary sewer overflow (SSO) plans, municipal stormwater programs, and nonpoint source and watershed planning efforts." The action strategy itemizes a number of important efforts to bring "green infrastructure technologies and approaches into mainstream wet-weather management." The Green Infrastructure Action Strategy is also intended to address projected impacts of climate change.

In September of 2007, the Environmental Council of the States passed a resolution (http://www.ecos.org/content/policy/detail/2861/) outlining its plan to use green infrastructure to reduce the negative environmental impacts associated with CSO and SSO events (Brown 2007). Another resolution was passed in 2006 by mayors across the US (http://www.usmayors.org/urbanwater/policyres_06c.asp) to show their interest in seeing the array of environmental benefits in wet-weather technology applied to their cities (U.S. Conference of Mayors, 2006). This resolution stated in part:

> Green infrastructure naturally manages stormwater, reduces flooding risk and improves air and water quality, thus performing many of the same functions as traditionally built infrastructure, often at a fraction of the cost.
>
> - U.S. Mayors' Resolution on Green Infrastructure

These steps by US political entities and lawmakers may signal a pending significant increase in the demand for solutions, and therefore for persons with the technical knowhow, that will accomplish these ambitious and broad reaching goals.

The technology outlined in this report has been tried and tested, and research findings demonstrate their usefulness in mitigating wet-weather control problems. The case studies presented in the following sections provide a snapshot of projects that have been completed or are ongoing across the globe. Data from these studies will go a long way in providing guidance and assurance to city planners and policy-makers in all parts of the world.

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## Section 4: Water Sensitive Urban Design (WSUD)

The following chapters highlight the approaches of many US and International case studies primarily for surface water/stormwater management. Case studies were selected based on having a suite of data available on performance as well as costs.

The primary goals of Water Sensitive Urban Design (WSUD) are similar to the core values of any water conservation practice. WSUD should follow the following principles (Melbourne Water, 2008):

- Protect natural systems
- Integrate stormwater treatment into the landscape
- Protect water quality
- Reduce runoff and peak flow
- Add value while minimizing development costs

What is new is the integrated approach to urban wastewater management that WSUD proposes. The integration goes by the term "treatment trains," which denotes the staggered and graduated approach to sediment and pollutant sequestration, as shown in Figure 2.

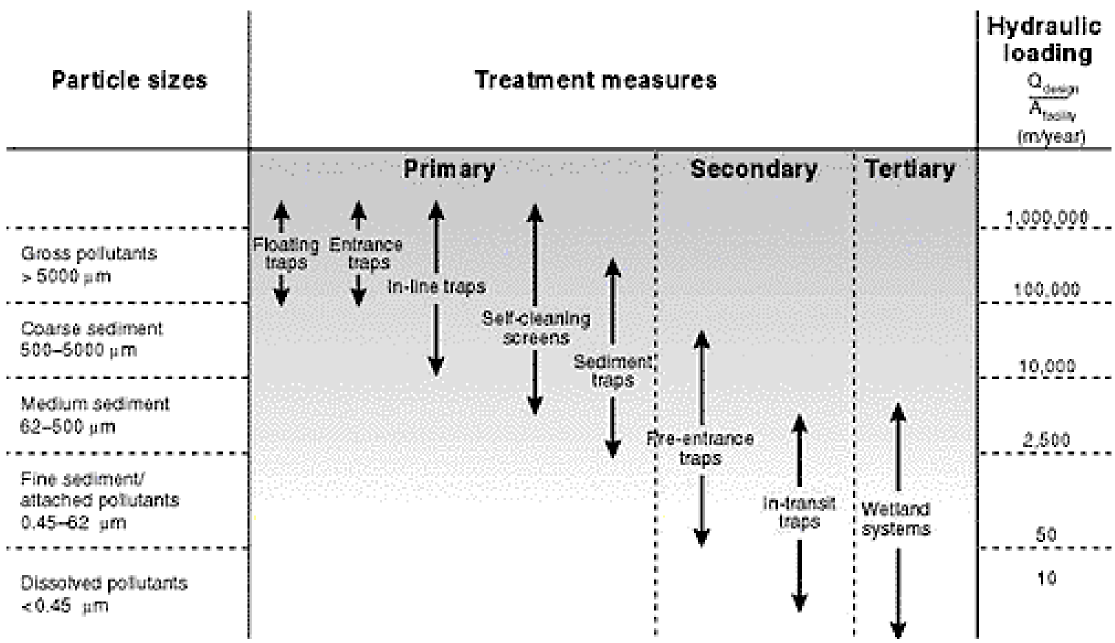


**Figure 2. Desirable design ranges for treatment measures and pollutant sizes (Melbourne Water, 2008).**

WSUD is an Australian term applied to the approach of using all available technologies in concert with each other to achieve the maximum wastewater and pollutant reduction (Melbourne Water, 2008). It is also known as SUDS, mostly in the UK, and LID, mainly in the US, but will be called WSUD in this report. This is a philosophy in which the end product should mirror, as closely as possible, the natural drainage conditions prior to development (Woods-Ballard, 2007). Minimizing sewage discharges (thus reducing combined sewer overflow events) and demand on water supply systems are other key benefits to this philosophy (Brisbane City Council, 2006).

The legislative backbone to the propagation of WSUD projects in Queensland, Australia, is the Integrated Planning Act (IPA). The IPA is centered on the goal of ecological sustainability by utilizing natural resources in such a way as to minimize the impacts on the environment (Brisbane City Council, 2006).

Part of what makes this approach successful is its ability to be integrated into an urban environment to achieve multiple benefits. The technologies used in WSUD use the topography of an area to maximize the aesthetic and recreational qualities of the landscape. Building systems into parks and along walking paths, as well as in riparian corridors, emphasizes the natural watershed drainage system and its functions (Melbourne Water, 2008). In the upcoming chapters we will explore the various technologies that contribute to a wastewater treatment train.

The following are the steps involved in implementing the WSUD approach (Brisbane City Council, 2006):

- Step 1 – Site Assessment: Assess the natural assets of the site and appropriate measures to minimize water impacts.

- Step 2 – Establish Design Objectives: Determine required design objectives based on local authority requirements.

- Step 3 - Device Selection: Determine short list of suitable WSUD measures or series of devices that can be incorporated within the site to meet design objectives.

- Step 4 - Determine Conceptual Design: The optimal suite of WSUD measures based on performance in meeting design objectives and life-cycle cost. Computer modeling may be required to demonstrate compliance with design objectives.

- Step 5 - Undertake Detailed Design: Detailed design of selected measures.

- Step 6 - Operation and Maintenance: Implement operation and maintenance plan for construction and operational phases.

There are two main types of treatment for urban drainage systems: outlet and distributed (Figure 3). The outlet method of treating at one site located at the catchment outlet is a more centralized approach, which is beneficial when there is a sizeable pollutant load located in one generalized area. Maintenance of centralized treatment structures can be relatively straightforward; however, the treatment structure would need to sequester a larger pollutant load than distributed practices. Also, to have the desired impact on wastewater treatment, the practice would have to cover a larger land area to facilitate a larger amount of infiltration (Melbourne Water, 2008). The benefits of a “distributed” system are many and the risks are small. Dividing a large urban landscape into manageable catchment areas makes it possible to target many areas of moderate to high pollution, extending water quality protection along a greater length of waterway. A technology may be chosen to best suit the topology of the site and the catchment area. The flow velocities passing through “distributed” treatment structures are lower and therefore provide more of an opportunity for infiltration and pollutant removal.

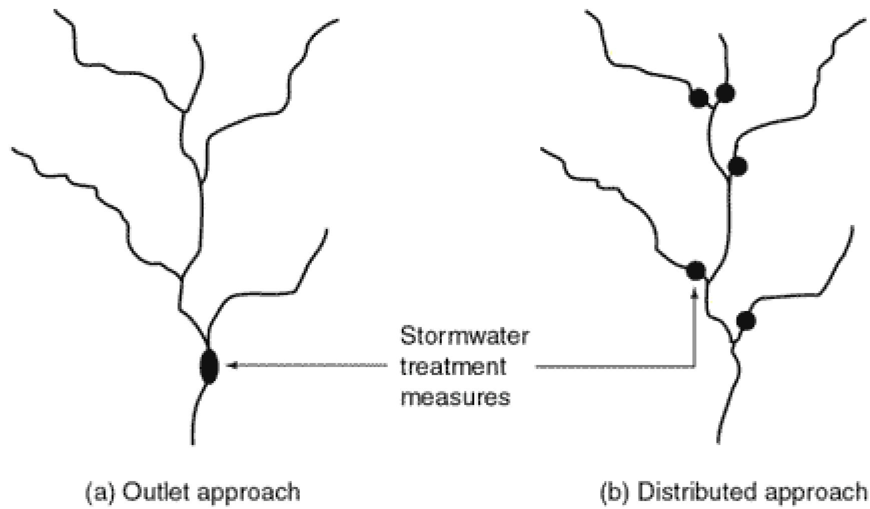


**Figure 3. The contextual significance of an outlet approach vs. a distributed approach (Melbourne Water, 2008).**

If programs implemented by the city, state/provincial, or local organizations have staged funding, then individual sites can be built one by one as the funding becomes available (Melbourne Water, 2008). Also, if one of the distributed treatment systems fails, the entire effort is not lost. Treatment systems fail for a number of reasons, which include inappropriate site topography (steep slopes), instability of soils or geology (highly erosive area), limited space to implement the technology effectively, and social constraints. Social constraints affecting the success of wet-weather technologies can range from odor associated with sequestered pollutants and detritus to contamination from pollutants (infection, etc.) and vermin such as mosquitoes or rats (Melbourne Water, 2008).

Ultimately, when the correct treatment option is chosen along with the correct size of the treatment area, there can be as much as a 90% or more reduction in gross pollutant load in water leaving the treatment site (Brisbane City Council, 2006). This is in comparison with traditional urban development practices, in which stormwater is not treated at all and is simply directed as efficiently as possible into a drainage pipeline system, which drains directly into the nearest water body.

When more techniques are used in series, the overall system becomes increasingly effective. Conveying stormwater from one treatment system to the next is an important consideration in the management of WWFs. During extreme storm events, having a well established overland flow route is necessary to convey water safely (Woods-Ballard, 2007). Proper maintenance and enhanced public perception of treatment structures will ensure their long-term success as pollution and water management systems.

## Case Studies

### Low Impact Development in Tyngsborough, Massachusetts, US

Marla Circle in Tyngsborough, MA is a subdivision with five lots that originally called for a conventional development and as such was submitted to the town's planning board for approval in June 2003. The required stormwater practices took the space planned for the fifth lot. The project was withdrawn and redesigned, with LID elements added. The new design was approved for construction in spring 2004. The major LID change was to retain all of the stormwater in the road, in a bioretention cell within a cul-de-sac. This change allowed space for the fifth single-family home to be built. Water-quality swales were installed along the uncurbed road's right-of-way. The last home was completed in September 2005 (Buranen, 2008).

The bioretention cell in the cul-de-sac and the swales will require periodic removal of sediments. Trees and shrubs were planted within the cul-de-sac, so routine landscape maintenance will also be required. Tyngsborough's Department of Public Works agreed to take on both of these maintenance responsibilities when the town accepted the road.

A narrower street (24 instead of 28 feet) and narrower driveways reduced paved areas and runoff. The homes were located closer to the street, reducing the length of driveways as well as sewer and utility lines. Street proximity also meant fewer disturbances to the land, and fewer trees needed to be removed.

Each of the five homes has its own rain garden. Owners are required to maintain their gardens, including removal of debris and sediment, remulching, and replanting vegetation as needed. With the public and private LID elements in place, rainwater will overflow into the town's drainage system only in extreme storm events.

This innovative project took longer to achieve—three years—than would a conventional development. City officials, unfamiliar with LID elements, required additional review time before granting final approval. The developer cited that time and money was saved by meeting with the Tyngsborough planning board to discuss the ideas before engineered plans were developed.

## Cluster Development in Ipswich, Massachusetts, US

In Ipswich, MA, the Partridgeberry Place project involves 20 innovative home sites built on 38 acres in the Ipswich River watershed (Buranen, 2008). By clustering the single-family homes on lots of 8,000 to 12,000 $ft^2$, 74% of the site was kept as woods and open space. Hiking trails lead to a nearby state park. Meridian Associates of Beverly, MA, did the design and engineering work for the project. The Martins Companies of Danvers, MA, developed and built the subdivision. The main LID features were constructed by December 2006.

The Massachusetts Department of Conservation and Recreation (DCR) chose Partridgeberry Place as a LID subdivision demonstration site. The DCR also selected an adjacent conventional subdivision as a basis for comparison. Runoff percentages for both subdivisions will also be compared to those found in the literature for LID and conventional development for a yearlong monitoring of stormwater runoff relative to rainfall. The US Geological Survey designed the monitoring plan and installed the equipment for the study in the winter and spring of 2007.

LID features of Partridgeberry Place include minimal land disturbance; reduced pavement areas and a subdivision road that is only 18 ft wide; reduced setbacks resulting in shorter driveways and smaller front yards and backyards; grass pavers for visitors' parking; an open grass swale that drains to a central bioretention area; rain gardens on each homeowner's lot; less space for lawns and more landscapes of native vegetation; and infiltration of roof runoff through drywells. Installation of a shared septic system made the clustering of the homes work and preserved more open space. The system allows on-site recharge of wastewater.

**A Holistic Approach to CSO Control: Green Streets, Ecoroofs, and Rain Gardens in Portland, Oregon**

Portland's stormwater officials are faced with runoff from an average annual rainfall of 37 in. Portland's Green Streets program combines rain gardens with such LID features as permeable pavement, green roofs, curb extensions with plantings, and planters that allow water to infiltrate (Buranen, 2008). With these features, Portland can reduce peak stormwater flows into their combined sewer system (CSS) by as much as 85%, stormwater volume by 60%, and pollution in runoff by up to 90%. But there's still a lot of runoff and more impervious surfaces from new developments. The City Commissioner stated that Portland's goals include 3,700 green streets; 250 acres of ecoroofs; and 250 acres of planters, swales, and rain gardens. An impressive example of a Portland project with multiple LID features is the retrofit at the Mt. Tabor Middle School. This innovative joint project of the Portland Public Schools and the Department of Environmental Services manages runoff from a total area of approximately 2 acres. It includes a swale, six planters, three drywells, a curb extension adjacent to the school, and, of course, a rain garden. In 2007, the American Society of Landscape Architects presented a national award to the project's rain garden, which replaced 4,000 square feet of asphalt.

Decentralizing stormwater management through on-site projects means that rain gardens, even those installed through community projects, become the homeowner's responsibility to maintain. Requiring homeowners to attend workshops to learn about their rain gardens and other LID features connects the homeowners to the programs over the long term.

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# Section 5: Litter Traps and Swales

## Litter Traps

Urban litter is one of the major contributors to water quality degradation in urban watersheds. The primary pretreatment method is to remove large debris so downstream treatment of wet-weather runoff occurs more effectively (Melbourne Water, 2008). There are numerous control technologies available to address litter problems, all with the designs to allow access for operation and maintenance. As seen in Figure 4, structures such as this litter collection basket are simplistic in nature and generally require maintenance intervals based on the amount of gross solids and floatables within each drainage system. An advantage of these systems is that they can be incorporated into existing drainage systems with little visual impact (Melbourne Water, 2008).

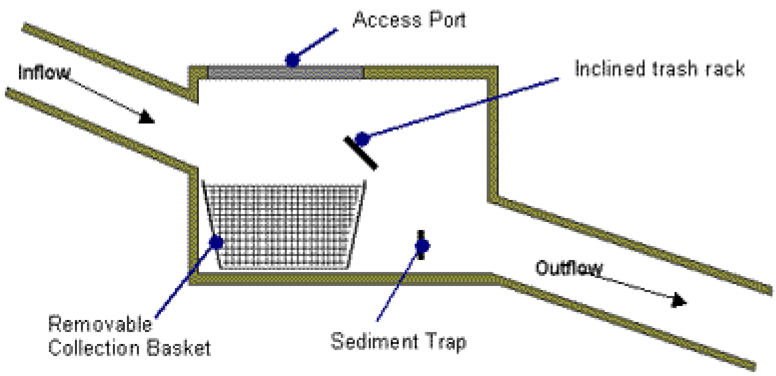


**Figure 4. Example of a litter trap structure good for high litter load areas (Melbourne Water, 2008).**

Release nets are another form of the litter collection and removal technique. As demonstrated in Figure 5, release nets are easy and inexpensive to install and maintain. The desired pore size of the netting is chosen based on the size and pollutants common to the area. They are not visually appealing if in a high traffic area out in the open, but they do allow for trash collection and removal (Melbourne Water, 2008).

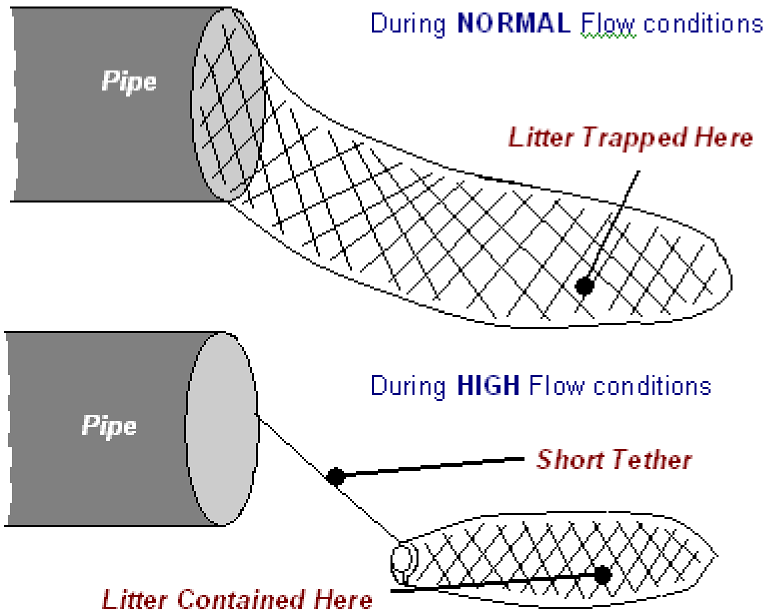


**Figure 5. Example of a litter trap for urban drainage system (Melbourne Water, 2008).**

Large sediment can be trapped also. Opening the channel in a sediment catchment slows the flow and allows for sediment to collect at the bottom of the catchment before the flow is passed on down the treatment train. Another option is to install sediment booms in high flow areas to capture sediment as it travels downstream. This option is less attractive because it does not capture finer sediments and is more area intensive (Melbourne Water, 2008).

The costs associated with the implementation of litter traps are contingent upon the following considerations (Melbourne Water, 2008):

- Installation – design, size, capacity, etc.
- Maintenance – contingent on installation factors
- Disposal – disposal costs should be estimated based on gross pollutant load

## Swales

Whether natural or man-made, swales can significantly reduce overland pollutant conveyance. Swales are wide, shallow, grassy channels with dense vegetation covering the sides and bottom. The advantage of utilizing swales as a stormwater treatment option is that they manage stormwater flows, capture particulate pollutants (suspended solids and associated pollutants), and promote infiltration (U.S. Environmental Protection Agency, 2006). In urban settings, swales can effectively replace traditional road medians and be strategically placed to filter and help infiltrate parking lot storm runoff (Melbourne Water, 2008). They provide a number of benefits, including (Clar, 2004):

- Stream channel protection
- Peak discharge control
- Water quality control
- Ground-water recharge
- The reduction of urban runoff impacts

It is important to note that there is an inherent seasonal functionality associated with any vegetative filtering system. During dormant months the effectiveness of the vegetation to filter pollutants is reduced. In addition to this annual inconsistency, there are a few possible negative impacts of swales; these include (U.S. Environmental Protection Agency, 1999):

- They are impractical in very flat and very steep topography
- They may erode in high water velocities
- Human health risks include drowning hazards and mosquito breeding areas
- Regular inspections are required

Figure 6 represents the total nitrogen removal and Figure 7 represents total suspended solids percentages associated with different swale slopes.

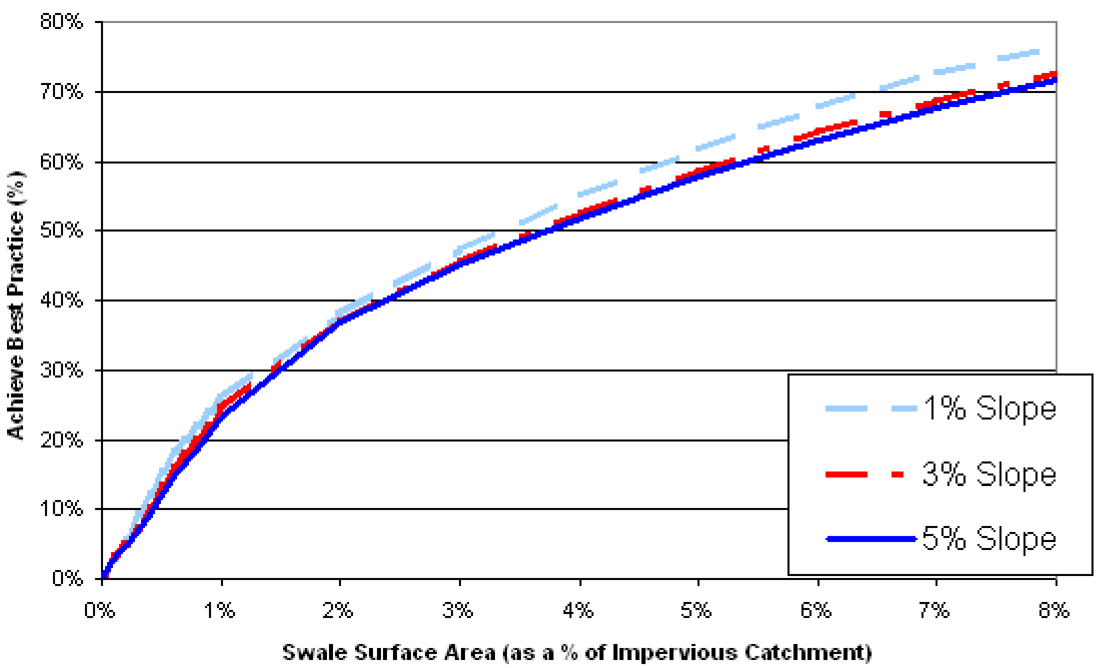


**Figure 6. Modeled total nitrogen removal of varying swale slopes and surface area (Melbourne Water, 2008).**

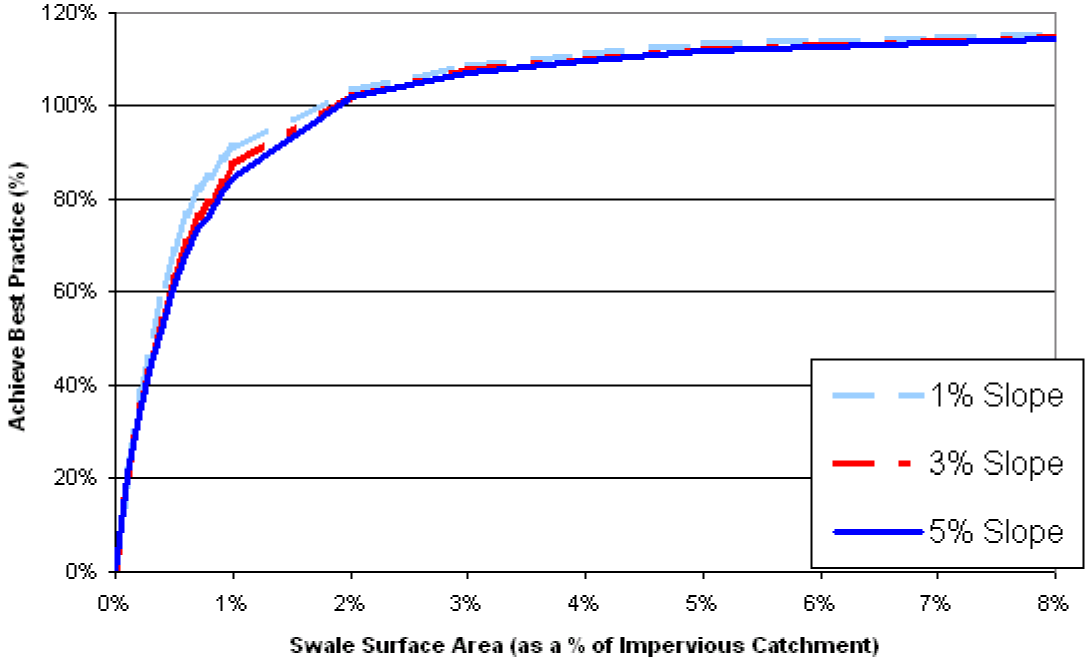


**Figure 7. Modeled total suspended solids removal of varying swale slopes and surface area (Melbourne Water, 2008).**

## Case Studies

### Swales for Stormwater Pollution Control in Northern Sweden

Swedish researchers used existing grassed swales to determine the pollutant reduction capabilities of swales from snow and snowmelt water sources (Backstrom, 2003). The pollutants measured were suspended solids, particulates, and total and dissolved metals (Table 1). Grassed swales proved to even out both peak flows from urban stormwater runoff as well as peak pollutant loading. During high flows and high pollutant rates, grassed swales did very well in reducing the amount of pollutants in water flowing out of the swale area. This was primarily due to sedimentation of particulate matter. However, the research also showed that during low flow rainfall events pollutants may be released rather than retained in grassed swale areas. This is likely a result of the inability of vegetation and soil to permanently sequester pollutants with the possible transfer to of dissolved constituents to ground water. Due to their limitations, grassed swales should be considered as primary treatment devices and should be used in combination with other treatment practices.

**Table 1. pH, suspended solids (SS), and heavy metal concentrations in snow and melt water in three roadside swales in Lulea (March–April 2000).**

| | | | | Total | | | Dissolved | | |
|---|---|---|---|---|---|---|---|---|---|
| | | pH | SS (mg/l) | Cu (μg/l) | Pb (μg/l) | Zn (μg/l) | Cu (μg/l) | Pb (μg/l) | Zn (μg/l) |
| Site A Bodenv. | Snow | 6.91 | 1,800 | 214 | 212 | 525 | 4.78 | 0.177 | 13.6 |
| 2000–03–29 | Melt water | 6.89 | 13 | 15.3 | 2.44 | 33.4 | 7.00 | 0.105 | 18.0 |
| | Reduction | – | 99% | 93% | 99% | 94% | –46% | 41% | –32% |
| Site B Hertsöv. | Snow | 6.69 | 1,000 | 83.7 | 55.9 | 275 | 1.43 | 0.137 | 13.5 |
| 2000–04–10 | Melt water | 6.70 | 12 | 5.00 | 1.93 | 60.5 | 1.84 | 0.097 | 56.7 |
| | Reduction | – | 99% | 94% | 97% | 78% | –29% | 29% | –320% |
| Site C Lulsundet | Snow | 6.99 | 5,400 | 520 | 189 | 1240 | 2.00 | 0.143 | 6.37 |
| 2000–04–10 | Melt water | 7.03 | 240 | 21.9 | 7.43 | 72.8 | 3.28 | 0.090 | 16.0 |
| | Reduction | – | 96% | 96% | 96% | 94% | –64% | 37% | –151% |

## BMP Developments in Scotland

The purpose of this study was to assess which wet-weather BMPs were most common already and which would be the most useful when planning future urban development (Scholz, 2007). The counties in which wet-weather BMPs were tested were Edinburgh and Glasgow, Scotland; 182 sites were identified and evaluated for their management effectiveness across these two counties. The results from this study were that the most common BMPs are ponds used in conjunction with permeable pavements. The indication of this study is that the combinations of ponds combined with shallow swales are the most effective BMPs for wet-weather technology implementation.

## Buffer Strip Development in the US

The Roadside Vegetated Treatment Sites Study was a two-year water-quality monitoring project undertaken to evaluate the removal of stormwater contaminants by existing vegetated slopes adjacent to freeways (Barrett *et al.*, 2004). The objectives of this study were to determine if standard roadway design requirements result in biofilter strips with treatment equivalent to those specifically engineered for water quality performance, and to generate design criteria. Variables such as width, slope, vegetation density, and hydraulic loading were evaluated by studying the runoff through existing vegetated slopes at four locations in northern California and four locations in southern California.

At each location, concrete channels, approximately 90 ft long, were constructed to capture freeway runoff after it passed through existing vegetated strips of varying widths. The quantity and quality of the runoff discharged from the buffer strip was compared to freeway runoff collected at the edge of pavement. The study found that buffer strips consistently reduced the concentration of suspended solids and total metals in stormwater runoff. The strips were generally less effective at removing dissolved metals and essentially no change in concentration was observed for nitrogen and phosphorus. Concentrations of organic carbon, dissolved solids, and hardness were observed to increase. For the constituents exhibiting a decrease in concentration, steady state levels were generally achieved within 15 ft of the pavement edge for slopes commonly found on highway shoulders and when the vegetation coverage exceeded 80%. Slope, vegetation type and height, highway width, and hydraulic residence time had little or no impact on the final concentrations.

## Summary of Grassed Swale Research in the US

### *Alabama Highway Drainage Conservation Design Practices—Particulate Transport in Grass Swales and Grass Filters*

The objective of this project was to demonstrate how a common Alabama Department of Transportation design and maintenance practice—the use of grass drainage swales—can help meet the requirements of the EPA's new Phase II Stormwater Regulations (Nara and Pitt, 2005). As part of the study, 69 sediment samples were collected at an outdoor grass swale located adjacent to Tuscaloosa City Hall, Alabama, during 13 storm events from August to December 2004. The samples were analyzed for turbidity, total solids, total suspended solids, total dissolved solids and particle size distributions. The total suspended solids concentrations observed during different rain events showed significant sediment reductions as a function of the length of the swale. The particle size distributions of the suspended solids at the swale showed preferential transport of small particles for all lengths of the swale and preferential trapping of large particles.

### *California - BMP Retrofit Pilot Program: Final Report*

Litigation between Caltrans and the Natural Resources Defense Council, Santa Monica BayKeeper, the San Diego BayKeeper, and the U.S. Environmental Protection Agency resulted in a requirement that Caltrans develop a Best Management Practice (BMP) Retrofit Pilot Program in Caltrans Districts 7 (Los Angeles) and 11 (San Diego) (CALTRANS, 2004). The objective of this program was to acquire experience in the installation and operation of a wide range of structural BMPs for treating stormwater runoff from existing Caltrans facilities and to evaluate the performance and costs of these devices. Each BMP was designed, constructed and maintained at what was state-of-the-art at the time the project began (in 1997).

Biofiltration swales and biofiltration strips were among the BMP types included in the study. These practices are considered technically feasible depending on-site-specific considerations. Overall, the reduction of concentration and load of the constituents monitored was comparable to the results reported in other studies, except for nutrients. Nutrient removal was compromised by the natural leaching of phosphorus from the salt grass vegetation used in the pilot study. This condition was not known at the start of the project but was discovered later in the program.

Biofiltration swales and strips were among the least expensive devices evaluated in this study and were among the best performers in reducing sediment and heavy metals in runoff. Removal of phosphorus was less than that reported by another study but may be related to leaching of nutrients from the salt grass during its dormant season. The swales are easily sited along highways and within portions of maintenance stations, and do not require specialized maintenance. In addition, the test sites were similar in many ways to the vegetated shoulders and conveyance channels common along highways in many areas of the state. Consequently, these areas, which were not designed as treatment devices, could be expected to offer water quality benefit comparable to the engineered sites. More research is needed to investigate this possibility.

### *Maryland - Grassed Swale Pollutant Removal Project*

In Maryland, grassed swales are routinely incorporated into highway medians and right-of-way as an aesthetically pleasing method for conveying highway runoff (MDOT, 2005). This project evaluated the performance of grassed swales as a stormwater management technology that can remove surface runoff contamination through sedimentation, filtration by the grass blades, infiltration to the soil, and some likely biological processes. Three storm events were monitored to evaluate pollutant removal effects of two grassed swales receiving highway runoff, and of the pollutant removal efficiencies of grassed swales. The researchers observed significantly reduced concentrations of many pollutants.

Results confirm the positive event mean concentration (EMC) removal (35 to 84%) of most pollutants of interest, including total suspended solids, nitrate, nitrite, total Kjeldahl nitrogen, copper, lead and zinc. The EMC was calculated by combining the flow and concentration data for a total pollutant mass. However, the swales demonstrated some export of phosphorus and chloride. Export of phosphorus in a natural system like a grassed swale is understandable because this element is present in all organic material.

***Minnesota - Improving the Design of Roadside Ditches to Decrease Transportation-Related Surface Water Pollution***

This project involved a field monitoring program that began in spring 2000 to test the ability of a grassy roadside swale to remove pollutants in stormwater (Biesboer and Elfering, 2003). A check dam was designed and installed into the vegetative swale. The check dam system incorporated some unique design features, including a peat filter to trap nutrients and metals and a low rock pool to trap water for the settling of suspended solids and for biological processing. The check dam was cost-effective and simple to install. The system was quantified and evaluated hydrologically and qualitatively before and after the check dam installation. Pollutants monitored included total suspended solids, total phosphorus, and orthophosphorus. The average pollutant removal rates for three storms were 54% for total phosphorus, 47% for orthophosphorus, and 52% for total suspended solids. Metals were also analyzed for two storm events, one before and one after installation of the check dam. Peat soil samples were analyzed for nutrients, organic content, water capacity, metals, and pH before and after check dam installation. The results suggest that properly designed short vegetative strips and swales can reduce pollutant levels from the stormwater that drains off roadways.

Further research is also needed to determine the efficiency of the check dam at removing large pollutant loadings similar to those exiting highly traveled roads. The pollutant loadings in this research were relatively small. Greater removal efficiency values may be realized with the addition of a series of check dams in longer roadside swales. Also, more research needs to be performed analyzing the check dam efficiency at reducing heavy metals.

***Texas - Use of Vegetative Controls for Treatment of Highway Runoff***

This study investigated the capability of two vegetative controls—grassed swales and vegetated buffer strips—to treat highway runoff (Walsh *et al.*, 1998). A grassed swale was constructed in an outdoor channel to investigate the impacts of swale length, water depth, and season of the year on pollutant removal efficiency, and two vegetated strips treating highway runoff in the Austin area were monitored to determine removal capabilities.

A grassed swale constructed in a steel channel removed over 50% of the suspended solids, zinc, and lead after 120 ft of swale treatment. COD (chemical oxygen demand) concentrations decreased 25 to 79% after 120 ft of treatment, while the reduction of nutrient concentrations varied from negative to 45%. In general, the majority of pollutant removal occurred in the first 60 ft of swale. Increasing the water depth and velocity of surface flow of runoff in the swale reduced the removal efficiency of the swale. More suspended solids were removed in the channel swale in the growing season than in the dormant season. During the growing season, new grass stood alongside dormant grass that increased the grass blade density in the swale. This increase in removal is attributed to the combined filtering capacity of the dead material and live grasses. The removal of nutrients and organic material may decline in the growing season, when decay of vegetation from the previous season contributes to the constituents in the runoff. The concentrations of constituents in runoff that had percolated through the soil in the swale were generally lower than the concentrations in surface runoff after 120 ft of treatment by the swale. However, the impact of swales on ground-water quality in the field will vary with thickness of soil to ground water, permeability of the soil, and the constituents in the highway runoff.

***Texas - Evaluation of the Performance of Permanent Runoff Controls: Summary and Conclusions***
This study found that pollutants in runoff from highways may produce adverse impacts in receiving waters under some conditions (CRWR, 2007). The Edwards Aquifer is particularly vulnerable to this type of nonpoint source pollution and concern about the potential impact on the aquifer has led to the construction of stormwater controls on highways in the Austin area. This study was designed to help the Texas Department of Transportation (DOT) identify the types of runoff control systems that are most applicable for highways in this area. The study investigated the capability of vegetative controls (grassed swales and vegetated buffer strips) and sedimentation/filtration systems for treating stormwater runoff.

For conclusions and recommendations for the study, data from channel swales indicated:

- Removal of total suspended solids, chemical oxygen demand, total phosphorus, total Kjeldahl nitrogen, zinc and iron was highly correlated with swale length. No trend was observed for nitrate.

- Most of the reduction in the concentration of constituents in runoff occurred in the first 60 ft of the swale. Little improvement in water quality was observed during the last 60 ft.

- The removal efficiency for suspended solids, organic material and most metals decreased with increased water depth. No relationship between water depth and removal efficiency was observed for nitrate and total Kjeldahl nitrogen.

- The removal efficiency of the grassed swale was about the same during the dormant and growing season for all constituents except for total suspended solids. Total suspended solids experienced the highest removal during the growing season, when there is a combination of new grass and remaining dormant grass.

- Percolation of runoff through layers of soil and gravel into the underdrain reduced concentrations of all constituents except nitrate.

- Excellent pollutant removal occurred in the channel swale when the hydraulic residence time was approximately nine minutes. The removal was similar to that of a site monitored in Seattle that had about the same residence time, but differed in other aspects. Hydraulic residence time appears to be an appropriate design criterion for grassed swales.

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## Section 6: Rooftop Greening

Green roofs provide myriad environmental benefits at an economical life-cycle cost. Since the discovery of their varied uses and contribution to environmental quality over 40 years ago, they have been utilized first by European nations, later by the US, Japan, and other nations (Figure 8). Although most of the advances in technology and public policy regarding green roofs have occurred in Germany, they have served as a case study and catalyst for the rest of Europe and the world to follow. In Melbourne, Australia around 90% of its central business district consists of green rooftops (Melbourne Water, 2008). With this opportunity for water sensitive project developments, Australia has become a leader in the use of WSUD strategies. One such project involved the use of a rooftop garden to contain stormwater and use it for toilet flushing (see Case Studies).

The UK has seen an increased interest in green roofs in the past decade, even though it remains without incentives, standards, or policies to propagate the use of green roof technology. This could be due to misinformation and myths that still surround green roofs. Many developers mistakenly see green roofs as an obstacle, given the myth that vegetated roofs cause structural problems. There is a preference among professionals in the UK to use pitched roofs instead of flat ones; this gives concerns that green roofs are more liable to leak than traditional roofs. Green roofs will actually introduce a number of measures that protect the roofs from degradation. These include waterproofing systems and protection against ultraviolet light, frost, erosion, and other forms of weathering. Urban regeneration schemes have brought a renewed focus on getting green roofs installed in UK cities. Government incentives and a strong regulatory framework are needed for green roof technology to really gain ground in any country.

In 1997 the Swiss undertook green roofing research as it relates to biodiversity. The concerns in Switzerland came from the development of brownfield land in urban settings; land which is important habitat for a number of scarce beetles and spiders. The following design principles were arrived at in regards to green roofs and biodiversity:

- The use of local substrates as growing mediums on green roofs helped replicate the conditions at ground level.

- Varying the depth of the substrate provided microhabitats for rare spiders and beetles associated with brownfields in the city.

- Planting with a local seed mix.

- The placing of objects associated with natural habitats such as dead wood and old branches increased the biodiversity of the roofs.

The goal of biodiversity with the installation of green roofs gave way to the coining of the term “brown roof” by the same Swiss researchers. Brown roof refers to a green roof that has certain specifications deliberately added to ensure biodiversity for development in brownfield areas. Designing roofs to be suitable habitat for specific indigenous species is just another adaptation of the flexibility of this technology for urban landscapes.

The US has benefitted from the efforts of the US Green Building Council (USGBC), which has been at the forefront of environmental design. The Council has introduced a new way to certify (and therefore publicly endorse) buildings that have the initiative to use green building techniques, green roofs being a big part of it. This certification is called Leadership in Energy and Environmental Design (LEED). This program creates levels of certification that gives people incentive to think and build green (USGBC, 2008).

**Figure 8. A terraced roof garden building in Fukuoka City, Japan (MetaEfficient, 2008).**

## Green Roof Benefits

### Water Quality

The hard, impervious surfaces that cover urban landscapes have made stormwater control an important issue to both conservationists and municipal sewer districts. During storm events wastewater and stormwater flows spike from the inability of sidewalks, buildings, and roads to control and slow the release of rainfall runoff. Green roofs reduce this runoff and store the water temporarily to release it slowly over time. The burden that storm events have on wastewater treatment plants is also mitigated by green roofs. The occurrences of CSO and SSO events declines in correlation to the percentage of green roof cover a city has. Green roofs return moisture into the atmosphere by evapotranspiration, and unlike other land intensive stormwater control technologies, green roofs use existing roof space. Depending on substrate depth, green roofs can retain 25 to 100% of rainfall (Beattie and Berghage, 2004), and reduce total building runoff by 60 to 79% (Köhler *et al.*, 2002).

### Thermal Insulation

Green roofs are an effective way to regulate energy flow in a building. The primary ways in which vegetation provides an insulating effect are weather dependent (Porsche, 2003). The first way is by heat transfer and the way in which vegetation works to prevent energy losses in the summer from air conditioning. The cavities in the soil and the absorption of heat by the plants, as well as the water retention by the soil provide excellent insulation in hot weather. Of course depending on the size of the building and the type of green roof application (extensive, intensive, strata depth, etc.) the savings in energy will change with respect to these variables. Environment Canada used a Micro Axess Simulation model to assess the energy saving in a typical one-story building with a grass roof and 3.9 in. of growing medium. The model found that this type of installation would have a 25% reduction in summer cooling needs (The Cardinal Group, 2003). The sod layer on a green roof with its rough surface as opposed to smooth tar roof also decreases convection losses.

## Urban Heat Island

The effects of urban heat islands have been widely documented. Replacing vegetation with dark, impervious surfaces has led to temperature increases between 2 to 10˚F in urban areas in contrast to surrounding rural areas. This effect impacts city dwellers by increasing energy costs (e.g., cost for air conditioning), air pollution levels, and heat-related illness and mortality. This effect is especially significant at night, when dark surfaces, absorbing heat from the sun during the day, radiate that heat into the air at night. The surface temperature of a traditional rooftop can be up to 90˚F hotter than a vegetated roof (EPA, 2008). A regional simulation model showed that a total of 50% green roof coverage distributed throughout Toronto would reduce temperatures by as much as 2˚C (Bass *et al.*, 2002).

## Biodiversity

In addition to the advantages green roofs have in protecting important native species as described earlier, these roofs are used by nesting and native birds, insects, spiders, beetles, plants, and lichens which have all been found on green roofs. For the human city dwellers, the benefits are seen in the relaxation, aesthetics, and stress-reduction effects that green roofs provide.

## Cost

Developers are driven by the market forces of both lowering overhead costs to build and consumer demand. With greater consumer demand for urban roof gardens, more developers will have to make it a standard practice wherever green roofs are applicable. They can be fitted for new buildings and retrofitting for old buildings. In Europe, green roofs have had the attention of public policy makers for decades, making them much more affordable now compared to the US green roof industry, which is just getting off the ground. In Europe, a green roof will cost approximately $4/ft$^2$ to 13/ft$^2$, whereas in the US it can cost upwards of $10/ft$^2$ to $25/ft$^2$ (depending on the type of roof chosen). In general a green roof will have an initial cost roughly three times higher than a traditional low-priced prefabricated or welded roof (Porsche, 2003). The trick, as with many emerging environmental technologies and renewable energies, is to look past initial cost to what is now driving city planners and public policy makers across international borders; the long-term sustainability of a green roof infrastructure. Lower priced traditional roofs often need replacement or significant repair every 15 years. Green roofs, however, will survive thirty years or more. Table 2 explores the life-cycle costs of green roofs in Germany over a typical 90-year building lifecycle for green roofs (Porsche, 2003).

**Table 2. Life-cycle costs of different types of roofs in Germany.**

| Type of Roof | Construction costs in $/m² | Repairs (interval in years) | Renovation after... years (average) | Renovations costs during life span ($) | Reconstruction RC /Disposal and recycling – costs: RECY * | Sum ($/m²) |
|---|---|---|---|---|---|---|
| Bitumen roof | 40 | Every ten years | After 15 years | 6 x 40 = 240 | 20 RC, 20 RECY | 320 |
| Gravel roof | 50 | Every 15 years | After 15 – 20 years. | About 200 | 25 RC, 25 RECY | 295 |
| Extensive green roof without PVC-products | 90 | - | Temporally only occasional renovation work | 40 | 40 RC, RE -.- | 170 |
| Extensive green roof with PVC products | 85 | - | Temporally only occasional renovation work | 40 | 40 RC, 20 RECY | 185 |
| Intensive green roof without PVC-Products | 380 | - | Temporally only occasional renovation work | At last in maximum up to 380 (the same cost as the building costs during the whole lifespan) | 100 RC, RECY -,- | 860 |
| Intensive green roof with PVC-products | 340 | - | Temporally only occasional renovation work | 340 | 100 RC, 40 RECY | 820 |

As mentioned previously there is a substantial practical gain in utilizing green roofs as thermal insulators. Green roofs also provide an economic gain as well. With energy prices what they are today, cutting cooling costs in the summer up to 25% would contribute to vast cost savings over both the short and long term.

## Case Studies

### Runoff Detention Effect of a Sedum Green Roof

This study was conducted at Lund University in Sweden by the Department of Water Resources Engineering (Villareal, 2007). A green roof plot was constructed to test the infiltration and peak attenuation rate of a sedum species of plant as the media for the green roof plot. The experiments were made in comparison to a traditional impervious roof as the control. The end result, as seen in the hydrographs in Figure 9, is that the green roof had a higher detention rate and lower peak flow for wet-weather events. The volume reduction observed for the green roof was up to 65% for some storms. A typical cross-section can be seen in Figure 10.

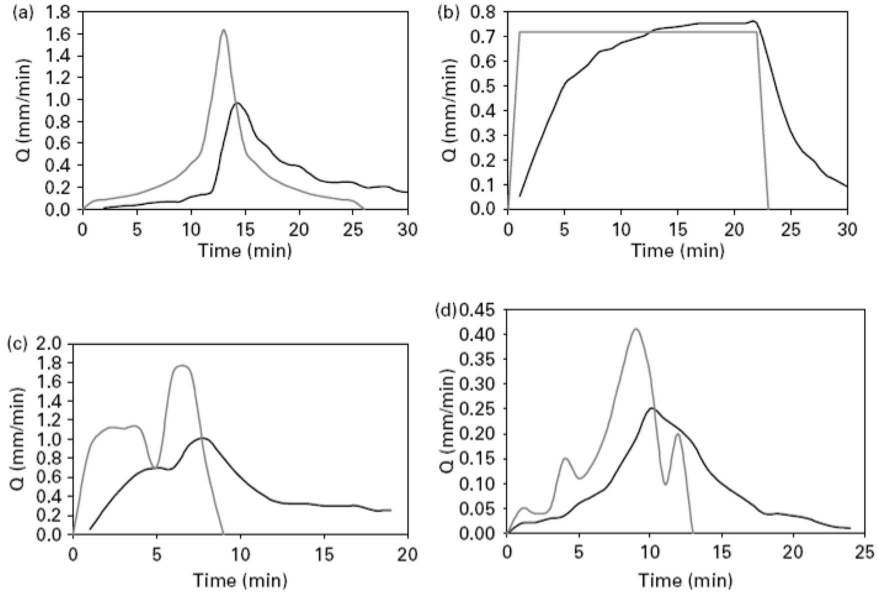



**Figure 9. Inflow and outflow hydrographs for a sedum green roof and traditional roof. Green roof (black line) and traditional roof (grey line) runoff for (a) two-year average (b) "test" rainfall of 0.8 mm/min for 22 min (c) rainfall event on August 2, 2002, (d) rainfall event, July 22, 2001.**

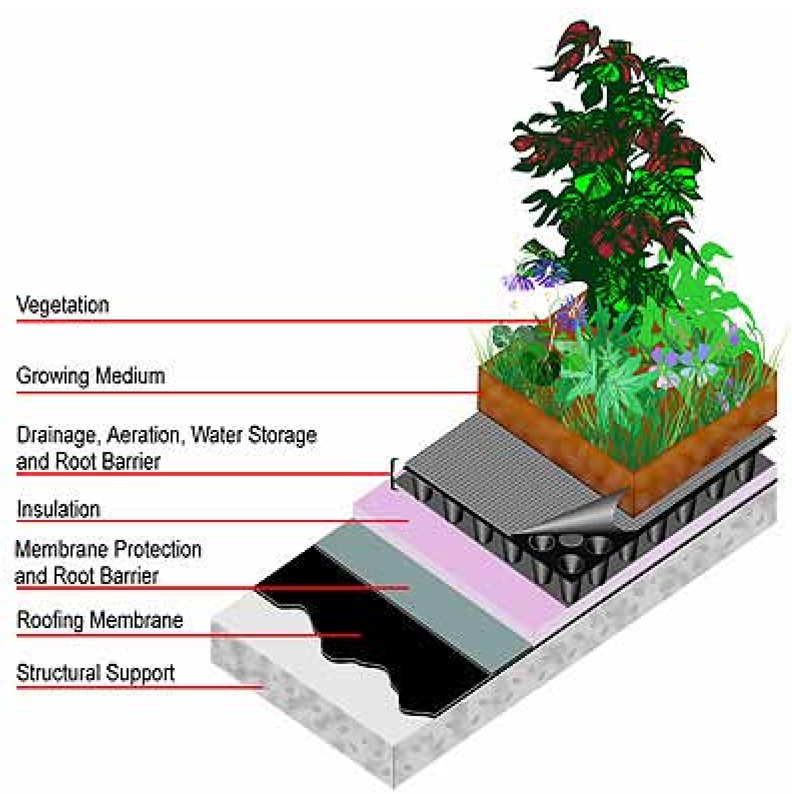



**Figure 10. Typical cross-sectional layout of a green roof.**

## Toronto Green Roof Study

Research was completed to provide technical data on the performance of green roofs in the City of Toronto to illustrate their benefits in an urban context (Liu and Minor, 2005). Two extensive green roof systems were installed on a community center in Toronto. Both systems contained the same components but differed in materials and designs (Figure 11). Green Roof System G consisted of a composite semi-rigid polymeric drainage and filter mat and a root-anchoring mat. It had 100 mm of lightweight growing medium containing small light-colored granules. Green Roof System S consisted of expanded polystyrene drainage panels and a geotextile filter fabric. It had 75 mm of lightweight, dark-colored growing medium containing porous ceramic granules. The green roofs, and a reference roof, were instrumented to provide thermal performance at the underlying impermeable membrane (moisture barrier) and energy efficiency data, as well as runoff measurements. Although the vegetation was not well established in the first year of monitoring, the extensive green roofs reduced the building's energy demand by lowering the heat flow through the roof, especially in the summer (Figure 12). The green roofs were shown to be effective in delaying and reducing stormwater runoff. The ability of roofs to retain volume depended upon the characteristics of the rain event (intensity and amount) and the wetting history of the growing medium. Preliminary observations and membrane temperatures recorded also suggested that green roofs could likely improve membrane durability by reducing heat aging, thermal stresses, ultra-violet radiation and physical damage.

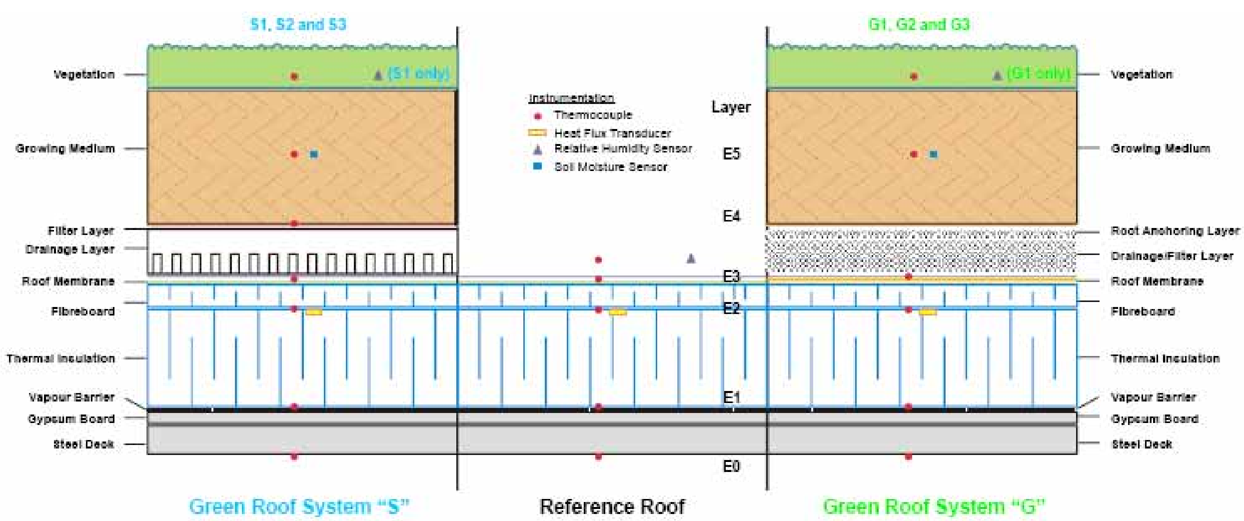



**Figure 11. Schematics showing components and the sensor locations in the roofing systems (Liu and Minor, 2005).**

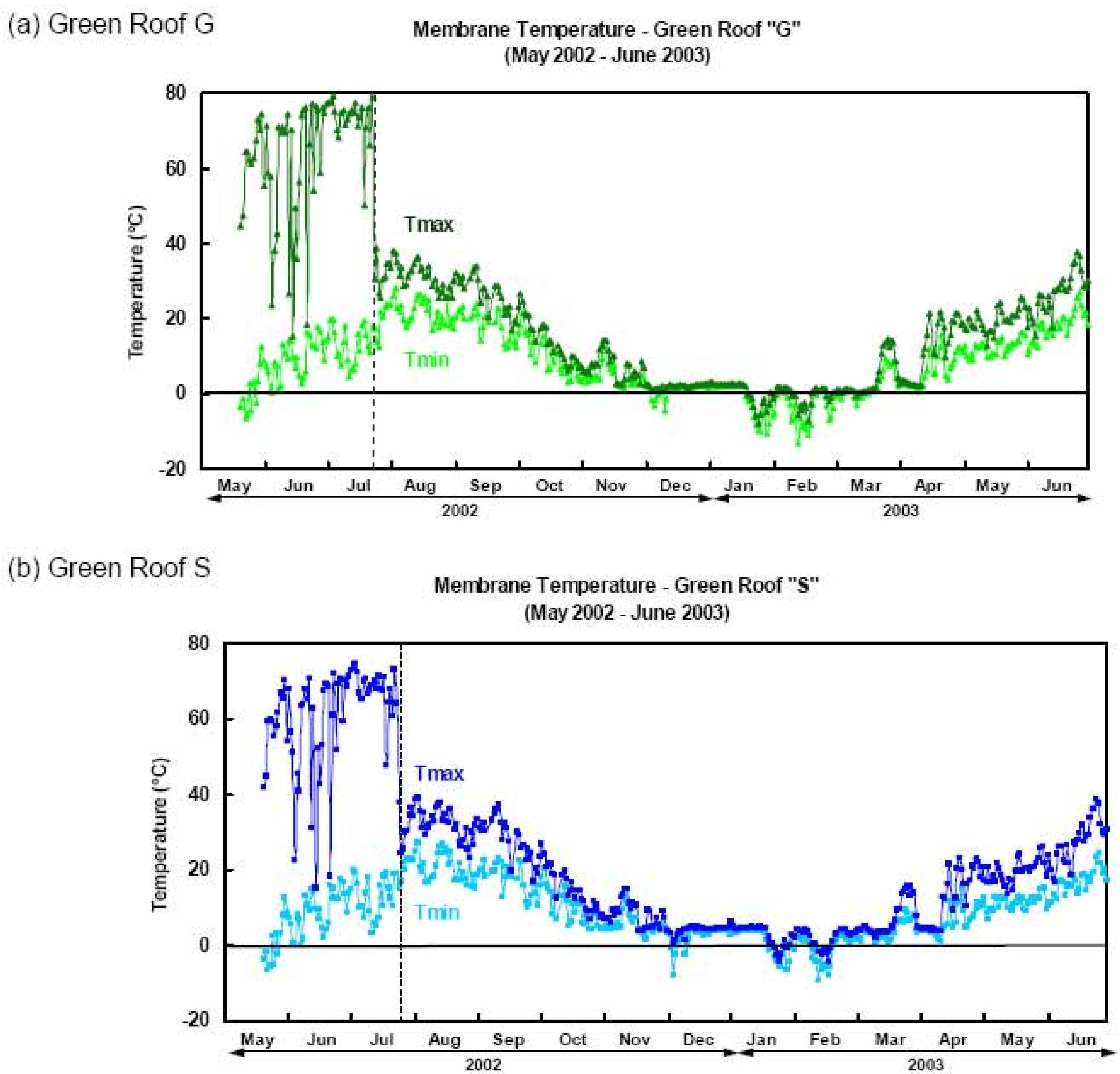



**Figure 12. Daily maximum (dark) and minimum (light) membrane temperatures on the green roofs.**

## A Review of 18 Green Roof Studies

Researchers analyzed the data that was reported in 18 different green roof publications (Mentens *et al.*, 2006). They obtained rainfall-runoff relationships for an annual and seasonal time scale from the analysis of the available 628 data records. They derived empirical models that allowed them to assess the surface runoff from various types of roofs, when roof characteristics and the annual or seasonal precipitation were given. Their analysis showed that the annual rainfall-runoff relationship for green roofs was strongly determined by the depth of the substrate layer (Figure 13 and Table 3). The retention of rainwater on green roofs was lower in winter than in summer.

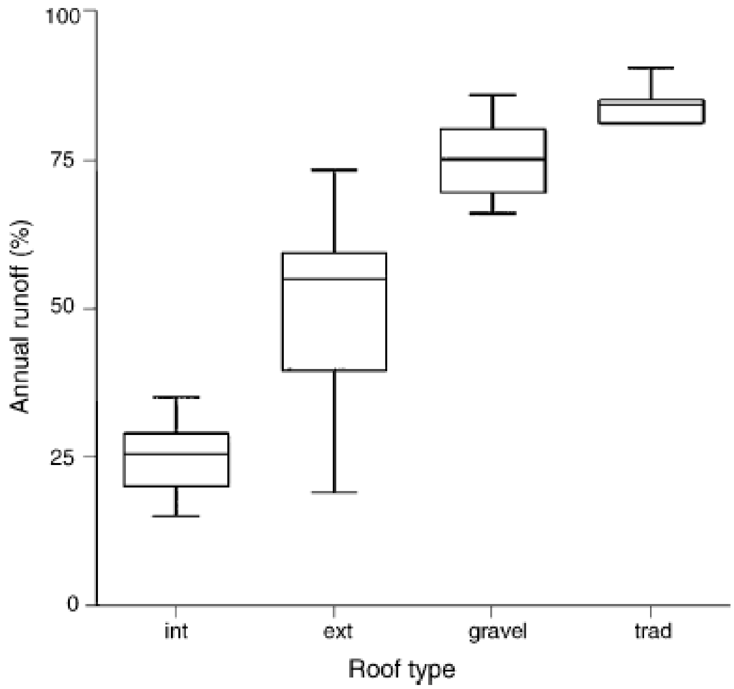



**Figure 13. Annual runoff of intensive green (int), extensive green (ext), gravel-covered (gravel) and traditional (trad) roofs as a percentage of the total annual rainfall. Data range (whiskers), 25% and 75% percentiles (box boundaries), and the median (line within box) are reported.**

**Table 3. Comparison of Substrate layer depth and percent runoff of intensive green (int), extensive green (ext), gravel-covered (gravel) and traditional (trad) roofs.**

| | Intensive green roof ($n = 11$) | Extensive green roof ($n = 121$) | Gravel-covered roof ($n = 8$) | Non-greened roof ($n = 5$) |
|---|---|---|---|---|
| Substrate layer Depth (mm) | | | | |
| Minimum | 150 | 30 | 50 | / |
| Maximum | 350 | 140 | 50 | / |
| Median | 150 | 100 | 50 | / |
| Average | 210 | 100 | 50 | / |
| Runoff (%) | | | | |
| Minimum | 15 | 19 | 68 | 62 |
| Maximum | 35 | 73 | 86 | 91 |
| Median | 25 | 55 | 75 | 85 |
| Average | 25 | 50 | 76 | 81 |

## Green Roofs in Sweden

An experimental station in Augustenborg, Sweden, was chosen as a site to test the hydrologic function of an extensive green roof (Bengtsson *et al.*, 2005). The site was chosen because of the strain on the area's combined sewer systems and frequent flooding. The study found that during a short storm, runoff in excess of field capacity is temporarily stored in soil and roof vegetation reducing and delaying peak flow (Figure 14). The maximum storage capacity for the thin, extensive green roof was found to be 9 to 10 mm.

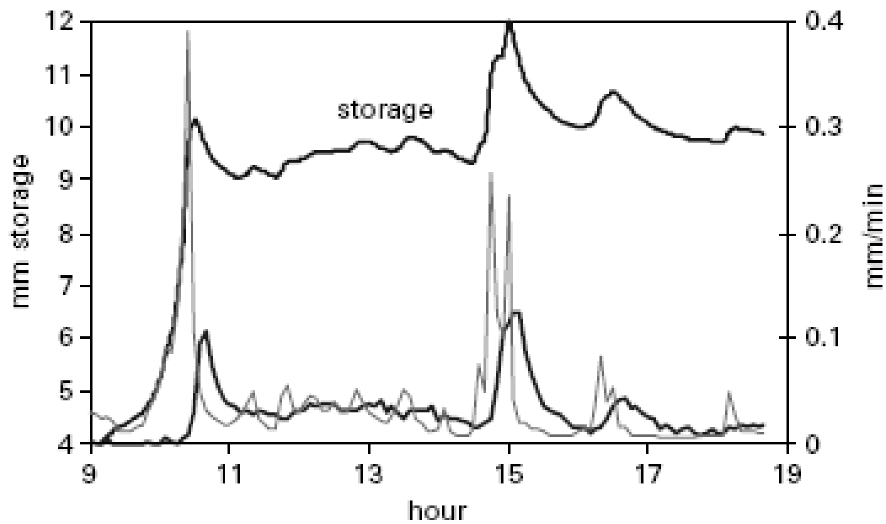


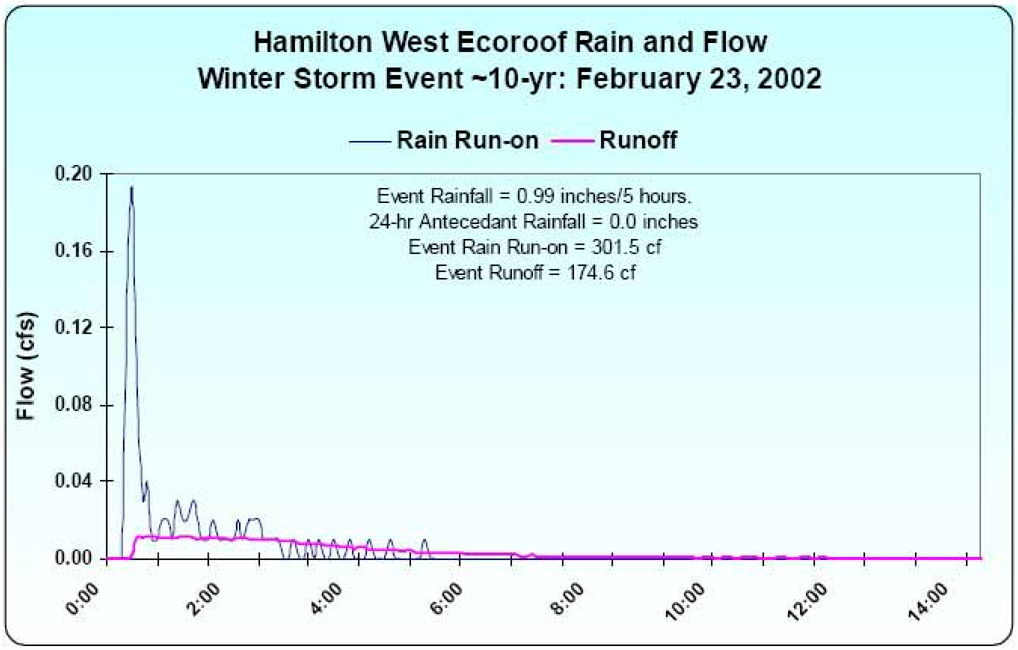

**Figure 14. Rain (dark line) and runoff (grey line) and water storage on a thin green roof in Augustenborg, Sweden.**

## Green Roof Research and Solutions in Belgium

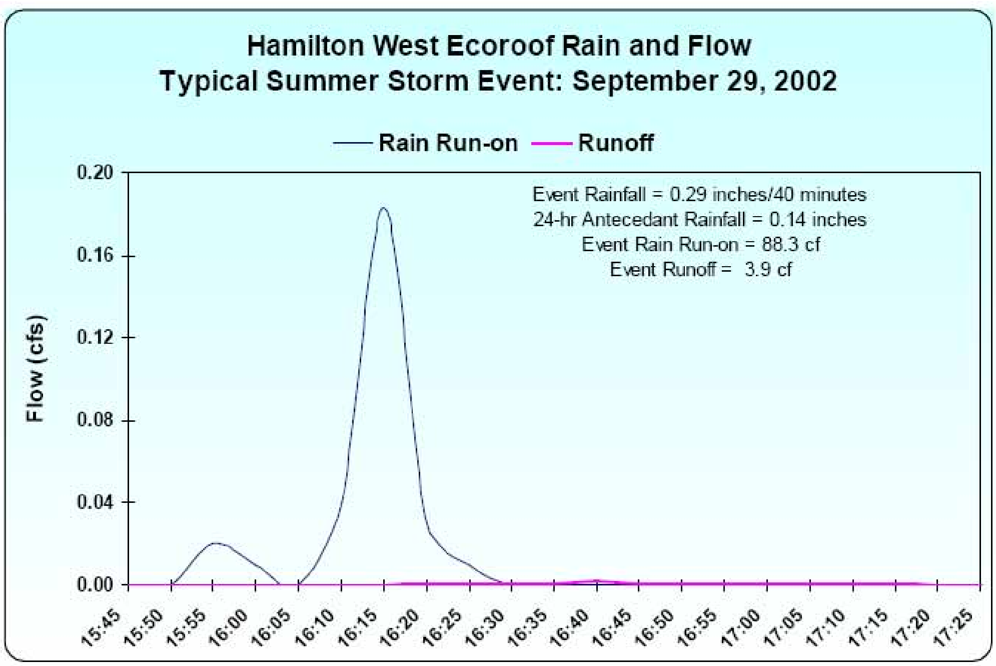
Using Brussels as an example, researchers ran a simulation to determine the effectiveness of green roofs in reducing rainfall runoff for an entire city (Mentens *et al.*, 2006). The results indicated that extensive green roof systems on 10% of the buildings would result in a reduction of 2.7% of annual runoff for the region, and 54% of annual runoff for individual buildings. This function is particularly important given that urbanization in developed countries is expected to have 83% of the population living in urban areas by 2030. The study came to the conclusion that green roofs are especially important tools because they do not take up "open space" on the ground to function. They also point out that using green roofs in conjunction with other infiltration technologies will have the impact needed to make cities sustainable into the future.

## Stormwater Monitoring of Two Ecoroofs in Portland, Oregon, US

When the City of Portland's Bureau of Environmental Services (BES) began considering ecoroofs for stormwater management, no applicable performance data could be located (Hutchinson *et al.*, 2003). To generate region-specific data, BES initiated a monitoring project of the Hamilton West apartment building vegetated with two different ecoroofs. More than two years of water quality monitoring and more than a year of flow monitoring have been measured. Precipitation retention has been calculated at 69% for the 4 to 5 in. ecoroof substrate section, and nearly all of the rainfall is absorbed during dry period storm events. Stormwater detention and peak intensity attenuation has also been impressive even when the roof was saturated during winter months (Figures 15 and 16). Some water quality benefits have proven more difficult to quantify, but important water quality lessons have been learned. In situations where a receiving water system may be sensitive to certain pollutants, substrate composition will be an important consideration in the ecoroof design. The researchers' work to date has proven that ecoroofs can be an effective urban stormwater management tool. Their next major endeavor will be to apply this information to system modeling efforts to determine hydrologic and hydraulic infrastructure and stream benefits that may be achieved. This information is also expected to assist bureau managers, planners, engineers and elected officials with policy decisions, such as zoning density bonuses, infrastructure designs, drainage fee discounts, and code compliance.

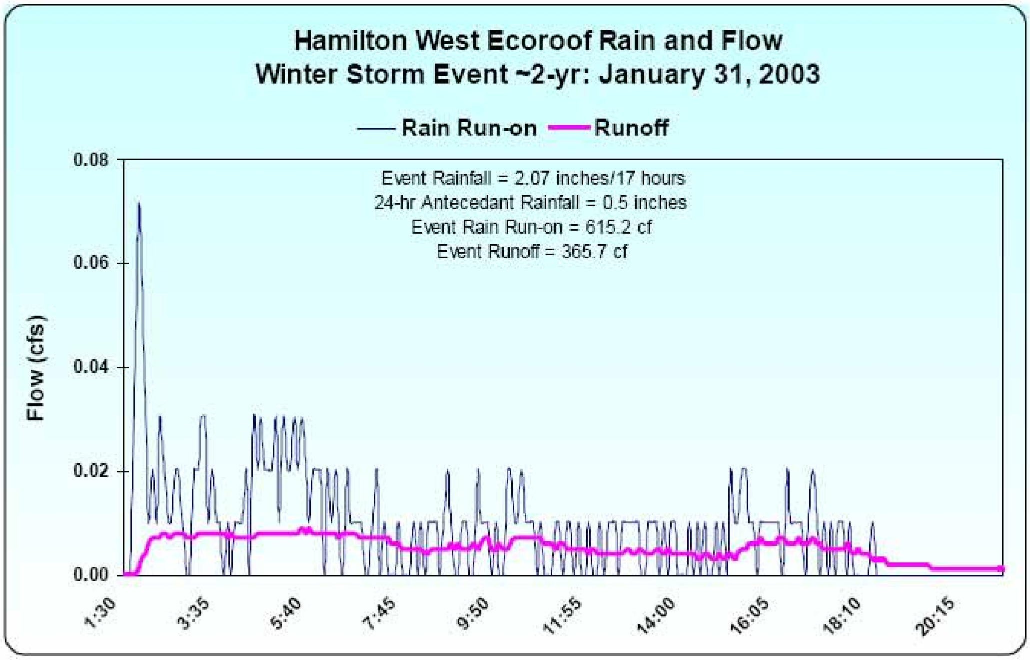



(a)

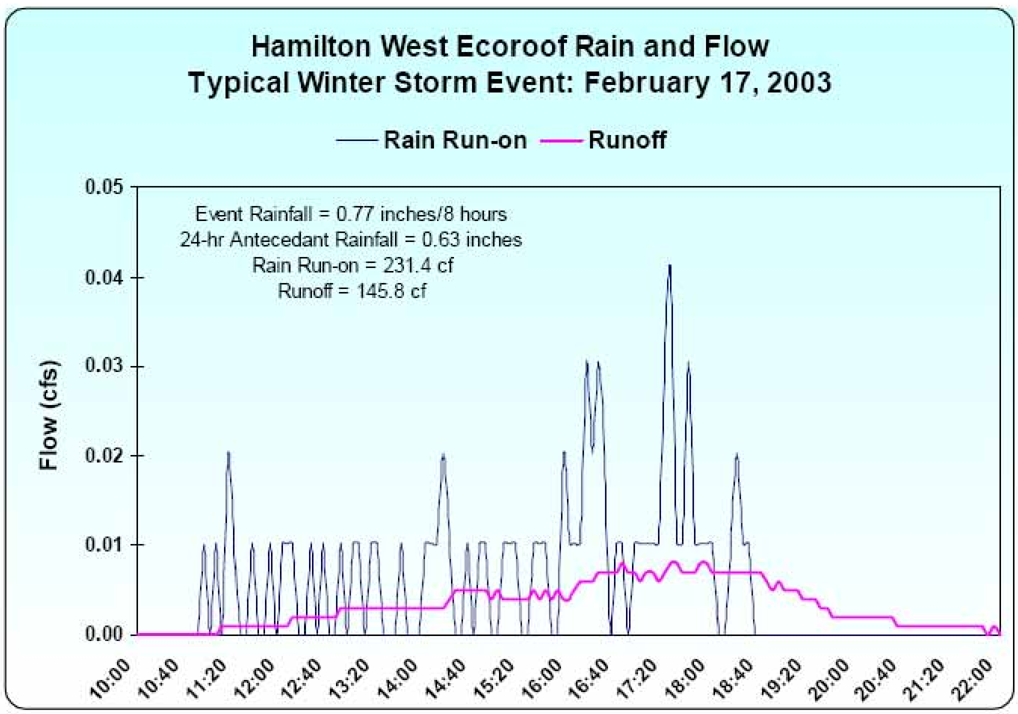



(b)

**Figure 15. Storm peak intensity attenuation for the Hamilton West Ecoroof: (a) high intensity, short duration winter storm; (b) high intensity, short duration summer storm (Hutchinson *et al.*, 2003).**




(c)




(d)

**Figure 16. Storm peak intensity attenuation for the Hamilton West Ecoroof: (c) low intensity, high volume winter storm; and (d) low intensity, low volume winter storm (Hutchinson *et al.*, 2003).**

## Performance of Two Green Roofs in North Carolina, US

Two green roofs were constructed and monitored in North Carolina's Neuse River Basin (Figure 17) (Moran *et al.*, 2006). The green roof at Wayne Community College (WCC) in Goldsboro was constructed in May 2002 and is approximately 750 $ft^2$. The original, flat rooftop of this storage building was divided into two equal halves for research purposes; one half remained unchanged and became the control for the experiment and the other half was transformed into the WCC green roof. The average soil media depth at this site is 3 in. Hydrodrain 300™ was used on the WCC roof; it has a non-woven filter fabric system incorporated into its design and has negligible storage.


**Figure 17. (a) WCC green roof in Goldsboro, NC (April 2003). (b) B&J green roof in Raleigh, NC (August 2004) (Moran *et al.*, 2006).**

The 1400 $ft^2$ green roof atop the Brown & Jones Architects, Inc (B&J) office in downtown Raleigh was constructed in February 2003 as a retrofit project. The rooftop was divided into two halves; one half restored as a control roof and the other half was constructed into a green roof. The green roof has a 7% slope and an average soil media depth of 4 in. Amergreen™ 50RS was used at the B&J green roof; this drainage material has a water storage capacity of 0.06 gal/$ft^2$.

The hydrologic and water quality performance of each green roof were investigated. Each green roof retained a significant proportion of the rainfall (Table 4 and Figure 18). Peak outflows were significantly reduced from the green roofs and each green roof had substantial delays in runoff (Figure 19). Runoff coefficients from the WCC green roof were calculated for storms at least 1.5 in. in size. The rational coefficient averaged 0.50 for ten storm events. Both the concentrations and amounts of total nitrogen and total phosphorus increased from rainfall to green roof outflow and from the control roof outflow to green roof outflow (Figure 20). It was determined that the soil media, composed of 15% compost, was leaching nitrogen and phosphorus into the green roof outflow. This field study demonstrated the importance of green roof media selection in locations where nutrients are a concern.

**Table 4. Summary of water retention and peak flow reduction for each research site**

| Green Roof Location | Total Rainfall | Total Rainfall Retained | Percent Retained | Average Peak Rainfall | Average Green Roof Runoff | Percent Reduction |
|---|---|---|---|---|---|---|
| **Goldsboro, NC** | 59.6 in. | 37.8 in. | 63% | 1.4 in./hr | .18 in./hr | 87% |
| **Raleigh, NC** | 12.4 in. | 6.8 in. | 55% | 1.7 in./hr | 0.75 in./hr | 57% |

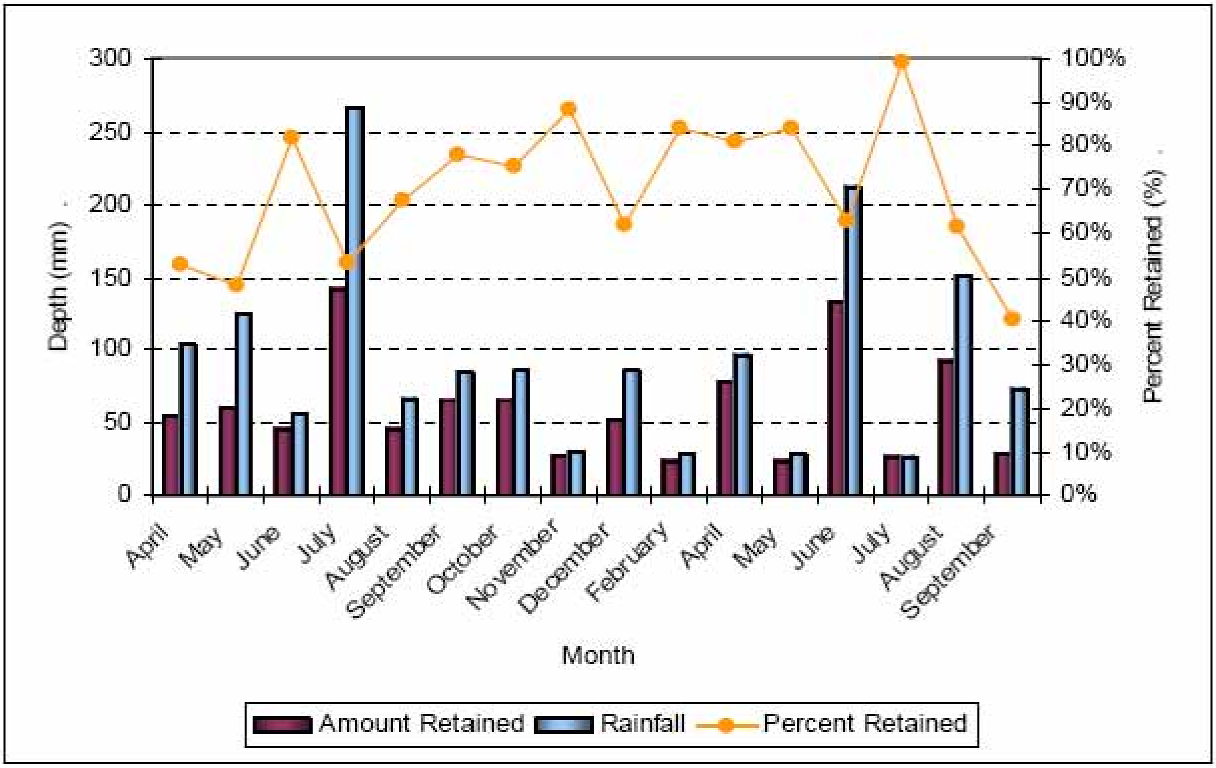



**Figure 18. Monthly retention rates of the WCC green roof from April 2003 to September 2004.**

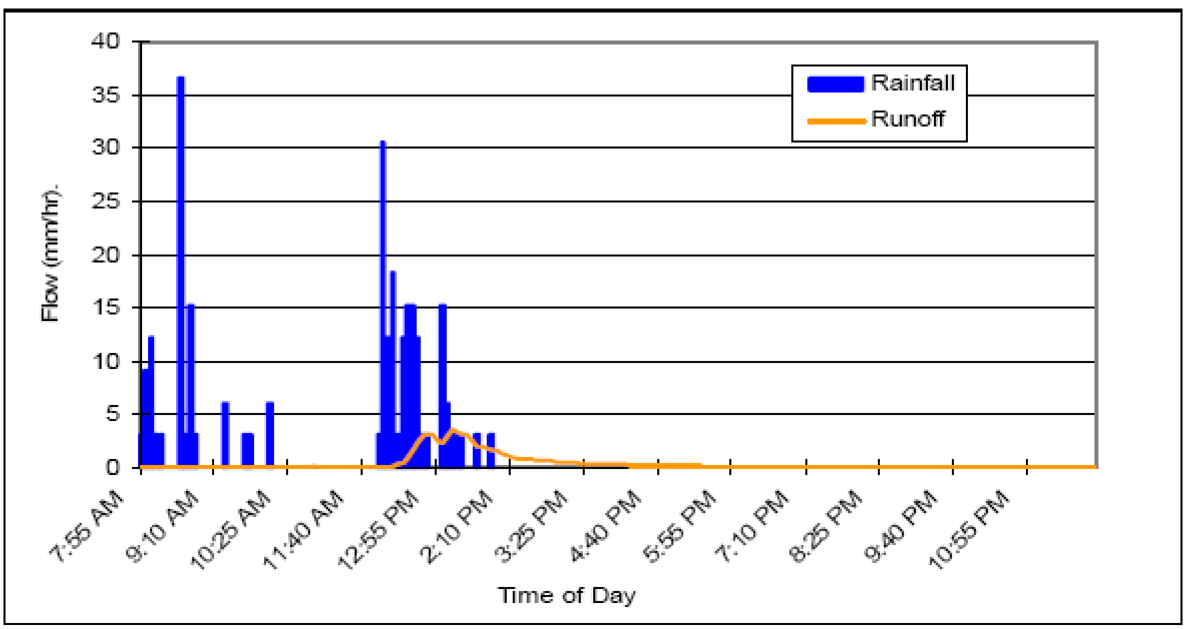
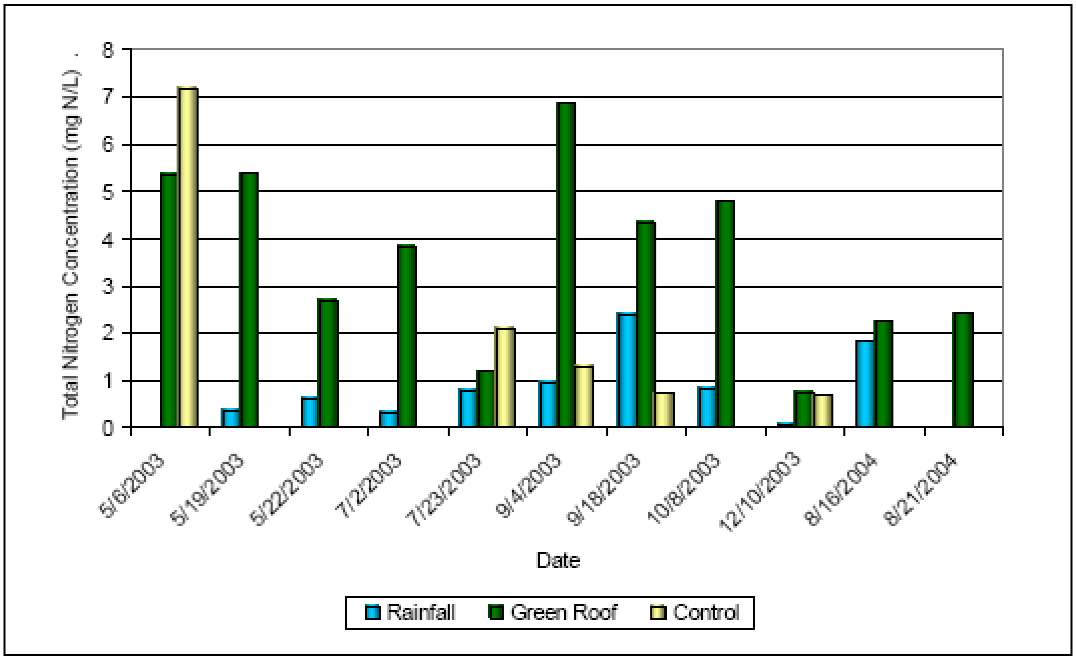



**Figure 19. Peak flow reduction of green roof runoff at WCC green roof on April 7, 2003.**



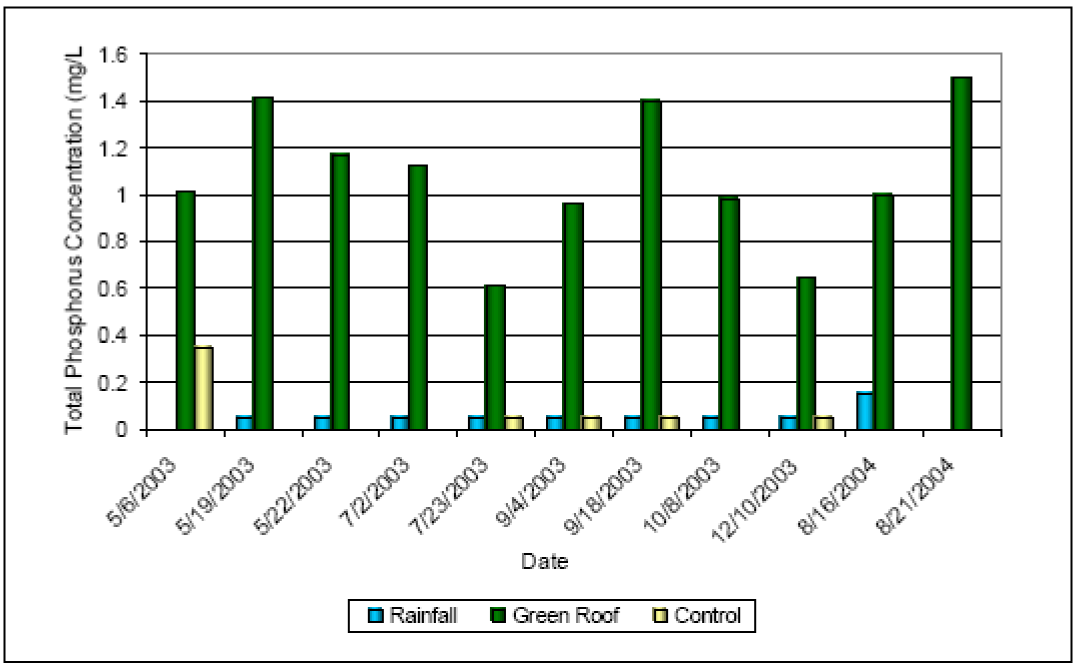




**Figure 20. Concentrations of total nitrogen (top) and total phosphorus (bottom) from April 2003 to September 2004 from WCC green roof runoff.**

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## Section 7: Porous Paving

Using existing infrastructure as much as possible while lowering maintenance costs are key components of watershed management. Using eco-paving, or porous pavement, instead of conventional impervious pavement allows for both benefits to coexist. Porous paving started being widely used as a flood mitigation technique in Europe during the early 1980s (Frederico, 2006). The needs of urban areas to plan effective water management systems comes out of the sprawling development that has characterized cityscapes around the world over the past few decades. More urban development means more impervious surfaces being laid down, such as ever-widening roads, sidewalks, roofs and parking lots. This means an ever-decreasing ability for natural rainfall to infiltrate back into the ground. Porous pavements are a method to help infiltrate storm runoff that fits well into urban landscapes (Figure 21). There is a wide range of permeable pavement types, each with its own benefits and drawbacks based on how the paved area will be used. No matter which type is utilized, they all can be expected to have the following benefits for urban ecology and wastewater management:

- Help decrease the frequency of CSO events
- Mitigate thermal pollution of neighboring sensitive waterways
- Provide water for groundwater recharge
- Control erosion of streambeds and riverbanks
- Facilitate pollutant removal
- Reduce imperviousness while maximizing land use
- Retain highway pollutants within the substructure of permeable pavements
- Improve aesthetics over conventional impervious pavements

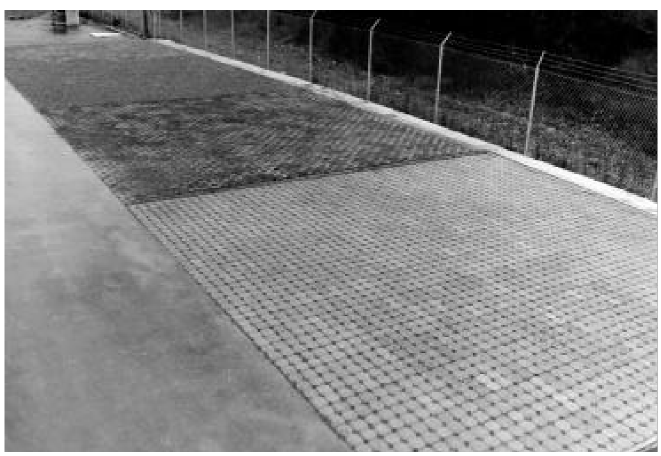

**Figure 21. Reinforced gravel (top left), reinforced grass pavement (middle), and 90% impervious blocks with gravel (U.S. Environmental Protection Agency, 2000).**

Although originally a method to control flooding, recent drought conditions in Australia have forced scientists and developers to use porous pavement in a different way. Using porous pavement in tandem with tanked systems can provide water-thirsty cities an option to reuse rainwater runoff instead of losing this resource (Figure 22). Outflow water from the tanked permeable pavements can be used for everything from gardening to flushing toilets (Federico, 2006).

**Figure 22. An example of a tanked permeable pavement system being built (Frederico, 2006).**

There are few studies showing the price competitiveness of permeable pavements and conventional pavements. Construction costs are relatively comparable with permeable pavements, but they have a somewhat higher initial cost. However, as with all sustainable infrastructure projects the cost savings will be measured with time. When the overall savings to stormwater infrastructure are considered, porous paving can be up to three times less expensive than traditional measures to manage the urban water cycle (Melbourne Water, 2008).

## Case Studies

### Review of the Performance of Permeable Pavers in Australia

In addition to the stormwater management benefits that controlling and slowing storm runoff provides; Rankin and Ball (2004) developed an experiment to see if permeable pavements filter the runoff and improve water quality as well (Figure 23). This case study in Sydney, Australia reviewed the performance of permeable pavements as pollutant reduction technologies. The results were a reduction of 42% imperviousness on the street. The porous pavement did reduce the pollutant loadings by reducing the overall flow from the street. However, the permeable pavement did not have a significant independent effect on water quality. The total load of phosphorus and other heavy metals were reduced because the total flow of runoff was decreased.

**Figure 23. An example of a permeable pavement infiltration.**

## Effects of a Porous Pavement with Reservoir Structure on Runoff Water in France

A study by Legret and Colandini (1999) in Rezé, France was conducted to determine the fate and transport of heavy metals in stormwater runoff through porous pavement. The effluent from a traditional catchment with impervious pavement in a separate sewer system was compared to that of a reservoir structure under permeable pavement. The metals studied were: copper, zinc, cadmium, and lead. Suspended solids were also measured. As seen in Table 5, the authors report that the quality of the water passing through the permeable pavement and flowing out of the reservoir structure is significantly improved compared to a traditional separate sewer system outflow, with the exception of copper which remained relatively similar.

**Table 5. Comparison of event pollutant loadings for porous pavement relative to a reference site.**

| | SS. (kg/ha) | Pb (g/ha) | Cu | Cd | Zn |
|---|---|---|---|---|---|
| **Porous pavement** | | | | | |
| Minimum | 0.32 | 0.17 | 0.57 | 0.001 | 3.2 |
| Maximum | 20.9 | 3.6 | 6.3 | 0.27 | 29.9 |
| Mean | 3.5 | 0.88 | 3.0 | 0.08 | 11.3 |
| Standard Dev. | 6.0 | 1.0 | 2.1 | 0.08 | 8.2 |
| **Reference catchment** | | | | | |
| Minimum | 1.3 | 1.9 | 1.1 | 0.11 | 34.1 |
| Maximum | 26.0 | 16.7 | 11.6 | 0.88 | 58.5 |
| Mean | 8.5 | 5.6 | 3.0 | 0.35 | 41.8 |
| Standard Dev. | 7.8 | 4.2 | 3.0 | 0.22 | 8.5 |
| **Mean difference (%)** | **59** | **84** | **-** | **77** | **73** |

## Heavy Metal Retention by Porous Pavement in Germany

Porous pavements as a means of pollutant load reduction were tested in Germany by Dierkas *et al.* (1999). Different base materials under porous concrete blocks were tested and the results were extrapolated for 50 years. The research showed that the porous pavement sequestered most heavy metals (Table 6). Those metals tested were lead, cadmium, copper and zinc (common urban street runoff pollutants). The German limits for seepage water were not exceeded within the structures.

**Table 6. Heavy metal concentrations and percentage of metal retained in runoff from porous pavement infiltration of 50 years of equivalent loads compared to permissible limits for seepage.**

| | lead | cadmium | copper | zinc |
|---|---|---|---|---|
| synthetic runoff | 180 µg/l | 30 µg/l | 470 µg/l | 660 µg/l |
| effluent (mean conc.) | | | | |
| gravel | < 4 µg/l | 0,7 µg/l | 18 µg/l | 19 µg/l |
| basalt | <4 µg/l | 0,7 µg/l | 16 µg/l | 18 µg/l |
| limestone | < 4 µg/l | 3,2 µg/l | 29 µg/l | 85 µg/l |
| sandstone | < 4 µg/l | 10,5 µg/l | 51 µg/l | 178 µg/l |
| retention | | | | |
| gravel | 98 % | 98 % | 96 % | 97 % |
| basalt | 98 % | 98 % | 96 % | 98 % |
| limestone | 98 % | 88 % | 94 % | 88 % |
| sandstone | 89 % | 74 % | 89 % | 72 % |
| limits for seepage | 25 µg/l | 5 µg/l | 50 µg/l | 500 µg/l |

## Monitoring Permeable Pavement Sites in North Carolina, US

Three permeable interlocking concrete pavement (PICP) sites were monitored across North Carolina in Cary, Goldsboro, and Swansboro (Figure 24) by Bean *et al.* (2004).

**Figure 24. Photographs of Cary (left), Goldsboro (center), and Swansboro (right) PICP sites (Bean *et al.*, 2004).**

The Cary site was located in clay soil and flow rates and samples of exfiltrate and rainfall over 10 months were collected and analyzed for pollutant concentrations (Tables 7 and 8).

**Table 7. Hydrologic summary of results from Cary PICP site (Bean *et al.*, 2004).**

| Date | Rainfall Totals (cm) | Volume Attenuation % | Peak Attenuation % | Delay to Peak (hrs) |
|---|---|---|---|---|
| 7/22/2004 | 1.5 | 88 | 81 | 1.3 |
| 7/29/2004 | 1.6 | 53 | 44 | 1.5 |
| 8/5/2004 | 1.7 | 57 | 75 | 1.1 |
| **Mean** | **1.6** | **66** | **67** | **1.3** |

**Table 8. Mean pollutant concentrations and factors of significance for Cary site (Bean *et al.*, 2004).**

| Pollutant | Rainfall (Inflow) | Exfiltrate (Outflow) | p-value |
|---|---|---|---|
| NO3-N (avg. mg N/l) | 0.39 | *1.66* | **0.043** |
| NH4-N (avg. mg N/l) | *0.64* | 0.06 | **0.034** |
| TKN (avg. mg N/l) | *2.33* | 1.11 | 0.143 |
| TN (avg. mg N/l) | 2.71 | *2.77* | 0.964 |
| PO4 (avg. mg P/l) | 0.08 | *0.34* | 0.133 |
| TP (avg. mg P/l) | 0.26 | *0.40* | 0.424 |
| TSS (avg. mg/l) | N/A | *12.3* | N/A |

The Goldsboro site was constructed to compare the water quality of asphalt runoff to exfiltrate of permeable pavement. The site was located on a sandy soil and samples were analyzed for pollutants over a span of 18 months. PICP exfiltrate from the Goldsboro site had significantly lower concentrations of Total Phosphorus and Zinc compared to asphalt runoff (Table 9). Total Nitrogen (TN) concentrations were close to significantly lower in exfiltrate, but did show an increasing trend of TN removal.

**Table 9. Pollutant summary for Goldsboro site (Bean *et al.*, 2004).**

| Pollutant Analysis | Mean Runoff | Mean Exfiltrate | p-value | Storms |
|---|---|---|---|---|
| Zn by ICP/MS-Water mg Zn/l | *0.067* | 0.008 | **0.0001** | 1-8 |
| $NH_4$-N/Water mg N/l | *0.35* | 0.05 | **0.0194** | 9-14 |
| TP/Waters mg P/l | *0.20* | 0.07 | **0.0240** | 1-14 |
| TKN/Water mg N/l | *1.22* | 0.55 | **0.0426** | 1-14 |
| Cu/MS-Water mg Cu/l | *0.016* | 0.006 | *0.0845* | 1-8 |
| TN Calculation mg N/l | *1.52* | 0.98 | 0.1106 | 1-14 |
| TSS mg/l | *43.8* | 12.4 | 0.1371 | 1-12,14 |
| $PO_4$ mg P/l | *0.06* | 0.03 | 0.2031 | 9-14 |
| $NO_{3+2}$-N/Water mg N/l | 0.30 | *0.44* | 0.2255 | 1-14 |

The Swansboro site was constructed and instrumented to monitor runoff flow and rainfall rates and collect exfiltrate and runoff samples from the permeable pavement lot over ten months. The site was located on very loose sandy soil and experienced no runoff.

## Testing Permeable Pavements in Renton, Washington, US

Research by Brattebo and Booth (2003) examined the long-term effectiveness of permeable pavement as an alternative to traditional impervious asphalt pavement in a parking area. Eight stalls were constructed with four types of commercially available permeable paving systems, with two neighboring stalls covered with each of the four permeable paving systems. The permeable pavement systems used in this study were:

- Grasspave2®, a flexible plastic grid system with virtually no impervious area, filled with sand and planted with grass.
- Gravelpave2®, an equivalent plastic grid, filled with gravel.
- Turfstone®, a concrete block lattice with about 60% impervious coverage, filled with soil and planted with grass.
- UNI Eco-Stone®, small concrete blocks with about 90% impervious coverage, with the spaces between blocks filled with gravel.

Each test parking stall was 3 m wide by 6 m long. A series of gutters and pipes were used to collect both surface runoff and subsurface infiltrate. The stalls were evaluated after six years of daily parking usage for structural durability, ability to infiltrate precipitation, and impacts on infiltrate water quality.

Visual inspection of the permeable pavement systems showed varying, but generally minor, signs of wear and tear after six years. In two small areas, the interlocking sheets of the Grasspave2® and the Gravelpave2® plastic matrix had shifted slightly and partly lifted out of the soil in the area where the rear wheels of the parked cars typically rest. The Turfstone® and UNI Eco-Stone® showed no areas of rutting, settling, or shifting. Grass was growing uniformly across the Turfstone® surface, but more spotty (and locally quite sparse) in the Grasspave2® stalls.

Virtually all rainwater infiltrated through the permeable pavements, with almost no surface runoff. The infiltrated water had significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area (Table 10). Motor oil was detected in 89% of samples from the asphalt runoff but not in any water sample infiltrated through the permeable pavement. Neither lead nor diesel fuel were detected in any sample. Infiltrate measured five years earlier displayed significantly higher concentrations of zinc, copper, and lead.

**Table 10. Mean concentrations of detected constituents from storm samples in 1996 and 2001-02.**

| | Hardness (mg $CaCO_3$/l) | Conductivity (μmhos/cm) | Copper (μg /l) | Zinc (μg /l) | Motor Oil (mg/l) |
|---|---|---|---|---|---|
| **Infiltration Samples** | | | | | |
| Gravelpave2® | 22.6<br>[20.3] | 47<br>[63] | 0.89 (66% <MDL)<br>[1.9 (67% <MDL)] | 8.23 (22% <MDL)<br>[2.0 (67% <MDL)] | <MDL |
| Grasspave2® | 14.6<br>[22.8] | 38<br>[94] | <MDL<br>[21.4 (33% <MDL)] | 13.2<br>[2.5 (67% <MDL)] | <MDL |
| Turfstone® | 47.6<br>[49.4] | 114<br>[111] | 1.33 (44% <MDL)<br>[1.4 (67% <MDL)] | 7.7 (33% <MDL)<br>[<MDL] | <MDL |
| Uni Eco-Stone® | 49.5<br>[23.0] | 114<br>[44] | 0.86 (77% <MDL)<br>[14.3 (33% <MDL)] | 6.8 (33% <MDL)<br>[7.9 (33% <MDL)] | <MDL |
| **Surface Runoff Samples** | | | | | |
| Asphalt | 7.2<br>[6.1] | 13.4<br>[17.0] | 7.98<br>[9.0 (33%<MDL)] | 21.6<br>[12] | 0.164 (11% <MDL) |

Note: 1996 results from Booth and Leavitt (1999) in square brackets.

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# Section 8: Infiltration Trenches, Bioretention Systems, and Rain Gardens

## Infiltration Trenches

*“Generally, an infiltration structure is designed to store a ‘capture volume’ of runoff for a specified period of ‘storage time’,” (Akan, 2002).*

Stream ecology alterations can begin when surfaces are only a few percent impervious. In addition, significant water quality and habitat degradation can occur when imperviousness reaches only 8-12% (Wang *et al.* 2001). Facilitating infiltration along multiple lines of stormwater interception gives a higher rate of overall success in achieving the benefits associated with wet-weather management. Infiltration trenches are excavated trenches, 3 to 12 ft deep, backfilled with a stone aggregate, and lined with filter fabric (Figure 25) (Bell, 1999).

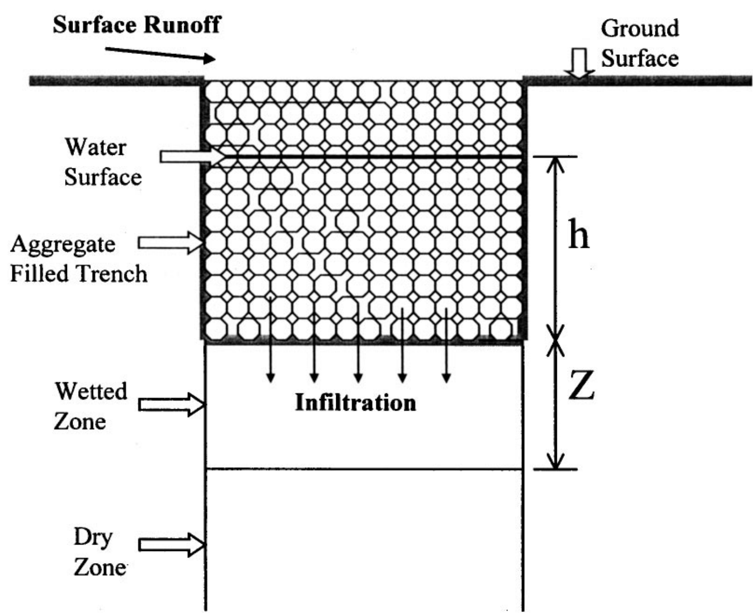


**Figure 25. Infiltration trench diagram (Akan, 2002).**

In addition to its ability to manage water, the pollutants that are targeted by infiltration trenches are: suspended solids, particulate pollutants, coliform bacteria, organics, trace metals, and nutrients from wet-weather runoff (Bell, 1999). Ground-water recharge and baseflow in nearby streams increase with the effective use of infiltration trenches. There are a few limitations that exist with the use of infiltration trench structures when planning urban infrastructure projects. Some of these limitations include: the potential for pollutants and sediment to clog the gravel and infiltration surface, ground-water contamination, and low dissolved pollutant removal. Additional limitations may include the preclusion of locating infiltration trenches on steep slopes and loose or unstable areas (Melbourne Water, 2008). The removal efficiency of an infiltration trench is based on the inspections and maintenance it receives. If not properly maintained many infiltration trench designs have a high likelihood of failure and potential for groundwater contamination (Bell, 1999). Regular maintenance and inspections also prevents clogging of the porous media.  Clogs can be removed by washing the porous material and replacing the fabric layer on top (Melbourne Water, 2008).

When considering sites for any infiltration project, ground-water contamination must be closely watched. Sites that store chemicals or hazardous materials should not be chosen as a good place to put an infiltration trench.  If this is the case, diversion structures can also be implemented to keep spills and potential spills away from infiltration systems (Bell, 1999).

## Bioretention Structures and Rain Gardens

On the street-scale level, bioretention systems can be introduced into source control methods to treat road and roof runoff before these waters end up in streams and rivers (Melbourne Water, 2008).  These systems can be lined, using underdrains if *in situ* soils are not well drained (Figure 26).  Generally, bioretention structures contain 2 ft to 3 ft of porous media (sand/soil/organic mater mixture) covered by a thin layer of hardwood mulch, grasses, shrubs, and small trees (Figure 27).  This layering and vegetation diversity promotes evapotranspiration, maintains soil porosity, and encourages biological activity (Davis, 2008).

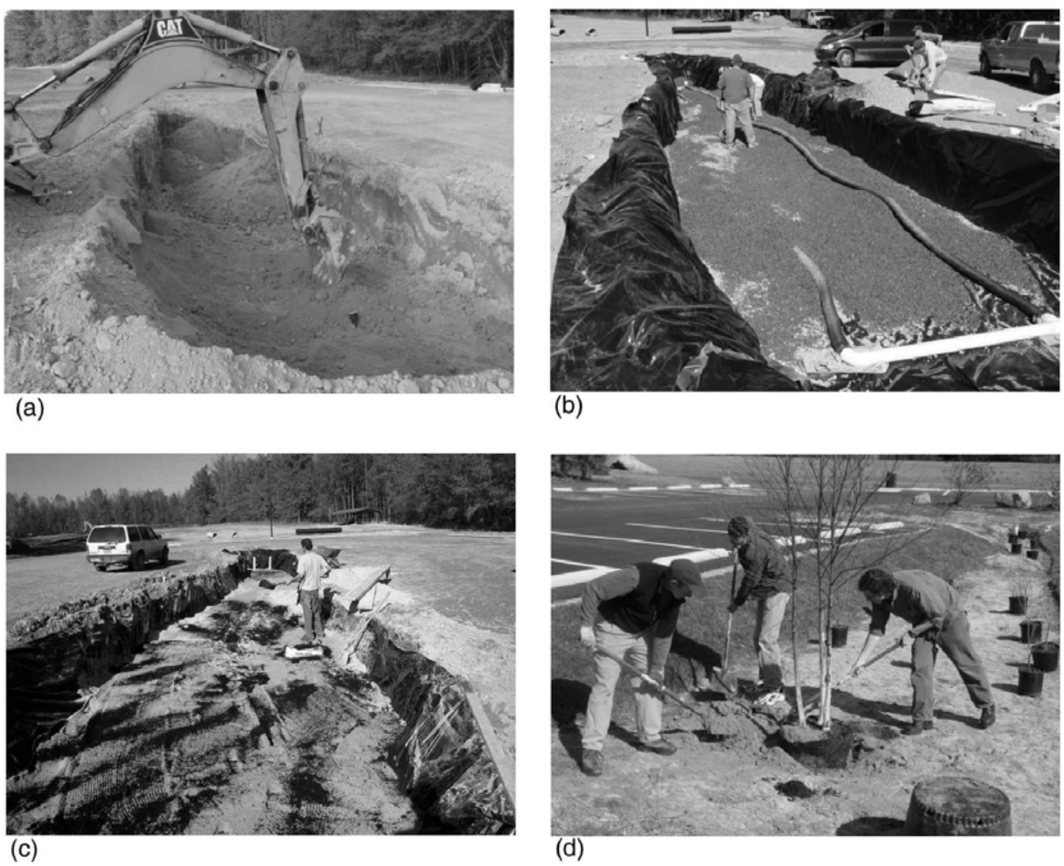


**Figure 26. Construction of a bioretention cell: (a) excavation; (b) placement of underdrains and gravel envelope; (c) spreadng of soil media; and (d) planting vegetation at surface of bioretention bed.**

Rain gardens work best under the most decentralized conditions. They are a kind of bioretention structure and as a bioretention structure they reduce peak flows, recharge aquifers, and allow stormwater to

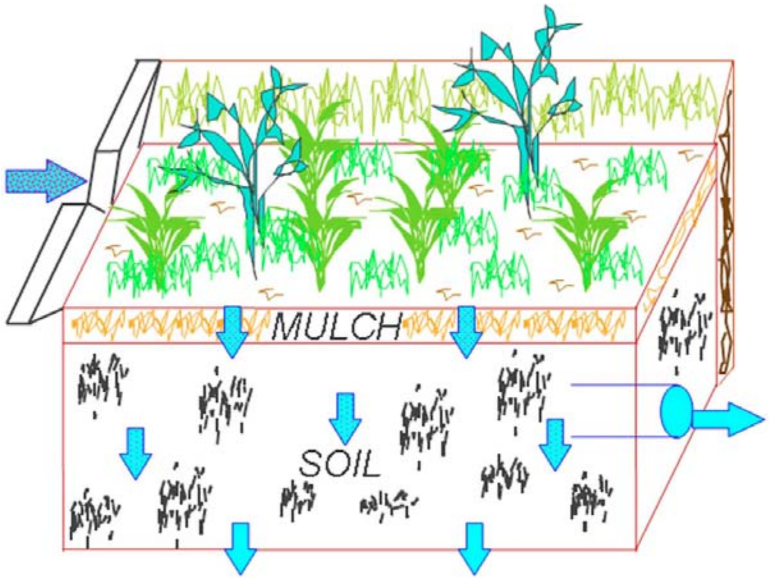


**Figure 27. Schematic of a bioretention/rain garden (Davis, 2008).**

infiltrate (Dietz, 2005). Rain gardens can be landscaped into residential lawns and around houses. They can be designed to landowner requests, because structurally they require the least design specifications compared to other infiltration structures. The low maintenance requirements (especially when planted with native species) for rain gardens is an appealing aspect to those seeking wastewater management on a localized level. They oftentimes do not require watering, mowing or fertilization after establishment, depending on rainfall quantities and timing (Melbourne Water, 2008).

## Case Studies

### <u>Heavy Metal Removal in Cold Climate Bioretention in Norway</u>

A study by Muthanna *et al.* (2007) set out to investigate the correlation between temperature and the heavy metal removal capabilities of bioretention media. The experiment was undertaken in Trondheim, Norway, in a constructed bioretention box. The sample box was put through runoff events corresponding to historical data of storms and rainfall. The months chosen for this experiment were April (average temperature of 5.8°C) and August (average temperature of 13.4°C) of 2005. It was shown across all heavy metal parameters that this type of pollutant removal is more efficient in warmer months. The authors indicate that this is due primarily to the partially frozen soil strata and less active above-ground biomass affecting infiltration and evapotranspiration rates in colder months. Overall, the bioretention system proved to reduce heavy metal pollutants significantly. Zinc was reduced by 90%, lead up to 89%, and copper between 60 and 75% (Table 11). The mulch layer was determined to be the major sink for metals removal. The authors also found that metal retention was independent of the selected hydraulic loading rates (equivalent to 1.4mm/h to 7.5 mm/h precipitation) showing that variable inflow rates during the tested set of events did not affect the treatment efficiency of the system

**Table 11. Average total metal inflow and outflow concentrations from bioretention box.**

| | | Inflow | | | Outflow | | |
|---|---|---|---|---|---|---|---|
| | | Copper | Zinc | Lead | Copper | Zinc | Lead |
| April | Mean concentration ($\mu g\ l^{-1}$) | 26[a] | 412[a] | 4.4[a] | 15.2[a] | 22[a] | 0.8[a] |
| | Standard Deviation ($\mu g\ l^{-1}$) | 7.8 | 233 | 3.0 | 5.9 | 19 | 0.7 |
| | Reduction (%) | | | | 40 | 95 | 82 |
| August | Mean concentration ($\mu g\ l^{-1}$) | 126[b] | 584[a] | 21.1[b] | 41.7[b] | 49[b] | 2.5[b] |
| | Standard Deviation ($\mu g\ l^{-1}$) | 32 | 149 | 5.6 | 16.6 | 31.0 | 1.0 |
| | Reduction (%) | | | | 67 | 92 | 88 |
| Overall | Mean concentration ($\mu g\ l^{-1}$) | 83 | 521 | 13.9 | 30.2 | 38 | 1.8 |
| | Standard Deviation ($\mu g\ l^{-1}$) | 56 | 195 | 9.4 | 17.9 | 29 | 1.2 |
| | Reduction (%) | | | | 63 | 93 | 87 |

Means followed by different letters for the same variable are significantly different at CI 95% using a paired *t*-test analysis

## Two Bioretention Cells at the University of Maryland, College Park, Maryland, US

### *Flow Attenuation*

Flows into and out of two bioretention facilities constructed on the University of Maryland campus were monitored for nearly 2 years, covering 49 runoff events (Davis, 2008). The primary objective of this work was to quantify the reduction of hydrologic volume and flow peaks and delay in peak timing via bioretention.

A bioretention research and education-site was constructed on the University of Maryland campus in College Park, Maryland, in Fall 2002/Spring 2003. The site contains two parallel bioretention cells that capture and treat stormwater runoff from an approximately 0.24-ha section of an asphalt surface parking lot. An asphalt curb was constructed along the perimeter of the parking lot to funnel sheet flow to the corner of the lot where the facilities were located. The parking area is high-use, employed year-round for commuter students and athletic events. Each bioretention cell is rectangular, with a width of 2.4 m and a length of 11 m. The resulting bioretention surface area is about 28 $m^2$ for each cell, producing a drainage-to-bioretention area ratio of about 45.

One of the bioretention cells (the shallow cell) was constructed according to the standard bioretention design outlined in the Prince George's County, Maryland, and Bioretention Manual. In addition to the standard media, the second cell incorporates an experimental anoxic zone at the bottom to encourage denitrification of runoff that passes through the cell (the deep cell).

Overall, results indicate that bioretention can be effective for minimizing hydrologic impacts of development on surrounding water resources (Figure 28). Eighteen percent of the monitored events were small enough so that the bioretention media captured the entire inflow volume and no outflow was observed. Underdrain flow continued for many hours at very low flow rates. Mean peak reductions of 49% and 58% were noted for the two cells. Flow peaks were significantly delayed as well, usually by a factor of two or more. Using simple parameters to compare volume, peak flow, and peak delay to values expected for undeveloped lands, it was found that the probabilities for the deep bioretention cell to meet or exceed volume, peak flow, and peak delay hydrologic performance criteria were 55%, 30%, and 38%, respectively. The probabilities were 62%, 42%, and 31%, respectively, for the shallow bioretention cell.

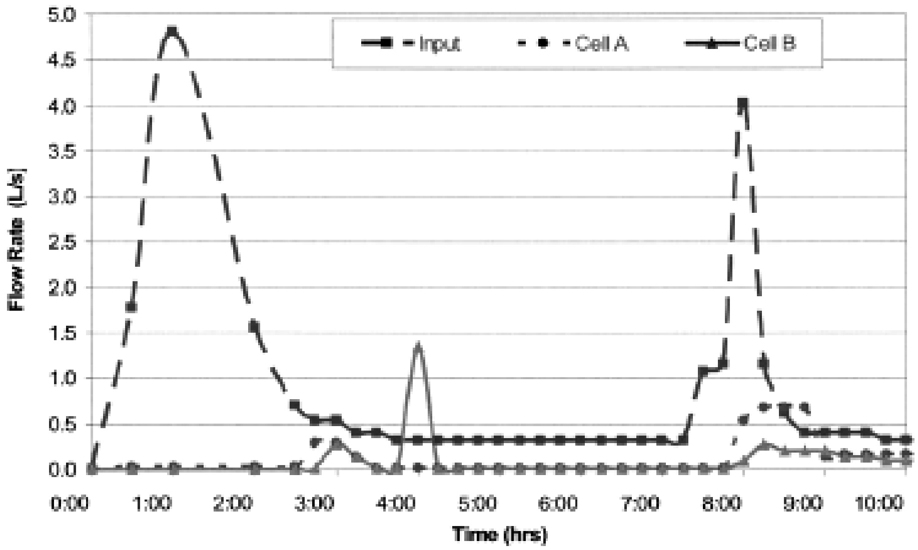


**Figure 28. Input and output hydrographs for University of Maryland bioretention facilities.**

***Water Quality***

The same two bioretention facilities described above were monitored from Summer 2003 through Fall 2004 to quantify water quality improvements to parking lot stormwater runoff (Davis, 2007). Twelve inflow/outflow water quality data sets were successfully collected and analyzed for total suspended solids (TSS), phosphorus, and zinc. Nine sets were collected for copper and lead, and three for nitrate. In two of the events, all of the runoff flow was attenuated by the bioretention media and no flow exited the cells, resulting in zero pollutant discharge. In all cases, the median pollutant output is lower than the input, indicating successful water-quality improvement through the bioretention media. Statistically insignificant differences were noted between the two cells for all pollutants examined. Median values for the effluent event mean concentrations and percent removals based on combined data sets (both cells) were TSS 17 mg/L and 47%; total phosphorus 0.18 mg/L and 76%; copper, 0.004 mg/L and 57%; lead 0.004 mg/L and 83%; zinc 0.053 mg/L and 62%; and 0.02 mg-N/L and 83% removal of nitrate (based on limited data). Mass removals were higher than those based on concentrations due to flow attenuation. These values are in reasonable agreement with those previously published from bioretention field and laboratory studies.

## Rain Garden Performance in Haddam, Connecticut, US

Replicated rain gardens were constructed and monitored in Haddam, Connecticut, US, to capture shingled-roof runoff (Dietz and Clausen, 2005). The gardens were sized to store the first 1 in. of runoff. Influent, overflow, and percolate flow were measured using tipping buckets and sampled passively. Precipitation was also measured and sampled for quality. All weekly composite water samples were analyzed for total phosphorus (TP), total Kjeldahl nitrogen (TKN), ammonia-nitrogen ($NH_3$-N), and nitrite+nitrate-nitrogen ($NO_3$-N). Monthly composite samples were analyzed for copper (Cu), lead (Pb), and zinc (Zn). Redox potential was measured using platinum electrodes. Poor treatment of $NO_3$-N, TKN, organic-N, and TP in roof runoff was observed. Many Cu, Pb, and Zn samples were below detection limit, so statistical analysis was not performed on these pollutants. The only pollutants significantly lower in the effluent than in the influent were $NH_3$-N in both gardens and total-N in one garden.

The design used for these rain gardens worked well for overall flow retention, but had little impact pollutant concentrations in percolate. Most of the influent left the rain gardens as subsurface flow

(98.8%). Only 0.8% of the inflow water overflowed during the entire study period (Table 12), which included an unusually cold and snowy winter with frequent frost in the soil.

**Table 12. Flow mass balance for rain gardens, Haddam, CT. Depth values are based on total rain garden area (Dietz and Clausen, 2005).**

| | Volume (L) | Depth (cm) | % of inflow |
|---|---|---|---|
| Inflow | | | |
| Roof runoff | 170,063 | 653 | 84 |
| Precipitation | 32,241 | 123 | 16 |
| *Total* | 202,304 | 776 | 100 |
| Outflow | | | |
| Underdrain | 199,933 | 767 | 98.8 |
| Overflow | 1,645 | 6 | 0.8 |
| *Total* | 201,578 | 774 | |
| Residual | 726 | 3 | 0.4 |

Overflow occurred four times for garden 1 and three times for garden 2 during the 56-week study period. The residual volume (0.4%) was assumed removed by evapotranspiration (ET) from the gardens. Precipitation and flow data for one event on October 1, 2003, demonstrate the ability of the rain garden to reduce peak flow rates and increase lag time (Figure 29). The timing and shape of the inlet (roof runoff) hydrograph follow the precipitation hyetograph closely. However, the underdrain outflow shows a lower peak flow rate and a delayed response to the precipitation event. No overflow occurred during this 42mm event.

These results suggest that if an underdrain is not connected to the stormwater system, high flow and pollutant retention could be achieved with the 2.54-cm design method.

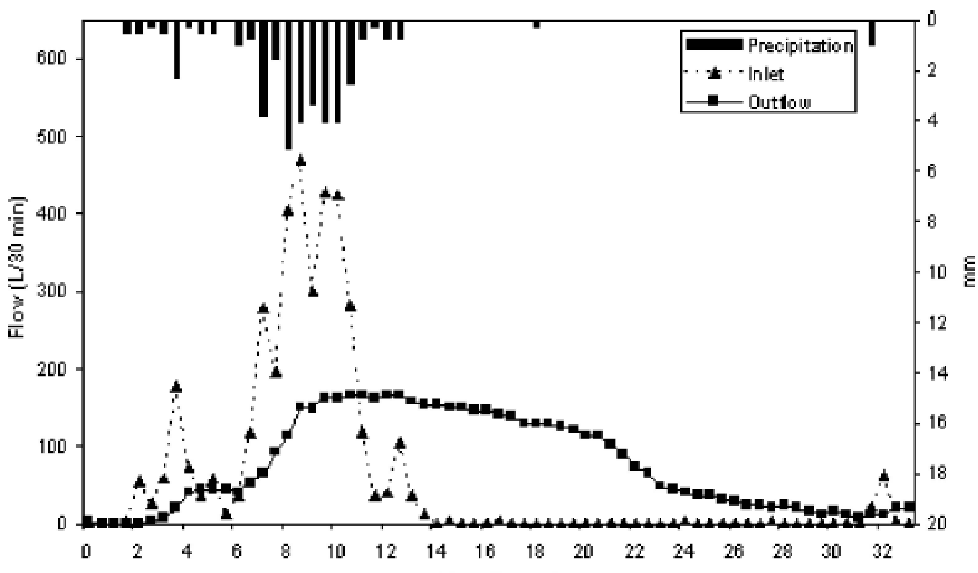


**Figure 29. Precipitation, inflow, and outflow (underdrain) for one event, Haddam rain garden (Dietz and Clausen, 2005).**

## Performance of Several Bioretention Facilities in North Carolina, US

Three bioretention field sites in North Carolina were examined for pollutant removal abilities and hydrologic performance (Hunt *et al.*, 2006). The cells varied by fill media type or drainage configuration. The field studies confirmed high annual total nitrogen mass removal rates at two conventionally drained bioretention cells (40% reduction each). Nitrate-nitrogen mass removal rates varied between 75% and 13%, and calculated annual mass removal of zinc, copper, and lead from one Greensboro cell were 98%, 99%, and 81%, respectively. All high mass removal rates were due to a substantial decrease in outflow volume. The ratio of the volume of water leaving the bioretention cell versus that which entered the cell varied from 0.07 (summer) to 0.54 (winter). There was a significant ($p<0.05$) change in the ratio of outflow volume to inflow volume when comparing warm seasons to winter. Cells using a fill soil media with a lower phosphorus index (P-index), Chapel Hill cell C1 (Figure 30) and Greensboro cell G1, had much higher phosphorus removal than Greensboro cell G2, which used a high P-index fill media. The authors concluded that fill media selection is critical for total phosphorus removal, as fill media with a low P-index and relatively high cation exchange capacity appear to remove phosphorus much more readily.

**Figure 30. Bioretention cell C1 in Chapel Hill 8 months after construction (Hunt *et al.*, 2006).**

Researchers examined the Hal Marshal bioretention cell (HMBC) in an urban setting in Charlotte, North Carolina, US from 2004 to 2006 (Hunt *et al.*, 2008). The HMBC is a retrofit BMP treating runoff from an asphalt parking area adjacent to the Hal Marshall Municipal Services Building in the City of Charlotte, North Carolina (Figure 31). The drainage area was 0.37 ha (0.92 ac) of an aging asphalt parking lot, which was last paved at least ten years prior to the study. The traffic load on the watershed was a mix of private vehicles and service vehicles. During office hours, use of the parking spaces was observed to be near 100%. The design of the bioretention area followed the recommendations made by the state of North Carolina Division of Water Quality Stormwater BMP Design Manual.

**Figure 31. Hal Marshall bioretention cell 16 months after the cell was revegetated and the study commenced (Hunt *et al.*, 2008).**

Flow-weighted, composite water quality samples were collected for 23 events and analyzed for TKN, $NH_4$-N, nitrate/nitrite-N, TP, TSS, $BOD_5$, Cu, Zn, Fe, and Pb. Grab samples were collected from 19 storms for fecal coliform and 14 events for *E. coli*. There were significant reductions ($p<0.05$) in the concentrations of TN, TKN, $NH_4$-N, $BOD_5$, fecal coliform, *E. coli*, TSS, Cu, Zn, and Pb. Iron concentrations increased significantly ($p<0.05$) by 330%. NO2-3-N concentrations were essentially unchanged. Efficiency ratios for TN, TKN, $NH_4$-N, TP, and TSS were 0.32, 0.44, 0.73, 0.31, and 0.60, respectively. Fecal coliform and *E. coli* efficiency ratios were 0.69 and 0.71, respectively. Efficiency ratios for Zn, Cu, and Pb were 0.77, 0.54, and 0.31, respectively.

The peak outflow of the bioretention cell for 16 storms with less than 42 mm of rainfall was at least 96.5% less than the peak inflow, with a mean peak flow reduction of 99% (Table 13 and Figure 32). These results indicated that in an urban environment, bioretention systems can reduce concentrations of most target pollutants, including pathogenic bacteria indicator species. Additionally, bioretention can effectively reduce peak runoff from small to midsize storm events.

**Table 13. Reduction from Peak Inflow to Peak Outflow at HMBC (Hunt *et al.*, 2008).**

| Event date | Rainfall amount (mm) | Peak inflow (L/s) | Peak outflow (L/s) | Reduction in peak (%) |
|---|---|---|---|---|
| 2/7/04 | 35.6 | 25.6 | 0.06 | 99.8 |
| 4/26/04 | 2.8 | 14.5 | 0 | 100 |
| 6/1/04 | 8.9 | 18.8 | 0.25 | 98.7 |
| 10/13/04 | 10.2 | 14.1 | 0.09 | 99.4 |
| 12/6/04 | 10.9 | 23.3 | 0.06 | 99.8 |
| 1/14/05 | 26.2 | 73.5 | 0.14 | 99.8 |
| 2/14/05 | 6.9 | 6.8 | 0.03 | 99.6 |
| 2/22/05 | 7.1 | 4.1 | 0.08 | 98.0 |
| 3/8/05 | 16.5 | 22.3 | 0.11 | 99.5 |
| 4/7/05 | 2.0 | 3.7 | 0 | 100 |
| 4/13/05 | 39.9 | 14.5 | 0.11 | 99.2 |
| 5/13/05 | 6.4 | 50.8 | 0.08 | 99.8 |
| 6/28/05 | 17.8[a] | 32.9 | 0.06 | 99.8 |
| 12/5/05 | 32.5 | 13.6 | 0.48 | 96.5 |
| 12/12/05 | 10.9 | 13.0 | 0.20 | 98.5 |
| 12/29/05 | 9.1 | 20.1 | 0.31 | 98.5 |

Note: Five additional storms exceeding 42 mm were monitored, but overtopped the bioretention cell.
[a]Data collected at municipal location within 0.3 km (0.2 mi) of HMBC.

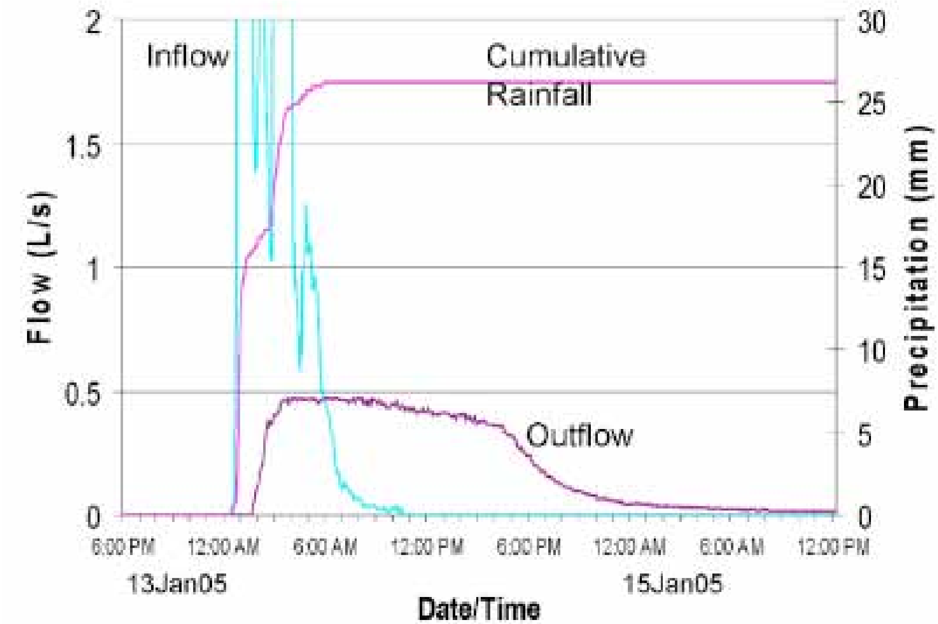


**Figure 32. Inflow and outflow hydrographs for HMBC for January 13–14, 2005 rain event (Hunt *et al.*, 2008).**

## Implications of Bioretention System Implementation in Wisconsin

Morzaria-Luna *et al.* (2004) analyzed the implementation of various bioretention systems, including rain gardens, vegetated swales, trenches, and infiltration basins in the St. Francis subdivision, Cross Plains, Wisconsin. Through the examination of archival data and interviews with key participants, it was found that although regulatory and political pressures encouraged the inclusion of bioretention, current standards for stormwater management prevailed. The developers had to meet both existing requirements and anticipated rules requiring infiltration. As a result, bioretention systems simply supplemented, rather than replaced, traditional stormwater practices. The confusion surrounding dual standards contributed to substantial delays in the negotiations among relevant stakeholders in the watershed. The authors concluded that the St. Francis subdivision serves as both a cautionary tale and a bioretention success story. As a caution, the situation demonstrated the need for careful review and refinement of existing stormwater ordinances to incorporate water quality improvement technologies, such as bioretention. The demonstrated success of the St. Francis development was that it became a positive prototype for best management stormwater practices elsewhere in the region. In addition, the water quality monitoring data from the site contributed to development of a new county ordinance, the first in Wisconsin to address both quantity and quality of storm water runoff. These findings suggest that any policy aimed at modifying the approach to stormwater management must originate within the governance structure. The authors believe that attention must be concentrated on reviewing and reconfiguring existing storm water regulations and ordinances.

## Mt. Airy Rain Catchers: Testing a Reverse-Auction Incentive in Cincinnati, OH

The Mt. Airy Rain Catchers Project, a joint venture of interested and motivated homeowners, the US Environmental Protection Agency, Horticultural Asset Management Inc., and Tetra Tech Inc, is the largest Economic Incentive and monitoring program of its kind in the country (Buranen, 2008). It is a pilot program to test a reverse-auction-based method of encouraging participation by homeowners, an idea of staff members in the EPA's Sustainable Environments Branch.

The Mt. Airy Rain Catchers Project began with the creation of a demonstration-site consisting of a rain barrel and two rain gardens in December 2006. Signs were added to educate the public on how rain gardens and rain barrels function. Information about the project, in an attractive, easy-to-understand brochure, was mailed to property owners in the spring of 2007. Each house in the Mt. Airy neighborhood was eligible to receive up to four rain barrels and a rain garden. Homeowners could choose to receive either or both. Installation, planting, and hardware costs were paid for by the U.S. Environmental Protection Agency.

The novel reverse-auction approach called for homeowners to submit bids with a dollar amount they wished to be paid for permitting the installation and maintenance of rain gardens and/or rain barrels on their property. Those who submitted the lowest bids were the most likely to be selected. Most of the bids were for $0; of the bids that asked for payment, most were less than $200.

In the summer of 2007, designated contractors installed 50 rain gardens, each measuring 150 to 160 square feet, and 101 rain barrels at the selected homes. Each property owner selected for the program received an owner's manual. The contractors will maintain the rain barrels and rain gardens and monitor the water quality in local streams through 2010. Homeowners are asked only to empty the rain barrels after each rainfall and to close the valve before the next rainfall.

## **10,000 Rain Gardens: Involving the Public in Combined Sewer Overflow Management in Kansas City, Missouri, US**

Kansas City needed to address its aging infrastructure, not only to help prevent catastrophic flooding, but also to improve stormwater quality, reduce the incidence of combined sewer overflows, and meet environmental regulations (Buranen, 2008). The price tag for addressing all of the region's infrastructure needs through engineered solutions was staggering: approximately $2 billion to address water quantity issues alone.

With early support from the Mayor, Kansas City's stormwater managers were able to develop and implement the 10,000 Rain Gardens Initiative fairly quickly. The initial media campaign roll-out occurred in January and February of 2006 and included television and radio spots showing interviews with garden experts, as well as print ads, stories, and editorials in local newspapers. The City's key messages for the media campaign were to stress the importance of keeping water on the property, reducing turf areas and the maintenance and inputs associated with them, and creating an attractive landscape feature. The City was aware of statistics that showed gardening was a common pastime, so they thought the Initiative would appeal to a broad audience.

A major part of the 10,000 Rain Gardens Initiative involved training for professionals. Early in the Initiative, the City sponsored three, day-long sessions for private landscaping businesses and retailers as well as municipal employees, and each event was sold out. How-to workshops continue to be held on a regular basis for both citizens and landscape professionals, and brief presentations are offered by request to provide an overview of the Initiative, rain gardens, and water quality concerns.

One of the most cost-effective tools employed by the City is the web site for the Initiative, www.rainkc.com, which is designed to offer citizens and other audiences a comprehensive suite of information about rain gardens in particular and stormwater management in general. The site acts as a clearinghouse of information pertaining to the 10,000 Rain Gardens Initiative: resources, news items, technical information, examples and photographs, background information, and more. The site reaches a broad audience "on demand" and can be maintained and augmented at a relatively low cost. Even though the media campaign has ended, the site still has more than 2,000 hits per week and more than 100,000 visits per year.

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## Section 9:  Rainwater Harvesting and Reuse

Arid and semi-arid regions can benefit greatly from a stormwater management system that includes stormwater capture and aquifer recharge to replenish and help ensure the long-term sustainability of water supplies.  Rainwater harvesting systems can also provide benefits for wetter climatic areas, as well. Rainwater can be collected for reuse in rain barrels, cisterns, and underground storage tanks.  This type of rainwater capture constitutes stormwater retention and removes a set volume of stormwater from offsite runoff, protecting downstream areas from some of the ill effects of urban runoff.  Property owners can use this water for irrigation, toilet flushing, or other non-potable uses.

Practices that promote stormwater infiltration, such as those mentioned previously, will contribute to ground-water recharge, reducing water temperatures (subsurface flows have lower temperatures than surface flows) and enhancing baseflow to streams during dry weather.

### Case Studies

#### Residential Area with Raintanks and Aquifer Recharge Area in Newcastle, Australia

The project at Fig Tree Place demonstrated what can be accomplished with regards to water reuse in a suburban residential neighborhood (Figtree Place, no date).  Results from this project can be applied to any number of sustainable urban design areas.  Started in 1998, Figtree Place, a neighborhood in Newcastle, Australia was designed with an aquifer recharge area.  Roof runoff from 27 inner city residences is stored in cisterns for personal use in each household (for hot water, toilet flushing, etc.). Any overflow from the personal cisterns flows to a grassed infiltration zone for aquifer recharge.  When on-site demands for water (irrigation or an adjacent bus-washing facility) increases, the aquifer can be accessed for use. Total water savings in this development are nearly 60%.  Figure 33 below shows a diagram of the neighborhood as a conceptual model of how the water conservation designs work.

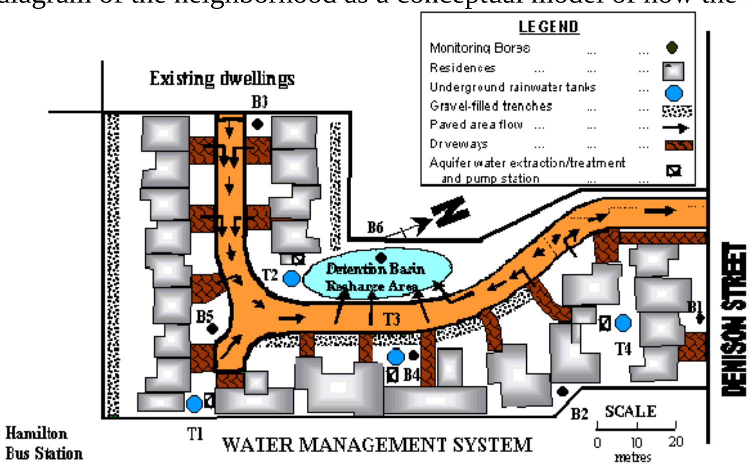


**Figure 33. Overview of water sensitive design elements at Figtree Place.**

#### Inkerman Oasis, Development with Integrated WSUD Techniques in Australia

This community near Port Phillip Bay, Australia, combined a number of WSUD techniques (Inkerman Oasis, no date).  This community is the first Australian community to integrate greywater and stormwater for reuse in a high-density residential development.  These residents use recycled and treated domestic greywater for baths, showers, and toilet flushing. Secondary systems for stormwater, second to raintanks, includes a native wetlands and sand filter area (part of which can be seen in Figure 34). The reuse of water reduces potable water demand by 45% and keeps up to 7 tons of nitrogen and phosphates from draining to Port Phillip Bay each year.

**Figure 34. Inkerman Oasis Sand Filter.**

## <u>A Greywater System of Rainwater Reuse at the Royal Melbourne Institute of Technology (RMIT) in Australia</u>

Estimated at $228,500, this project to use rooftop and basement storage tanks for beneficial use of rainwater for toilet flushing is an example of innovation to capture runoff from urban impervious surfaces (Melbourne Water, 2008). In addition to providing much needed water conservation in Australian cities, this practice has converted 720 $m^2$ of outdoor space into a garden plaza attractive to students and aesthetically pleasing in a heavily urban environment (Figure 35). The maintenance considerations are based on results from periodic monitoring to achieve maximum success.

> We have evicted nature from the city, much to our cost. But nature has all the answers it's the only sustainable system we know, and we need to learn from it. It's time we invited nature back in.
>
> -Terry White, developer of this project in Melbourne

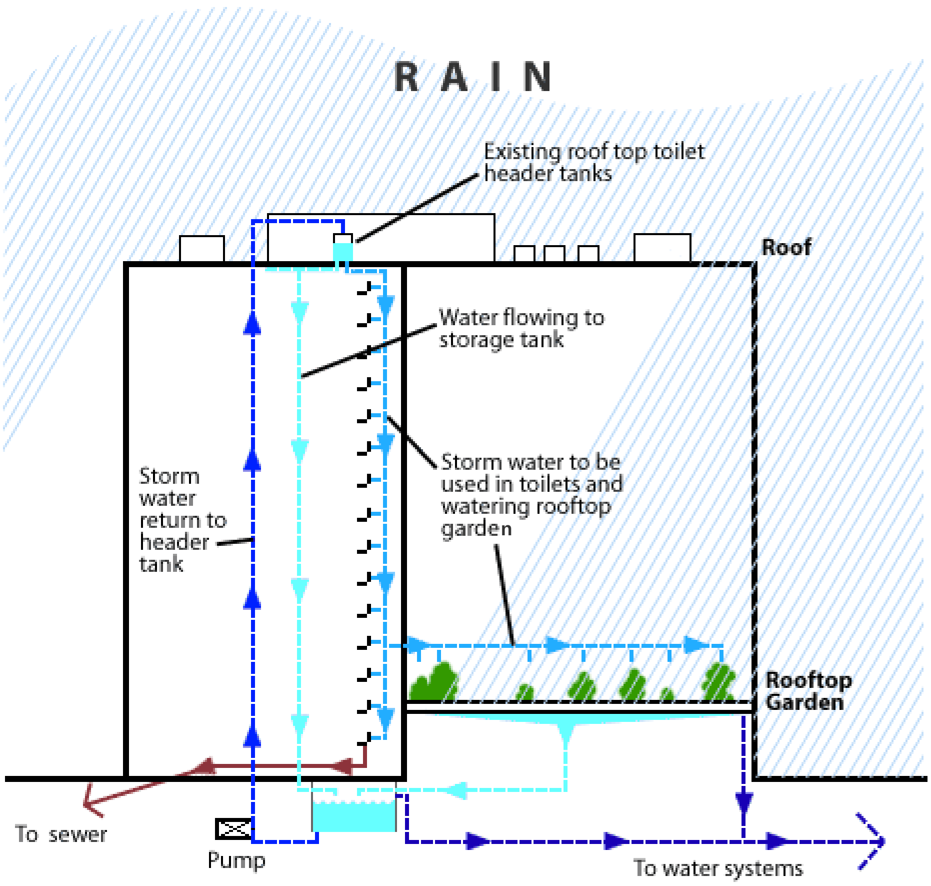


**Figure 35. Schematic drawing of the proposed greywater system showing how the water is captured and stored for future reuse.**

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