出國報告（出國類別：進修）

美國水資源技術及政策研習
報告書

服務機關：內政部建築研究所
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派赴國家：美國西雅圖
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目　次

摘要

為因應全球氣候變遷及溫室效應造成之全球暖化問題，並使國人有更優質、舒適及健康之居住環境，我國於90年開始執行「綠建築推動方案」，且於97年起擴大實施「生態城市綠建築推動方案」，使我國的綠建築政策更進一步邁入永續都市的階段。

台灣都市化嚴重造成大氣中二氧化碳濃度增加，都市暖化效應明顯，進而產生都市「熱島效應」，另外台灣因都會區綠地不足與社區過度不透水化，都市內建築物密集，不透水鋪面大量取代原有綠色空間，使得綠化面積驟降，建築與環境無法形成良性互動，迫使環境與人為建築相互抗衡，熱島效應與都市雨洪等相關問題相繼發生。此外傳統集中末端處理的排水觀念，使得都市屋頂缺乏保水機能，故應重新考量建築屋頂與水循環之關係，試圖建立與環境互動良好的建築，進而達到與環境共生之都市。

鑑此，世界各先進國家重新考量建築物屋頂綠化與都市雨洪之關係，並將屋頂綠化納入成為解決都市熱島效應與洪澇災害有效方法之一，故國內應積極重視屋頂綠化相關議題。為瞭解國際間相關發展現況及未來趨勢，爰藉由參訪西雅圖市社區及公共建設之雨水利用及屋頂綠化工程設施，瞭解其在雨水利用及屋頂綠化設計、技術及實施概況，蒐集取得相關實施經驗，作為我國未來提升雨水利用系統應用於降低都市熱島效應及屋頂綠化澆灌技術研究能力及綠建築政策擬訂之參考。

壹、出國目的

人是群居的動物，當人口逐漸增加，為了生存便開始向內陸發展，都市也漸漸形成。在都市發展過程中，為了追求經濟成長，對於自然資源不斷開發，如森林砍伐、土地過度開發、地下水超抽等等，當開發程度不超過水環境承載力時，自然環境仍具有自淨回復的能力；當開發程度超過水環境承載力時，原來單純的水文循環機制將會增加不少複雜的變數因子，其結果將會造成水環境的負面的影響。因此，維持水文循環正常進行以達到永續城鄉水環境為一積極重要的課題。

過去我們的大地環境可說是充滿了無數的坑洞間隙，並具有貯集大量水分的功能，例如疏鬆的土壤孔隙以涵養雨水，天然埤塘窪地以匯集逕流水，甚至有許多的地下溪谷以容納伏流、湧泉。現在的都市環境不但使地面大量不透水化，也使地面喪失許多積水的溼地埤塘，甚至連地面下的土壤也因地下室興建以及土壤改造而漸漸形成「無孔隙化」，除造成土壤涵養水分的能力減弱，對生態也有莫大的傷害。

目前水資源的經營方式傾向於集中、大型及單目標利用；大型的水資源系統雖可降低營運與保養的人力與經費；如一旦失控，將發生無水可用的窘境。且大型的水資源工程對環境生態的衝擊亦大，災害發生時亦較嚴重，而且集中末端處理洪澇的方式亦無法完全去除洪澇之災害。而小型的水資源工程不僅對生態環境衝擊較小，同時亦可藉由聯合的操作，避免因大型水資源系統的損壞而造成重大的損失。因此兩種水資源系統的搭配使用，才是符合經濟效益與分散風險的最佳做法。而雨水的貯集、滲透利用即為小型水資源系統的應用典範。

在現今歐美最新的生態防洪對策中，均規定建築及社區基地必須保有貯留雨水的能力，以吸收分散部分洪水量，達到軟性防洪的目的，以別於傳統將各區地表逕流集中後，匯集於集水區末端排出的處理方式。一項新的暴雨

洪水的管理方法－低環境負荷法（Low Impact Development, LID）即提供更有效率的都市洪水控制。基本上 LID 是在各區原址透過許多的滲透貯留設施系統組合，以儲蓄（Retain）、滯留（Detain）、滲透過濾（Filter）、處理（Treat）及使用（Use）等方式，來達到減低暴雨逕流之目標。因此可說是一種分散式的減洪策略。為配合狹小擁擠的都市環境，LID 可提供適用於停車場、道路、花圃及接臨建築物的景觀綠地等都市區域的設計手法。其他像是屋頂花園、在低交通量道路或人行步道採用的透水鋪面等較為創新的方式，都是目前 LID 可提供的設計手法。而 LID 設計的主要目標有二，一為透過入滲滯留設施，以減少暴雨逕流量，二為求得最佳效益的水處理方式。

屋頂綠化因具有美化景觀、降低都市熱島及符合綠建築概念之功能，近年備受國外各大都市採行。囿於屋頂綠化有植物竄根、增加建築物載重及導致漏水等問題，國內並無相關設計規定，故本所收集國內外相關工法及技術，於 2010 年完成「屋頂綠化建構技術之研究」報告，以供國內設計及增修訂相關法令之參據。

當全球氣候暖化的效應愈趨明顯，驟雨、暴風等天災頻現，人類自覺對自然環境的破壞，重新思考環境與人的關係，城市發展過程中，也不再只重發展，而是將居民及自然環境條件皆納入規劃考量中，打造人與自然和諧共存的城市。美國西雅圖，是美國第一個達到京都議定書溫室氣體減量標準的城市，西雅圖如何邁向節能減碳的生態城，成為全美最適合人居的大城市，為進一步瞭解其在雨水利用及屋頂綠化設計、技術及實施概況，本次出國藉由參訪該市社區及公共建設之雨水利用及屋頂綠化工程設施，蒐集並瞭解其在雨水利用及屋頂綠化設施之規劃、設計、應用及管理情形相關資料與實施經驗，作為本所未來提升雨水利用系統應用於降低都市熱島效應及屋頂綠化澆灌技術研究能力及綠建築政策擬訂之參考。

貳、出國行程

出差人	徐虎嘯 歐俊顯	出國事由	赴美國進修「美國水資源技術及政策研習」

日期	行程	任務	備考
9/9（日）	台北-西雅圖	啓程、抵達西雅圖	搭乘長榮航空
9/10（一）	西雅圖	參觀雨水管理(滯洪及 BMP 水質處理)設施包括 Bellevue 市滯洪池(與公園、綠地共構)及 BMP	
9/11（二）	西雅圖	參觀西雅圖市 SEA streets, Northgate Mall LID 重要建設	
9/12（三）	西雅圖	參觀西雅圖市 High Point 社區 LID 重要建設	
9/13（四）	西雅圖	參觀 Lakemont 社區水量、水質處理設施, Coal Creek Parkway 公路 BMP	
9/14（五）	西雅圖	參訪華盛頓州 LID（Low Impact Development） Stormwater Research Center	
9/15（六）	西雅圖	參觀西雅圖市雨水利用公共建設包括圖書館、Seattle Center(Space Needle)	
9/16（日）	西雅圖	參觀西雅圖市農夫市場(Pike Place Market) 及水岸碼頭建設 (Seattle Waterfront)	
9/17（一）	西雅圖	參觀西雅圖地區雨水利用設施包括鮭魚保育及孵育設施, Hiram M. Chittenden Locks 及 Issaquah Salmon Hatchery	

9/18（二）	西雅圖	參觀西雅圖市重要綠屋頂（Green roofs）設施包括 Gate Foundation, Seattle Justice Center, Zoomazoium, Fire Station 10, Ballard Library 等，並觀摩垂直綠化（Vertical Green）設置	
9/19（三）	西雅圖	參觀西雅圖市重要綠屋頂（Green roofs）設施包括 Gate Foundation, Seattle Justice Center, Zoomazoium, Fire Station 10, Ballard Library 等，並觀摩垂直綠化（Vertical Green）設置	
9/20（四）	西雅圖-台北	返程	搭乘長榮航空
9/21（五）	西雅圖-台北	抵達台北	

參、進修參訪內容

在都市區大部分地表被建築物、鋪面所覆蓋，雨水無法入滲補助地下水；大量逕流造成洪水危害，更夾帶污染物進入水體影響水質，爲保護表面水體水質及地下水資源，各項開發計畫應以最小逕流增加量爲設計目標。依污染物之來源與性質可區分爲點源污染（Point Sorce Pollution）與非點源污染（Non-point Source Pollution），前者指污染源有集中且明確的產生與排放地點，其控制方式係將污水收集處理，使符合放流水標準之後排放。累積於地表之塵埃、垃圾、車輛產生之重金屬物質等則爲都市地區主要之非點狀污染源，降雨期間雨水淋洗地面，將晴天累積於地面之污染物沖刷進入水體，這一類污染伴隨降雨產生，沒有集中而明確的發生地點，因而稱之非點源污染。

暴雨管理系統主要用來減緩洪患及都市暴雨逕流所產生之污染物，近年各國投入大量資金進行暴雨管理研究。依據美國環保署（EPA）估算，目前美國70%以上的水污染來自非點源，有的城市如西雅圖市，90%以上的水污染來自非點源，隨著環境法規日趨嚴格，美國聯邦和州環境管理部門對暴雨管理提出了更高要求，暴雨引起的地表污染已經被美國環保署列入了國家污染排放消除系統（NPDES, National Pollutant Discharge Elimination System），建築工地，工業設施和市政設施都被要求向環保主管部門申請排放許可證，在申請過程中需要提交明確的暴雨管理規劃，在規劃裏需要提供防止暴雨引起的非點源污染的最佳管理措施，而暴雨引起的非點源表污染中最難解決的問題之一就是雨汙合流所產生的溢流（Combined Sewer Overflows或簡稱CSO），特別是在舊市區，雨汙合流排水系統是地表污染的主要來源。

在1970年代暴雨控制常用最佳管理措施（Best Management Practice, BMP）方式處理，主要在削減沈砂與污染源，而非以減洪爲主要目的，惟

兼具部分防洪之功能，其包含結構性及非結構性方法，非結構性的BMPs則透過一些軟性的策略，耕作方式改善、肥料管理等，預防或降低暴雨逕流及污染所可能造成的危害，結構性的BMPs就是透過一些外加的工法，主要爲捕捉滯留並過濾逕流中之污染物質進入承受水體。結構性BMPs措施有多種類型，包括：滲透浸透系統、草溝、乾濕滯流池、濕地及緩衝帶等。由於設施係藉由池蓄（Ponding）方式處理，因此池蓄滯留時間越長效果越佳，因此所需空間範圍較大，且會衍生營養鹽蓄積造成水質污染之優氧化情形發生，近年已逐漸被LID工法取代。

LID技術是1990年代末期由美國東部馬里蘭州的Prince George’s County和西北地方的西雅圖市、波特蘭市同時創新開發出的一種暴雨管理技術，其原理是通過分散的，小規模的源頭控制機制和設計技術來達到對暴雨所產生的逕流和污染的控制，使開發地區儘量接近於開發前的自然水文循環，它不僅不需要大塊的土地資源就能將雨水逕流的大部分留在原地對地下水進行補助，使雨水變爲資源，而且還能結合景觀設計對非點源污染進行處理，使開發後的都市水文循環儘量接近於開發前的狀態，美化城市和社區的環境。LID的水文功能包括綜合利用土壤和植被的蓄流、入滲、過濾和蒸發等方式減少地表逕流排水量，通過使用綜合的或者分佈的暴雨蓄滯區控制水交換的進度和頻率，以及交換的水量，還能減少暴雨流域不透水面積，延長水的流路和逕流時間，此外LID具有保護環境敏感區，例如河流兩岸的緩衝區、濕地陡坡、有價值的樹木、洪泛區、林地等功能，其技術包括綠屋頂（Green Roof）、透水鋪面（Porous Pavement)、雨水花園（Rain Garden)、草溝（Vegetated Swales)及自然排水系統（Natural Drainage System），這些技術措施不僅僅可以減少暴雨帶來的城市洪澇災害和水質污染，而且還會帶來很多生態、社會和經濟的效益，比如緩和城市的熱島效應、節省能源、創造都市內的野生動物棲息地，並爲人們創造出舒適的都市生活環境和空間。

LID 主要目標之一爲增加雨水入滲至地表以補注地下水、增加蒸發散量等以降低逕流體積並有效利用水資源。LID 設計可幫助開發區仿造開發前水文環境降低污染物，其強調成本效益，並利用多種策略使其接近開發前水文狀態及降低因開發所造成之衝擊；同時利用 LID 設計可增加當地透水環境、保護公眾健康及減緩開發者與當地政府的資金問題；當逕流近乎於資源，將可取代大量投資於暴雨疏導及管理之工程成本。

由於LID不同於以往傳統暴雨管理工程之方法，係以小區域（micro-scale）概念管理降雨落於地表所形成之逕流；其方法牽涉各項措施的配置聯結以削減特定污染物、流速及體積，其設施包含：貯雨桶、植生溝、緩衝帶、人行道貯留、樹木之保存、雨水花園、透水鋪面、土壤改良及不透水面降低與區隔等。LID技術因可以解決合流污水和生活污水溢流（Sanitary Sewer Overflow或簡稱SSO），目前紐約市、華盛頓哥倫比亞特區、芝加哥和舊金山等大都會，均在制定利用LID技術控制CSO和SSO的發展規劃，並已於近期更名爲綠色暴雨基礎設施（Green Stormwater Infrastructure, GSI）。

1997年，聯合國氣候變遷綱要公約組織（UN Framework Convention on Climate Change, UNFCCC）通過京都議定書，規範主要工業國家溫室氣體排放減量，希望簽約的141國能在2012年時降低1990年CO_2排放量的7%；但是溫室氣體排放量全球名列前茅的美國並未簽署。當美國聯邦政府拒絕簽署京都議定書時，西雅圖卻發起全美850個城市簽署西雅圖氣候變遷計畫，其減碳成績遠遠超前京都議定書目標，他們利用LID技術仿照大自然運作的模式整治河川、滲濾雨水逕流、蓋綠建築、公投百年綠地計畫與復育水岸，全力增加綠地，值得台灣借鏡參考。

以下將透過案例介紹，清楚瞭解其技術在西雅圖市之落實與實踐。

（一）貝爾維尤市(Bellevue)暴雨管理設施

貝爾維尤市位於美國華盛頓州的金郡(King County)，是華盛頓州人口第五多的城市，與西雅圖市隔著華盛頓湖相對，為避免暴雨造成的都市洪水，影響居民生活安全，該市於全市境內共規劃設置8座洪水控制設施及超過100多座滯留池設計，並藉由解說牌製作達到教育民眾目的（如圖1）。以下將介紹參訪Foest Glen公園、Northgate Mall滯留池及Lakemont 社區洪水控制設施設計。

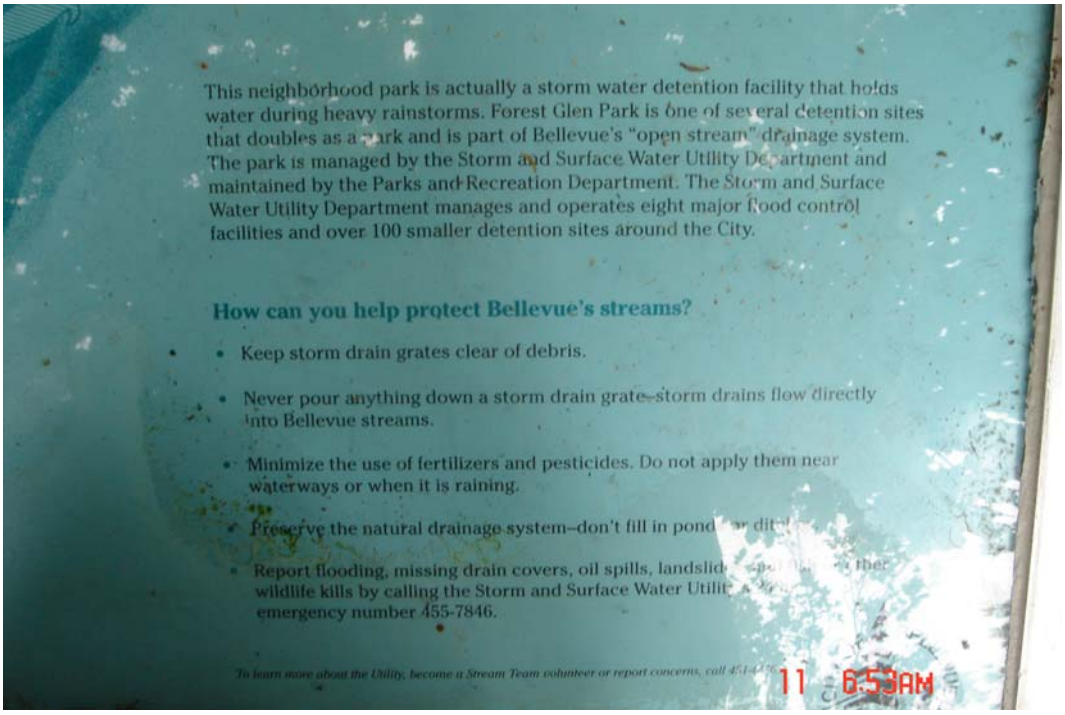


圖1　貝爾維尤市的Foest Glen公園滯留池設計解說牌

Foest Glen公園是貝爾維尤市100多座鄰里公園結合滯留池設計的公園之一，該公園基本上在平時為一民眾休憩之鄰里公園，其內並設置有兒童遊戲區（如圖2、3）。為匯集暴雨發生時附近社區雨水，該公園在設計時依其地形採下凹式滯留池設計（如圖4、5），其形式與一般水土保持開發所採用的沈砂滯洪池無異，只不過兼具有休憩功能，為避免蓄積雨水影響鄰近社區安全，滯留池於鄰社區仍採築堤方式興建（如圖6），另在設計上針對暴雨過大至蓄積雨水過多超出滯留設計容量時，該公園於匯集低處設有溢流口，將多餘雨水直接排放置鄰近下游河川（如圖7）。此外在公園附近鄰道路兩旁

圖2　貝爾維尤市的Foest Glen公園（1）

圖3　貝爾維尤市的Foest Glen公園（2）

圖4　Foest Glen公園下凹式滯留池設計（1）

圖5　Foest Glen公園下凹式滯留池設計（2）

圖6　Foest Glen公園滯留池安全設計

圖7　Foest Glen公園滯留池溢流口設計

之排水溝則配合基地開發與自然低窪地形採草溝方式設置（如圖8、9），除可儲存地表逕流至地下含水層外，並兼有滯留池功能可將部分污染源去除。

圖8　Foest Glen公園草溝設計（1）

圖9　Foest Glen公

園草溝設計（2）

Northgate Mall爲位於貝爾維尤市的一座購物商場，該商場於興建時，西雅圖市政府爲避免大面積開發致衍生都市暴雨之洪水問題，於該商場之停車場四周搭配景觀設置有生態滯留池系統（如圖10），並製作告示牌教育民眾不得隨意穿越破壞（如圖11）。生態滯留池系統是採小型分散方式設計於停車場四周之分隔島，因配合地形故系統規模不大（如圖12），惟爲使系統能發揮功效，工程在設計上有2項重點必須予以考量：

圖10　Northgate Mall生態滯留池系統

1. 分隔島設計時爲使廣場逕流雨水匯集，應於匯集口處設置開口（如圖13），使逕流雨水流入生態滯留池中。同時爲避免水流過大將雜物帶入滯留池中，匯集口鋪設有礫石（如圖14），將可有效降低雜物流入池中影響功能。
2. 分隔島設計需採下凹式蓄水設計（如圖15），同時爲增加池蓄（Ponding）效果，池中應種植植栽，除可增加地表摩擦延遲流動速率外，亦具有去除污染源之功能。此外，爲避免水量過大造成溢流，池內

並設有溢流口，且溢流口上置有格柵可避免雜物流入阻礙水流流動（如

圖11　Northgate Mall生態滯留池系統告示牌

圖12　Northgate Mall分隔島之生態滯留池系統

圖13　Northgate Mall分隔島之生態滯留池系統開口設計（1）

圖14　Northgate Mall分隔島之生態滯留池系統開口設計（2）

圖15　Northgate Mall分隔島之下凹式生態滯留池系統設計

圖16　Northgate Mall分隔島之生態滯留池系統溢流口設計

圖16）。

Lakemont 社區爲貝爾維尤市的私人社區，在開發時西雅圖市政府於該社區規劃置1座洪水控制設施，爲貝爾維尤市8座洪水控制設施之一（如圖17），該洪水控制設施類似滯洪池設計，相較於Foest Glen公園及Northgate Mall滯留池，係屬大規模之滯洪設施，平時爲社區居民之遊憩空間，惟爲儲蓄社區洪水，其設計亦採下凹式設計（如圖18），同樣爲增加池蓄（Ponding）效果，設施內種植草皮以增加地表摩擦延遲流動速率（如圖19）。此外，爲避免水量過大造成溢流，設施內並設有溢流口，且溢流口上置有格柵可避免雜物流入阻礙水流流動（如圖20）。由於該滯洪設施除滯洪效果外，爲避免匯集社區洪水所產生的污染物直接排放置河川衍生的污染問題，在設計時亦採BMP規劃將其作爲非點源污染設施，透過土壤滲透將這些非點源污染物去除，爲增加滲透效果，池底土壤採用不同配比之級配土鋪設，同時爲增加池蓄之滲透時間，除於設施內種植草皮外，設計上亦採雙池延長流路方式設計（如圖21）。因設施具有去除非點源污染物之功能，爲確保設施功能，並避免污染物附著於級配造成優氧化的氣味問題，設施需定期進行級配更換。

圖17　Lakemont 社區滯洪池設計

圖18　Lakemont 社區滯洪池下凹式設計

圖19　Lakemont 社區滯洪池植栽設計

圖20　Lakemont 社區滯洪池溢流口之隔柵設計

圖21　Lakemont 社區滯洪池之雙池設計

（二）SEA Street街道排水設計

本計畫全名為Street Edge Alternative Project計畫，基地位於西雅圖北部介於117街和120街的第二大道（2nd Ave）的路段（如圖22），為2000年由西雅圖市政府公共事業局（Seattle Public Utilities）、交通局（Seattle Transportation）和部分居民利用多項LID技術的試驗項目共同合作完成的一項實驗性計畫，全長660英尺，係將街道邊緣的設計提供別於傳統的替代方案，目標是減少暴雨逕流，從設計到施工，皆由西雅圖公共事業局和街道居民共同參與制定了最終開發方案，一般簡稱為SEA Street計畫。

圖22　SEA Street街道

全案由西雅圖市政府公共事業局以自然排水的觀念和作法，將這個路段改頭換面，由於這個路段位於純住宅區，車流量不多，設計團隊將原本筆直且過寬的25英尺街道大量縮減為14英尺，勉強容納兩輛車可以擦身而過（如圖23），並將道路設計的彎彎曲曲，一方面減低車速，一方面利用道路彎曲產生的剩餘空間設計成生態窪地（Swale）（如圖24），並將街道兩邊用此生態窪地取代了傳統的路溝和管道種植耐水的植栽，以容納並淨化柏油路街道所產生的地表逕流，除此之外，這條路段的改造還包括了原本沒有的人行

圖 23　SEA Street 車道設計

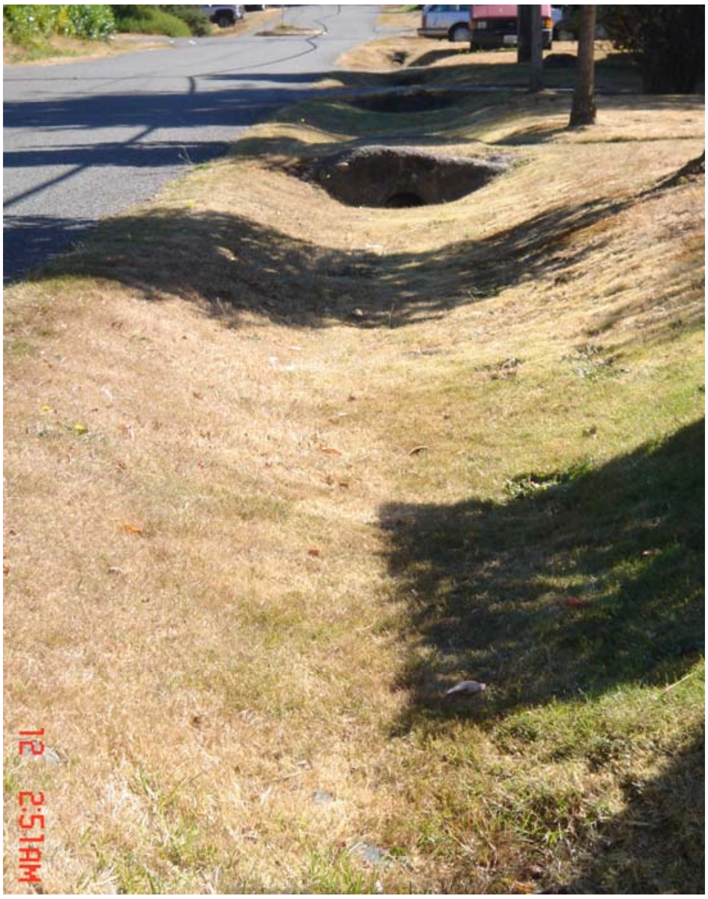


圖 24　SEA Street 街道生態窪地設計

步道（如圖 25），整個工程設計約減少不透水面積超過 18%。總經費約爲 65 萬美元。

圖 25　SEA Street 街道人行道設計

由於SEA Street是一個實驗性的計畫，SEA Street專案所在的區域，原來沒有單獨的雨水排水系統，雨水全部進入污水系統。2001年自然排水系統建成後，西雅圖公共事業局就一直監測評估其自然排水的成效，作爲日後街道排水設計的參考，經受了2007年12月3日100年一遇的暴雨，社區沒有一家房屋進水，98%的暴雨逕流留在了原地（降雨量爲6小時193mm），可以成功的在現地處理98%的逕流量，也就說是，利用地窪植栽地的自然排水設計，幾乎可以取代傳統下水道的功能，此外，研究也證實，SEA Street所選用的植栽和土壤也成功的移除了徑流中所含的污染物質。SEA Street的目的除了藉由自然排水來保護河川生態，免除不必要的工程，同時也致力於於塑造一個更舒適、美觀的街道環境，更進一步，SEA Street也希望扮演教育的功能，透過有別於下水道的開放露天的設計，讓民眾對都市硬鋪面、雨水逕流、和生態環境的關係有更進一步的認識。

（三）High Point社區改造計畫

High Point（高點）社區位於西雅圖南邊 Long Fellow Creek 流域，面積約爲 0.5 平方公里，是生態非常敏感的區域，原本是一個貧民區，住著許多從東南亞與東非過來的移民，早期大部分的人，對這裡的印象是一個青少年死亡率高並藏有毒品交易的危險區域，這些二次大戰後陸續出現的貧民區，凸顯美國民貧富不均的嚴重問題。在柯林頓政府時期開始執行一項名爲「希望計畫」的貧民區改造計畫，在西雅圖住宅管理局(Seattle Housing Authority，SHA)的努力下，不僅讓高點社區徹底改頭換面，同時在這裡也可以看到許多設法與自然和諧共存的成功案例（如圖 26）。

圖 26　High Point 社區

Long Fellow Creek 曾是鮭魚生活的河流，但近百年來，都市的發展造成對水環境的嚴重破壞，鮭魚數量劇減。2000 年聯邦通過了西雅圖所有水域的鮭魚爲瀕臨危機之生物後，開始修復河道、恢復鮭魚的棲息地便成了首要任務。High Point 社區是二次大戰時期爲政府工人修建的臨時住房，1952 年交予西雅圖市政府作爲低收入居民社區。社區的排水系統大部分是雨汙水合

流機制，暴雨逕流未經處理便直接排放進入大海和河道，對迴游的鮭魚造成很大的威脅。所以西雅圖市政府在 High Point 社區改造中選用 LID 技術來解決暴雨逕流引起的非點源污染問題，並且將暴雨管理與生態景觀結合起來，創造一個綠色的舒適的居住環境。社區內建有自然排水系統（如圖 27）、雨水花園（如圖 28）、生態蓄水池（如圖 29）、透水路面（如圖 30）、生態過濾草溝（如圖 31）等 LID 單元，所有的 LID 單元都是依 25 年頻率的暴雨設計。

圖 27　High Point 社區自然排水系統設計

High Point社區的生態蓄水池基本上也是一座滯洪池，然其規模並不如想像中來的規模龐大，該社區住戶爲數不小，但僅僅利用這樣大的滯洪池，這是因爲整個社區使用自然排水法的草溝及許多的入滲植被與透水鋪面，如果沒有這樣的設計，那麼滯洪池會是目前所看到大小的五倍，這些不起眼的草溝、滲植被與透水鋪面又再次的發揮功能，誰說滯洪池一定要大，只要每個社區都能夠規劃一個適當的滯洪池，將雨水留在地表下，水患將可大幅降低。

圖 28　High Point 社區雨水花園設計

圖 29　High Point 社區生態蓄水池設計

圖 30　High Point 社區透水路面設計

圖 31　High Point 社區生態過濾草溝設計

（四）Puyallup研究推廣中心

Puyallup 研究推廣中心爲西雅圖市政府與華盛頓州立大學共同成立（如圖 32），其目的在於提供一個示範性教學，研究和推廣環境，以促進自然資源保護，強化社會責任，解決社會和經濟發展，並遵循環境、社會和經濟實踐。

圖 32　Puyallup 研究推廣中心

LID 的設計理念是著重於從源頭上控制暴雨逕流，利用植被、土壤、透水路面等儲蓄、入滲、過濾和蒸發功能儘量使水文循環與開發前的自然水文循環接近。同時 LID 的設計理念與景觀、綠化、園林建造等融入一體，不需要多餘的土地資源，使其技術可以在不同的地區和不同的氣候條件下合理應用。在流域範圍，如果將 LID 與流域管理實踐結合，會取得流域性的環保和生態效果，其應用的效率取決於當地的條件和情況，但其應用不會受到空間的限制。在資源性缺水的城市，LID 的作用主要是對地下水進行補注，而在雨量充沛的城市，LID 的主要作用是防止都市洪水和減少非點源污染。爲了有效的利用 LID，設計前應當對土壤的滲透率進行評估，同時，地面坡

度和地下水的深度也需要考慮在內。儘管 LID 技術在美國得到推廣應用，但所用的水文模型多採用傳統的都市水文循環模型，與實際情況有很大的差別，不能較好地反映 LID 技術的特性，這主要是由於 LID 的植被、改良後的土壤所主導的水文循環與傳統的水文循環不同。

圖 33　Puyallup 研究推廣中心大尺度現地 LID 試驗

爲確實瞭解並得到實證，西雅圖市政府與華盛頓州立大學合作，於 Puyallup 研究推廣中心進行一系列大尺度現地 LID 試驗（如圖 33），透過該試驗中心進行現地之 LID 工法試驗分析，除作爲後續實際規劃設計之修正參考外，並可提供作爲對外說明該工法實際成效之依據。該中心的停車場全部採透水混凝土（如圖 34）或透水瀝青（如圖 35）方式設計，因當地土壤屬透水性不佳之黏土，爲確保此透水性鋪面能發揮成效，在設計時係以保排水設計方式取代其透水性設計，亦即透過鋪面孔隙及鋪面下導水性良好之級配層，迅速將地面之積水導入地面下以避免造成人車行動之不便（如圖 36）。

爲便於觀察及瞭解這些透水混凝土或透水瀝青之實際保排水成效，該中

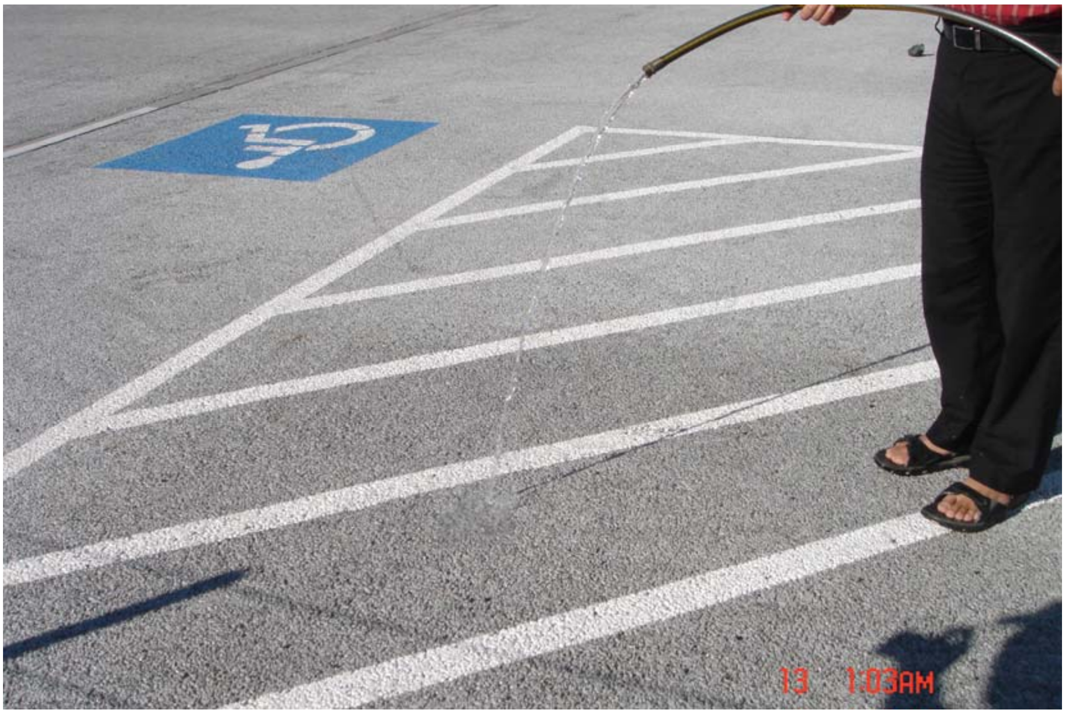


圖 34　Puyallup 研究推廣中心停車場透水混凝土試驗

圖 35　Puyallup 研究推廣中心停車場透水瀝青試驗

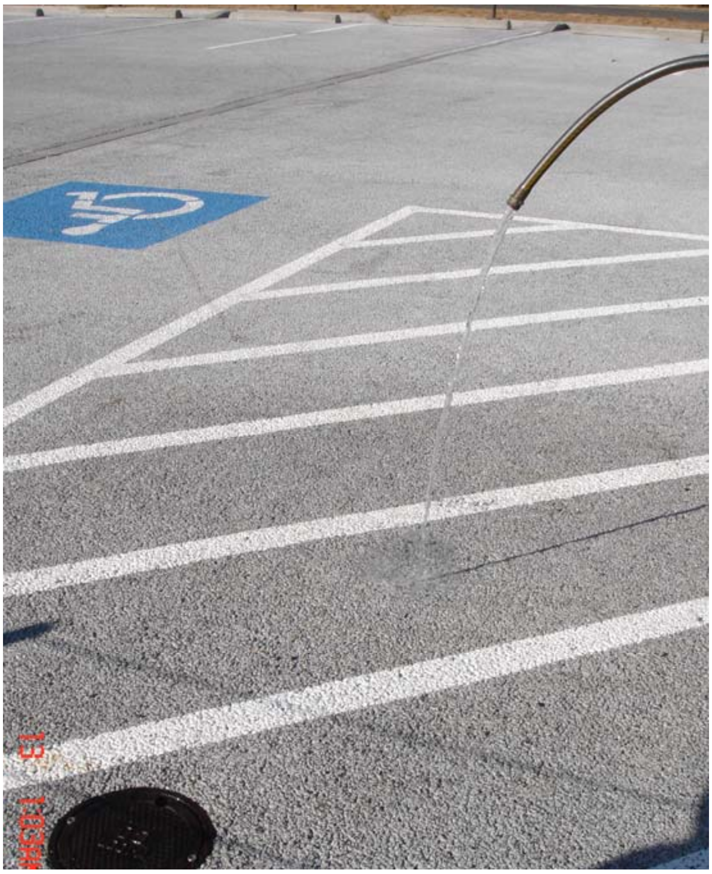


圖 36　Puyallup 研究推廣中心停車場透水混凝土透水性能

心於場址周邊設置有監測設備（如圖 37），透過該監測設備可詳實記錄並瞭解其保排水性能。另為確保其保排水成效並避免車載重造成鋪面之不均勻沈陷，該鋪面設計厚度高達 80 公分（如圖 38）。此外該中心另一項試驗重點為用於綠屋頂、雨水花園及生態滯留池等之植栽試驗，由於西雅圖市政府為減緩都市開發造成的雨洪水問題，先前已介紹過在許多開發設計案已將雨水花園及生態滯留池設計引入，而這些設計基本上為增加成效，皆須將植栽納入設計，藉由增加地表摩擦方式，延遲水流流動速率，達到增加池蓄（Ponding）的效果，並藉此發揮去除污染源之功能。由於都會區污染源多含有重金屬，因此植栽的選取非常重要，除對水量要求不高外，其對水質要求也必須予以考量，在選取上一般係以澆灌頻率低及能去除重金屬等營養鹽之耐旱植物為優先考量。

圖 37　Puyallup 研究推廣中心停車場透水試驗監測設備

圖 38　Puyallup 研究推廣中心停車場透水混凝土鋪面厚度設計

圖 39　Puyallup 研究推廣中心綠屋頂試驗

圖 40　Puyallup 研究推廣中心雨水花園試驗

圖 41　Puyallup 研究推廣中心雨水收集系統（1）

圖 42　Puyallup 研究推廣中心雨水收集系統（2）

圖 43　Puyallup 研究推廣中心雨水花園土壤配比試驗

爲提供符合西雅圖市氣候環境需求之植栽，該中心於現地分別針對綠屋頂（如圖 39）及雨水花園（如圖 40）規劃設計了 2 組試驗設施。另爲模擬並瞭解屋頂雨水對植栽之影響，該中心於現地收集屋頂雨水作爲現地植栽澆灌使用（如圖 41、42）。爲瞭解土壤配置對植栽存活之影響，在綠屋頂試驗部分共設置 16 組不同土壤條件，在雨水花園部分則利用 4 種土壤，5 種配比方式共搭配出 20 組不同組合進行相關試驗（如圖 43）。此外，爲充分觀察及瞭解這些植栽對重金屬營養鹽之去除效率，2 組試驗設施均設置有監測裝置（如圖 44、45），透過採樣水體進行相關化驗，以進一步瞭解其去除效力。

LID係整合性之概念，係在都市開發的同時將治水的新思維予以融入。LID對於暴雨事件所產生逕流及污染物可進行攔阻削減，此外LID主要目標之一爲增加雨水入滲至地表以補注地下水、增加蒸發散量等以降低逕流體積並有效利用水資源。由於LID不同於以往傳統暴雨管理工程之方法，透過小

圖 44　Puyallup 研究推廣中心雨水花園監測設備

圖 45　Puyallup 研究推廣中心綠屋頂監測設備

區域概念方式進行降雨落於地表之逕流管理，加上可用方法眾多，並涉及各項措施的配置聯結，方能有效達成削減特定污染物、流速及體積，為確保這些設施發揮應有功能，西雅圖市政府於此推廣中心設置並進行一系列現地模擬試驗，並將相關研究成果落實於實際案例，成功發揮都市減洪成效，廣泛成為美國各大都市競相學習仿效，這就是LID在美國進年來迅速發展的主要動力之一。

（五）WoodLand Park 動物園LID設施及綠屋頂

WoodLand Park 動物園位於西雅圖市區，為一私人經營的動物園，曾於 2008 年榮獲全美 Top Ten 動物園之一（如圖 46）。由於動物園本身兼具教育目的，因此業主配合西雅圖市政府於園區內設置許多 LID 設施及綠屋頂。進入園區即可看出業者之用心，首先印入眼簾的即為企鵝管旁一片由西雅圖市政府製作的透水鋪面及雨水花園解說牌（如圖 47），透過解說教育民眾透水鋪面可使雨水滲透至地下，減少地表逕流，如此將可減低雨水排水系統負荷，大大降低污染水流入河海機率，同時還能有效補注地下水資源。

圖 46　WoodLand Park 動物園

圖 47　WoodLand Park 動物園透水鋪面及雨水花園解說牌

此外，解說牌也針對一般住家，提供透過雨水花園設置亦可達到雨水截流的目的，同時也透過現場實例教導民眾雨水花園之設置重點（如圖 48）。

圖 48　WoodLand Park 動物園雨水花園設計

而同樣在企鵝館旁，園方也製作了另一面有關如何利用雨水花園的植栽進行水質淨化的解說牌（如圖 49）。透過解說牌解說讓民眾瞭解雨水花園

圖 49　WoodLand Park 動物園雨水花園解說牌

圖 50　WoodLand Park 動物園雨水花園水質過濾設計

除有上述將雨水截流、入滲的功能外，還同時兼具有濕地之天然過濾效果，能藉由植物之吸附作用將水中的重金屬營養鹽去除，現地並設置有實例以加深民眾印象（如圖 50、51）。由於企鵝館對水質需求高，除透過前述雨水

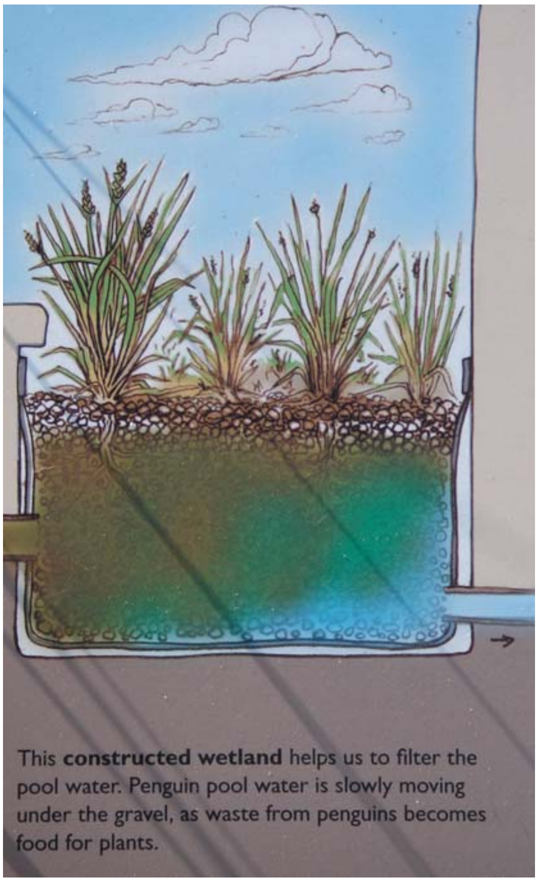


圖 51　WoodLand Park 動物園雨水花園水質過濾解說牌

花園進行水質過濾外，為維持企鵝所需之低溫，園方亦透過地中管設計，將企鵝館內之循環水打入地底 300 英尺深度，藉由該處地下水終年可維持在 55°F的特性，以提供企鵝生活所需，相關資訊同樣亦藉由解說示意圖方式，提供民眾瞭解（如圖 52、53）。

園區另一項參觀重點為遊客休憩區的綠屋頂設計，由於園區佔地廣大，為提供一般遊客一個舒適休憩空間，園方特規劃設置一座遊客休憩區，並於休憩區屋頂上方設置一座綠屋頂，除提供作為園區一項 LID 之減洪設施

外，同時亦可有效降低休憩區屋頂因日照直射的輻射高溫（如圖 54）。該

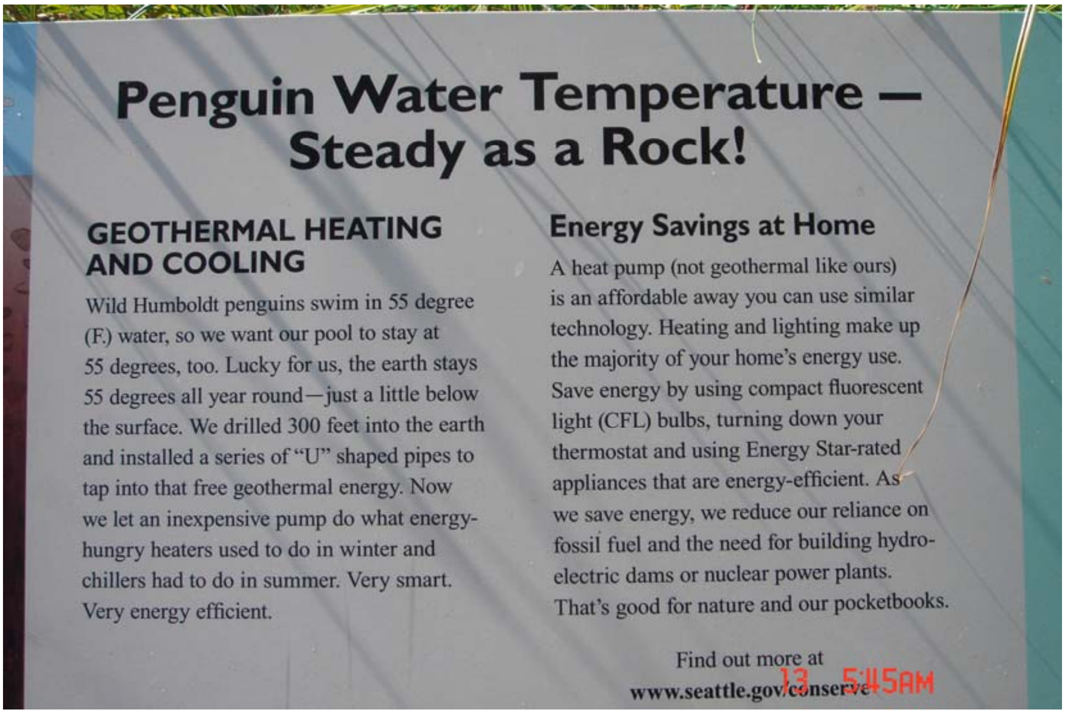


圖 52　WoodLand Park 動物園地中管設計解說牌（1）

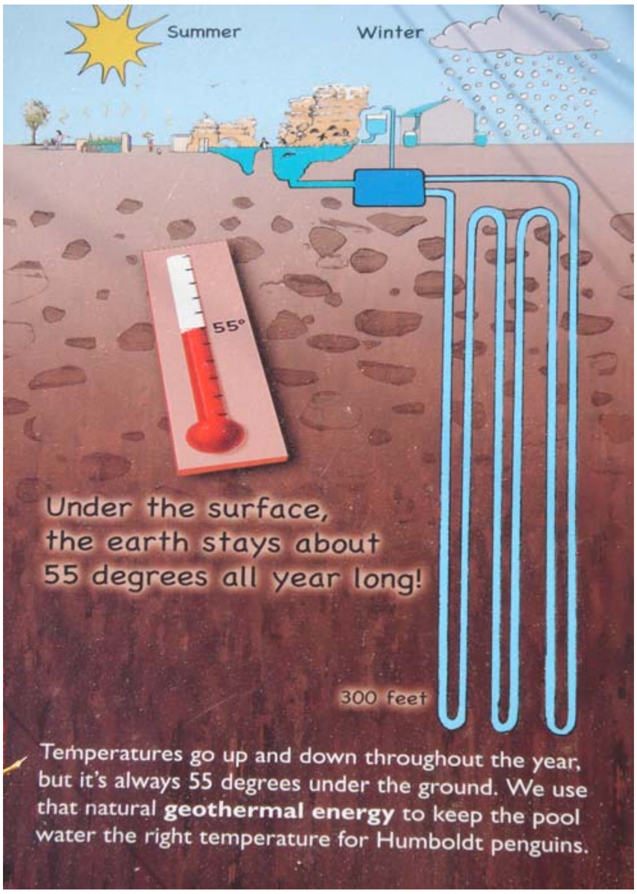


圖 53　WoodLand Park 動物園地中管設計解說牌（2）

綠屋頂基本上屬一斜屋頂構造形式，因此在維護管理上並不容易，加上西雅圖市之年雨量並不多，故可明顯看出綠屋頂雖能維持功效，但呈現的是粗放

圖 54　WoodLand Park 動物園綠屋頂設計（1）

圖 55　WoodLand Park 動物園綠屋頂設計（2）

式雜草叢生景象（如圖 55），與一般人的印象應有段差距，經園方管理人員解說，該綠屋頂設計之初即考量當地氣候環境，規劃採粗放式管理，完全不需人工維護，讓植物自由生長，現在所看到的植栽亦非園方當初栽植的植物，均是經過自然演替由大自然透過其他媒介所帶來的植栽，因此園方並不用「屋頂花園」這樣的名詞，而是採用「綠屋頂」或「生態屋頂」的稱謂，以避免民眾誤導。

（六）西雅圖司法大樓與市政廳之綠屋頂

「綠屋頂」(GreenRoof)，又有人稱作生態屋頂(Eco-roof)、自然屋頂(Nature Roof)、植物生長的屋頂（vegetated Roof）、有生命的屋頂(Living Roof)，一般是指有植物覆蓋的屋頂，也就是屋頂綠化，從1970年代開始，德國用法令以及財政支持來提倡綠屋頂，其後技術才逐漸推廣至美國、加拿大，近幾年新加坡與大陸的北京市則亦於如火如荼地進行綠屋頂政策推動工作。綠屋頂存在的目的是爲了在到處都是建築物的都市中，將地面所失去的綠地從屋頂上找回來。其好處除了能改善都市熱島效應外、也能降低空氣污染、增加都市綠色空間，並能減緩大雨的水流入下水道的速度，減少下水道的負荷大大減低淹水的機率。

美國奧勒岡州（Oregon）最大的城市波特蘭市，則是推行綠屋頂政策最早，一般公認爲北美綠屋頂的領導者。波特蘭市發展綠屋頂的主要動機是爲了暴雨管理，尤其是配合下水道氾濫的議題。爲了因應管理暴雨逕流的挑戰，波特蘭環境服務局（Breau of Environmental Serives, BES）提議對建築物所有人提供誘因來使其於該地點採用管理暴雨最好的方式。綠屋頂，環境服務局稱作生態屋頂，只要符合城市標準，則生態屋頂被認爲是現在的最佳管理實踐（the Best Practice）。

而西雅圖市政府則承襲了波特蘭市綠屋頂之推動，於2002年10月在西雅圖司法大樓（Seattle Justice Center）建置了第1座綠屋頂（如圖56）。

圖56　西雅圖司法大樓綠屋頂設計

該大樓並於2004年取得美國綠建築協會LEED銀級綠建築之認證（如圖57）。該處屋頂花園係採開放式設計，大樓並於周邊設置有涼亭及桌椅，提

圖 57　西雅圖司法大樓 LEED 銀級認證

供作爲來此大樓洽公民眾休憩之場所（如圖 58）。由於該綠屋頂自興建後，均委請專人定期進行維護管理，因此仍能保持原有之生態風貌（如圖 59）。參訪當天正逢管理人員於現場進行除草澆灌工作，於訪談中瞭解爲維

圖 58　西雅圖司法大樓綠屋頂開放設計

圖 59　西雅圖司法大樓綠屋頂生態現況

持這樣的景象，該大樓每年必須編列相當維護經費，並由專人進行照護工作，尤其需定期進行除草，否則原有植栽存活機率將大爲降低。然而考量因設置於屋頂，加上西雅圖原本雨量就不多，澆灌情況受限，故植栽的耐旱性能必須列爲選取的重點。此外爲使土壤內多餘水分自然排除避免積水造成危害，該綠屋頂採傾斜式設計（如圖 60），同時爲避免暴雨造成淹水影響安

圖 60　西雅圖司法大樓綠屋頂之傾斜設計

全，該綠屋頂也設置有溢流排放口，並透過周邊排水溝將其匯集排放（如圖 61），另外爲避免排水量過大將土壤帶出造成排水溝阻塞，設計時於該排放口置有礫石予以攔阻（如圖 62）。

而與西雅圖司法大樓鄰近的西雅圖市政廳則爲該市建置的第2座綠屋頂（如圖63）。該綠屋頂於2003年7月建置，該大樓並於2005年取得美國綠建築協會LEED黃金級綠建築之認證（如圖64）。此綠屋頂因無對外開放，故僅能於司法大樓遠眺，據司法大樓管理人員表示，該大樓綠屋頂原本也是委由該管理人員負責維護管理，爲樽節經費已將該經費刪除，故後續維護已採放任方式辦理，因此其綠屋頂現況（如圖65）已與圖63所示之原先景況差異

圖 61　西雅圖司法大樓綠屋頂之排水溝設計

圖 62　西雅圖司法大樓綠屋頂之排放口設計

圖 63　西雅圖市政廳綠屋頂設計

圖 64　西雅圖市政廳 LEED 黃金級認證

甚多，幾乎已完全枯死，照片中部分區域仍維持鮮綠，則是該管理人員私人進行測試，僅該處維持澆灌其他區域採放任方式處理，可明顯看出兩者之差異。

圖 65　西雅圖市政廳綠屋頂生態現況

肆、心得與建議

一、心得

台灣地區各都市持續開發土地，以追求創造高經濟成長，隨著都市發展，大量的人工構造物導致都市環境大部分是不透水表面，而也因都市化不透水面積增加，導致改變原本平衡的水文機制，衍生都市熱島效應、水患、水污染及水資源等問題。目前大多數都市逕流管理的對策均以加大排水系統輔以集中末端處理之觀念，使逕流加速排放至下游或鄰近地區。但集中末端處理雖可降低逕流停留時間，但其體積並未相對減少，反而使得下游排水系統處於高流量狀態，結果即使是小頻率之降雨亦會造成下游地區之水患。同時也因這種集中末端處理、加速排放逕流的排水概念，使得現有都市區域缺乏保水、滲透及蒸發機能，造成流域整體的水土保持機能降低，也因都市發展範圍一再擴大，造成許多非點源污染物質隨著逕流直接排入下游，產生許多都市水環境之不利影響。在此一集中末端處理的排水概念下，將所收集的都市地區地表逕流直接且迅速地排放至河川或流域下游地區，因而造成下游地區的洪澇問題。

水資源就像能源一樣，是城市和所有人類集居地所不可或缺的，但是它的價值卻像能源一樣被徹頭徹尾的低估了。人類棲息地的未來，需倚靠政府保衛這些重要財產的意願，然而處在這快速成長的城市中，政府在土地使用管理上就須採取更多更適當的控制，且其挑戰也會越高，因此對這些雨水；與其想藉由更高的堤防，或是更多的抽水機來避免洪水的侵擾，到不如認真地去思考如何導引這些原爲人類生命支援的雨水流往他原本該去的方向。

由於都市生活機能完善，成爲人口匯聚之地，人口集中的結果，導致都市居住用地需求急遽增加，舊都市土地一旦不敷所需，都市居民勢必向都市周圍發展，造成都市區域擴展，當擴展至郊外時，原有的溼地、水田、森林、綠地等區域也因而開始產生都市化之現象，如此將使得這些土地原有之

逕流機制發生改變，進而造成城鄉水環境之丕變。近年來，為了容納大量的移入人口與快速經濟發展之需求，都市街道擴寬或新闢、建物密度增加且樓層增高，停車場與大型賣場等公共設施不斷增建，造成地表不透水區域增加，導致雨水入滲至地表下之機會減少，進而影響地下水補注量，造成洪峰流量及逕流體積增加、集流時間縮短，致使都市洪水災害時有所聞，嚴重威脅居民之生命與財產安全。過去國際水資源經營的方式，傾向於集中、大型及單目標的利用，而水資源系統集中，雖有利於營運與保養，然一旦失控，將無從取得任何替代方案。此外，大型的水資源工程對環境衝擊頗大，因此災害發生時亦較為嚴重，況且這樣地集中末端洪澇處理方式，並無法真正有效去除洪澇災害。反觀小型的水資源工程，不僅對生態環境影響衝擊較小，同時藉由各小系統的聯合操作，將可有效避免因集中系統損換所造成的重大損失，故採大型與小型水資源系統的互相配合，才是符合經濟與分散風險的新世紀利用方式，而雨水的貯集、滲透利用即為極佳的小型水資源系統，應為未來發展的重點。

內政部建築研究所自 1999 年起推行綠建築政策以來，鑑於國內水資源先天分配的缺陷，提出了「基地保水」及「水資源」兩項指標，以達到水資源永續目的，並為協助政府落實相關「保水」政策，本所於 2006 年完成並提出適於臺灣水文及地文條件標準之「建築基地保水滲透貯集技術」研究，並針對部分工法內容，辦理法制化作業及規範之擬定，以作為政府落實永續城鄉建設之參考依據。

本次考察係蒐集瞭解美國西雅圖市在都市暴雨管理及屋頂綠化技術現況、推動實績與未來趨勢，並藉此提升我國在此方面對於相關規範技術之瞭解，可有效作為本所未來訂定相關研究能量及推廣之參考，俾能拓展我國綠建築、智慧建築與生態社區視野，以提升我國在智慧綠建築與屋頂綠化技術領域之影響力。以下亦針對本次考察重點心得，摘要分述如下：

1.相較於臺灣的豐沛雨量，西雅圖當地基於年降雨量的先天條件，對於水資源可以說是錙銖必較，從生態屋頂、雨水收集乃至遍布於社區中傳統型式的 BMP 滯洪池，從生活周遭的小地方都可以看見將水視為重要資源的用心；不單只是講究水量與儘量利用雨水循環用以澆灌、衛生沖洗；基於對於鮭魚等迴游魚類的保護，在水質方面更是用心，對於各類植栽品種適用於何種處所，除了有紮實且長期收集數據的基礎研究，更進一步從傳統滯洪觀念進一步邁入 LID。

2.臺灣有最幸運的地理氣候條件，同時也是最不幸的地方，強降水以及歷來慘痛的洪澇經驗，在在使我國國人對於淹水深惡痛絕，既有公共建設皆以快速排除積水為首要考量與指標，然而工程有其極限，面臨極端氣候日益頻繁的同時，如果再以此思維除了徒增工程建設成本，能否抵禦不可預期的大量降雨(人力永遠無法預期絕對極大值)，以及是否需要投資如此沉重成本來預防這不可知且非常態的災害，其間所得利益與所生損失的權衡，值得我們深思；況且在潔淨可飲用淡水日益匱乏的未來，我國人實應重新省思淹水即為災害的觀念，教育理解水的入滲除了儲存更需要時間，學習與水和平共處，並且導正屋頂綠化等同屋頂花園的刻板觀念，唯有以上形成團體共識落實根植於思想中，我國始能真正從 BMP 只是儲洪的觀念，進一步邁向低度環境衝擊的 LID 領域。

3.近年來，世界各國都面臨著城市擴張帶來的各種各樣的問題，其中之一就是城市發展需要消耗綠地，機動車輛暴增，原來的郊區不到幾年就成為市中心。這些發展都會給城市環境帶來壓力。可是在生態建設中，人們往往認為生態就是綠化，以一個城市有多少綠地，多少樹木來評估城市的生態好壞。因此，在生態城市建設中一味追求漂亮的草坪、名貴的樹木加上人造景觀。為了維護這些名貴的樹木和草坪，往往造成綠化與人爭水的局面，特別是在資源型缺水的城市，這個矛盾更為突出，而且每年的維護費

用也相當的昂貴。人們對建設生態城市的另外一種看法是追求大型的人造生態公園和濕地，而這些生態公園和濕地不是在已經開發的對生態造成嚴重破壞的市中心建造，而是破壞原生態去建造，而在寸土寸金的城市中，很難找到生態公園和人工濕地所需的空間，且僅僅靠幾個生態公園和人工濕地是無法從根本上解決目前的城市生態問題的。這部分可透過西雅圖市的 LID 多樣化小區域設計，藉由從源頭上控制暴雨逕流，利用植被、土壤、透水鋪面等儲蓄、入滲、過濾和蒸發功能，儘量降低因開發造成之水文循環差異，所衍生之都市水資源問題，值得我國借鏡學習。

4.永續計畫的推動應是全方位的思考，惟需藉由評量指標之建構來達成，故應深入瞭解每一個國家、都市甚至城市鄉村，在氣候、水文、地形及生態等方面的差異，研擬水資源永續發展政策及評量指標，循序漸進地推動，始可落實。

二、建議事項

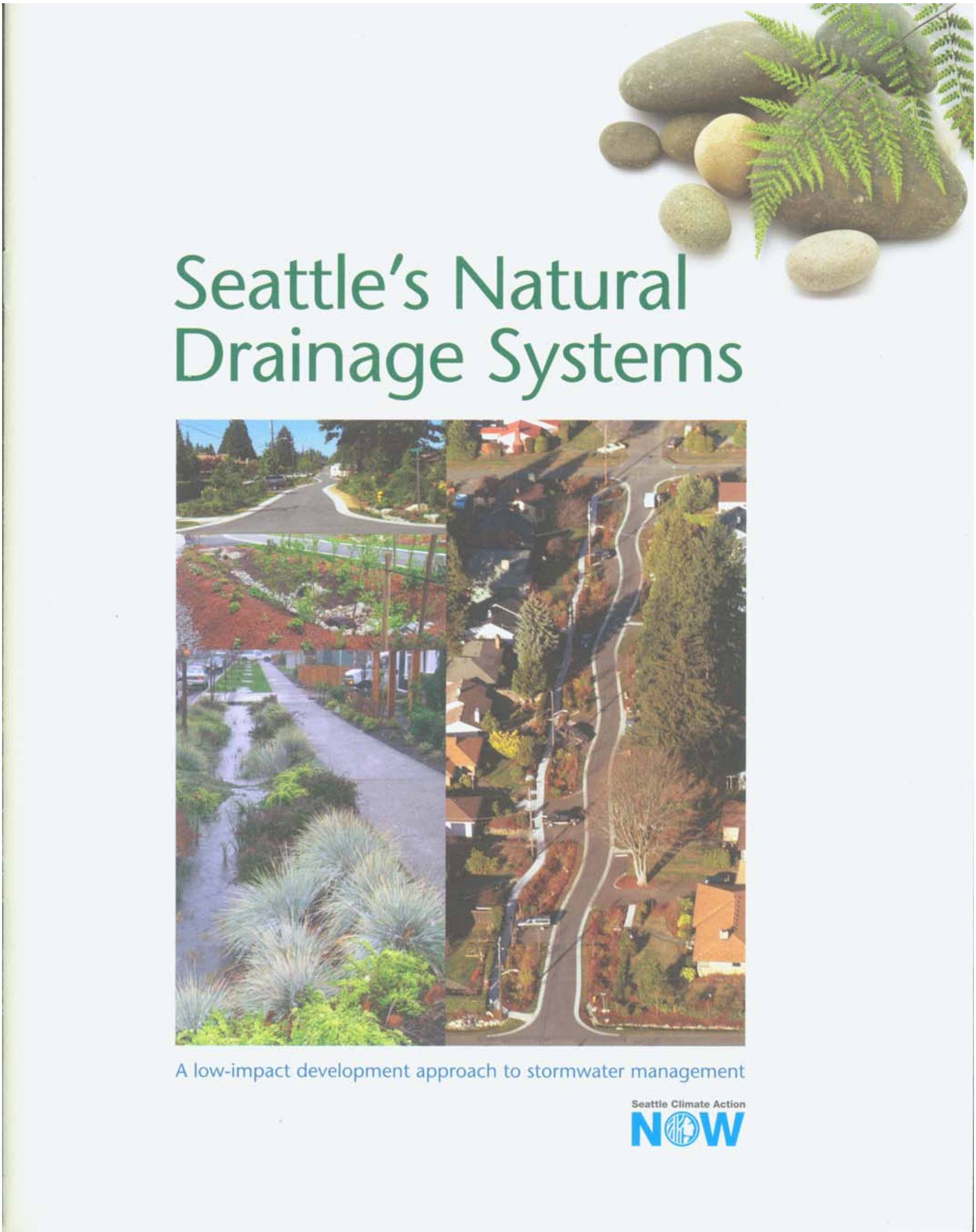
1.由於 LID 是於現地原址透過儲蓄、滯留、滲透過濾、處理及使用等滲透貯留設施系統組合，以達到減低暴雨逕流之目標，因此可說是一種分散式的減洪策略。特別針對狹小擁擠的都市環境，LID 可提供適用於停車場、道路、花圃及接臨建築物的景觀綠地等都市區域的設計手法。其他像是屋頂花園、在低交通量道路或人行步道採用的透水鋪面等較爲創新的方式，都是目前 LID 可提供的設計手法。所以 LID 的設計理念係與景觀、綠化、園林建造等融入一體，不需要多餘的土地資源，使其技術可以在不同的地區和不同的氣候條件下合理應用。在流域範圍，如果將 LID 與流域管理實踐結合，會取得流域性的環保和生態效果，其應用的效率取決於當地的條件和情況，但其應用不會受到空間的限制。在資源性缺水的城市，LID 的作用主要是對地下水進行補注，而在雨量充沛的城市，LID 的主要作用是防

止都市洪水和減少非點源污染。在現今歐美最新的生態防洪對策中，均規定建築及社區基地必須保有貯留雨水的能力，以吸收分散部分洪水量，達到軟性防洪的目的，以別於傳統將各區地表逕流集中後，匯集於集水區末端排出的處理方式。在本次考察可以發現即便 LID 技術已在美國得到推廣應用，但爲確實瞭解並得到實證，西雅圖市政府仍須透過一系列大尺度現地 LID 試驗，作爲後續實際規劃設計及相關工法實際成效之修正參考。本所鑑於國內水資源先天分配的缺陷，雖於綠建築政策中提出了「基地保水」及「水資源」兩項指標，以達到水資源永續目的，並爲協助政府落實相關「保水」政策，於 2006 年完成並提出適於臺灣水文及地文條件標準之「建築基地保水滲透貯集技術」研究，並針對部分工法內容，辦理法制化作業及規範之擬定，但工法之實際成效並未有相關監測數據可提供，同時在教育宣導方面也似乎欠缺實際案例可供建築設計者參考，建議可比照西雅圖市政府之作法，於本所台北及台南試驗中心，利用南北區域水文及氣候條件差異，實際建置相關工法之現地試驗，以充分提供作爲政府落實永續城鄉建設之參考依據。

2.「綠屋頂」(GreenRoof)，又稱爲生態屋頂、自然屋頂、有生命的屋頂，一般多指有植物覆蓋的屋頂，也就是屋頂綠化，自 1970 年代開始，德國透過法令以及財政支持提倡綠屋頂以來，其後技術逐漸推廣至美國、加拿大，近幾年亞洲的新加坡與大陸的北京市亦如火如荼地進行綠屋頂政策推動工作。由於綠屋頂具有美化景觀，並可於到處都是建築物的都市中，將地面所失去的綠地從屋頂上找回來，改善都市熱島效應外、亦能降低空氣污染、增加都市綠色空間，同時具有減緩大雨的水流入下水道的速度，減少下水道的負荷大大減低淹水的機率，近年備受國外各大都市採行。囿於屋頂綠化有植物竄根、增加建築物載重及導致漏水等問題，國內並無相關設計規定，故本所收集國內外相關工法及技術，於

2010 年完成「屋頂綠化建構技術之研究」報告，以供國內設計及增修訂相關法令之參據。本次考察也發現，由於屋頂綠化之植栽位處於屋頂，在陽光烈焰及澆灌不易之嚴峻條件下，如無專人維護，即便在美國，亦可發現其呈現的景象多爲粗放式雜草叢生，此與一般人綠意盎然的印象應有相當大的差距，但基本上只要考量當地氣候環境，即便採粗放式管理，完全不需人工維護，讓植物自由生長，讓植栽經由大自然透過其他媒介所帶來的自然演替，依然可以發揮其原有的功效，尤其屋頂綠化在都會區是暴雨管理政策之最佳實踐，因此爲提升國內推廣成效，建議本所應進一步研訂屋頂綠化在建築設計上之設計指引外，同時爲避免民眾誤導，應避免使用「屋頂花園」這樣的名詞，而是全面改用「綠屋頂」或「生態屋頂」的稱謂，同時藉由教育宣導使民眾有正確認知。

附錄 1－西雅圖市政府公共事業局「自然排水系統」文宣



A message from Mayor Greg Nickels

Seattle Climate Action NOW
SeattleCAN.org

The world's cities are facing a dilemma: around the globe, climate change is expected to bring more intense storms—overloading existing drainage systems and increasing the risk of urban flooding. In Seattle, nearly a third of the city has no storm drains. In these areas, stormwater gathers in street-side ditches, plunges through culverts and—laden with roadway pollutants—pours into small lakes or natural creeks leading to Puget Sound or Lake Washington.

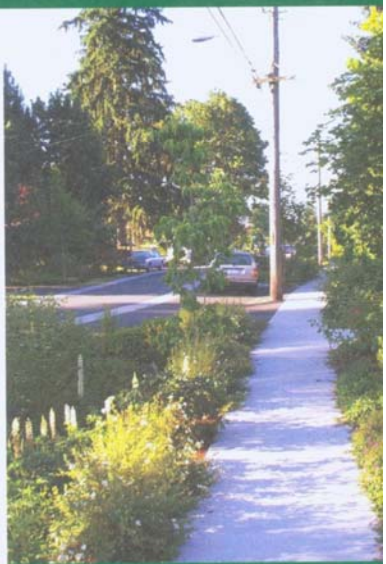
Residents of these neighborhoods have long clamored for the kinds of amenities that exist in the rest of the city—sidewalks, curbs, gutters and, of course, storm drains. Now, as environmental awareness has grown and with the advent of climate change, the city is seeking new ways of controlling flooding.

One of the answers to cities' drainage problems, it turns out, may be to create an entirely different kind of neighborhood street: one where planted swales along the pavement do the work of gutters and drains, capturing stormwater and letting it soak into the ground. In the swales, healthy plants and soils break down pollutants through natural processes while reducing runoff, except during the very largest storms, to almost nothing. This concept has been demonstrated with Seattle's pioneering natural drainage systems (NDS) projects, which incorporate a variety of low-impact development techniques to store and infiltrate stormwater, and to capture and begin the biological breakdown of water-borne pollutants.

Today, in several Seattle neighborhoods—with more to come as funding becomes available—natural drainage systems have become a much-admired community amenity. Their technologies are being used to provide a variety of community and environmental benefits, including:

- Drainage control, thanks to narrower roadways which reduce impervious surface, creating more space for vegetated street-side swales which temporarily hold and often absorb rainwater.
- Improved water quality through "biofiltration"—pollutant removal provided by healthy plants and soils in swales where they capture and break down pollutants washing off roadways and parking areas.
- Increased street-side landscaping, beautifying and adding value to neighborhoods.

The first SEA Street just after completion in 2001



SEA Street in 2002

- Traffic calming due to narrower pavement, the narrower visual corridor created by street-side vegetation and at some locations by gradually curving roadways that still allow for emergency vehicle access.
- Increased community interaction thanks to residents' collaborative involvement in landscape maintenance, watershed stewardship and the pedestrian friendliness of new sidewalks and streets.

This report was produced to tell the story of these successes and provide information that other neighborhoods, cities and towns may use as a tool to address potential drainage problems resulting from climate change. The benefits for community residents, neighborhood traffic management, water quality, the environment and drainage utilities like Seattle Public Utilities can be significant.

GREG NICKELS
Mayor of Seattle

Tackling the problem

Seattle, like other U.S. cities, struggles with a host of infrastructure challenges, many involving storm drainage volumes and storm water runoff which can pollute surrounding streams, lakes and salt water with nutrients and toxic chemicals picked up from streets and parking lots, roofs and lawns. Increasing populations and motor vehicle use exacerbate the pollution problem. Nevertheless, storm runoff pollution must be controlled within specific limits set by the National Pollutant Discharge Elimination System (NPDES). In Washington,

What if, instead of grabbing it in pipes, rain water was slowed and stopped at the source, in private yards and parking lots and along the city's streets, and allowed to soak into the earth?

NPDES enforcement and permits for limited discharges are the responsibility of the state Department of Ecology (DOE).

Adding urgency to this, two runs of Puget Sound Chinook salmon that pass through Seattle waters were declared threatened in 1999 under the Endangered Species Act (ESA). The four major streams that years ago Seattle hijacked into its storm drainage system are all capable of supporting salmon runs. Chinook have been found in Thornton Creek in northeast Seattle. The other urban creeks host other varieties, most often coho, sockeye and chum salmon and migratory or resident cutthroat and rainbow trout. In recent years, SPU research has found high coho pre-spawn mortality in the city's streams and NOAA Fisheries research points to contaminants in stormwater runoff as the cause.

For more than two decades many of Seattle's school children have raised salmon fry in tanks in their classrooms and each spring released them into the streams, with high hopes for their return. They've had some success. On Piper's Creek in northwest Seattle, the fall count of returning chum salmon is a community event.

Even before the ESA put official urgency to the need for salmon habitat restoration, Seattle and its citizens had begun that work. With state support from initiatives for the cleanup of Puget Sound, the city and community organizations together developed Watershed Action Plans. Since the early 1990's, these plans have guided efforts to improve riparian habitat on several streams. Building on that work, creek restoration became one of the city's Millennium Projects and more than $14 million was spent on Urban Creeks Legacy improvements in 1999 and 2000. Logs have been placed to create pools where fish can rest and culverts have been redesigned or removed to restore the natural complexities of stream beds. Along the banks thousands of native shrubs and trees have been planted to replace invaders like Himalayan blackberry. Today at one location on Longfellow Creek, beavers returning to the improved habitat have pitched in with a dam of their own.

Seattle Public Utilities, which was consolidated from other city departments as a combined solid waste, water, wastewater and drainage utility in 1996, quickly embraced environmental stewardship as its unifying corporate mission. Given this focus and the other environmental forces at work, it wasn't long before SPU planners realized that NPDES regulatory goals, ESA requirements for habitat protection and community demands for creek restoration could not be satisfied with work along the creeks alone. The real solutions - stormwater control and pollutant reduction - had to take place upstream. Traditionally, that meant curbs and gutters, storm drains and pipes and at the bottom of the hill, large detention pipes or ponds, all in the end discharging into Lake Washington or Puget Sound - and likely into the creeks. Even then, without a stormwater treatment plant at the discharge point, the traditional infrastructure would not reduce the amount of this "non-point" pollution dumped into the receiving waters.

Therein lay the germ of the NDS idea. What if, instead of grabbing it in pipes, rain water was slowed and stopped at the source, in private yards and parking lots and along the city's streets, and allowed to soak into the earth? What if you could recreate or mimic the natural systems that existed before development, before roofs and driveways and streets took over the land? What would that look like?

Seattle's drainage system, or "Drainage 101"

In Seattle, what happens to stormwater depends on where it falls. The city has three different types of storm drainage systems - each serving about one-third of the city's area - created at different times in Seattle's development.

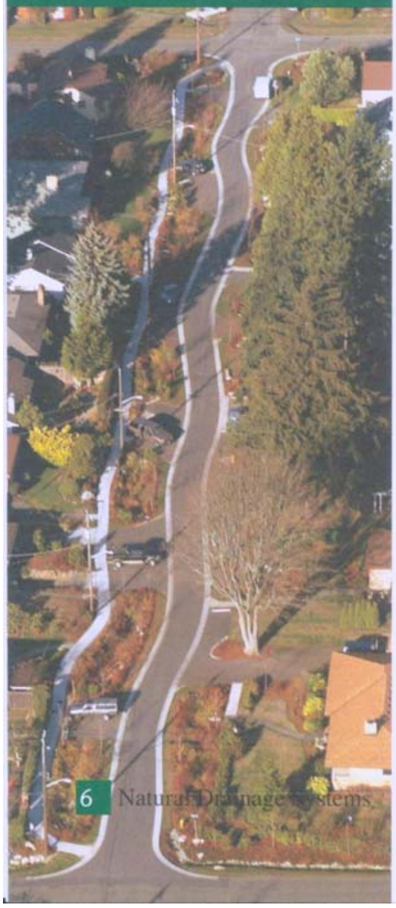
The oldest area, downtown and the neighborhoods immediately surrounding it, are served by combined sewers, pipes that collect sanitary sewage from offices and homes and, when it rains, also fill with water from roofs and streets. All this water - sewage and storm water combined - goes to sewage treatment plants before its release offshore, deep in Puget Sound. Unfortunately, in heavy rains, some of the combined sewer pipes reach and exceed capacity. At that point, to prevent sewage backups, as an emergency measure the system is designed to overflow directly into Puget Sound or Lake Washington. The city is required by NPDES regulations over time to steadily reduce these combined sewer overflows (CSOs). Generally, this has been done by increasing storage capacity with larger pipes or large underground vaults.

The second area includes those neighborhoods outside of downtown that were part of the city before 1950. In those areas, thanks to 1958 voter funding of Metro, a new county-wide agency to clean up Lake Washington, sanitary sewer mains - large trunk sewers - were constructed to intercept existing pipes and carry sanitary sewage direct to a new sewage treatment plant at West Point. Also in this area, new, separate piping was built to collect stormwater flowing into street drains, separating it from the sanitary system and sending the runoff untreated to Lake Washington and Puget Sound. This area is called "partially separated" because roof drains from most houses and commercial buildings still contribute stormwater to the sanitary sewers.

From both the combined and partially separated areas, storms add significant amounts of rainwater to the flow through sewage treatment plants, contributing to the burden on those facilities and limiting their capacities. That's why, in these areas

The city has three different types of storm drainage systems - each serving about one-third of the city's area - created at different times in Seattle's development.

The first SEA Street before and after



as well as in the creek-drained area described below, SPU planners are examining possible applications of NDS and other low-impact development techniques to mitigate stormwater peak flows and total volumes. Because these areas, particularly around downtown, are intensely developed, finding space for NDS applications in street rights-of-way is more difficult. Most of this area has curbs, gutters and sidewalks, suggesting smaller scale NDS applications and the use of NDS and other low-impact development (LID) techniques on private property.

Seattle's third drainage system type is primarily in the north end, an area annexed in 1954. There are similar, smaller areas near the southern city limits, also annexed after 1950. Here, as in the other parts of the city, the Forward Thrust interceptors ended the dumping of raw sewage into Lake Washington and Puget Sound. But most of these areas, particularly the residential neighborhoods, never received formal storm drainage systems. For the most part, except where Natural Drainage Systems have been constructed, rainwater flows off roofs and yards and streets, travels along street edges into drainage ditches, then through culverts under driveways and street intersections. The runoff eventually makes its way directly to the lakes and Puget Sound or flows into the remaining urban creeks in each of the four corners of the city. Carrying pollutants dangerous to fish and all the smaller creatures in their food chain, when it reaches the creeks this stormwater scours out the gravel where salmon spawn and washes away riparian vegetation. It's in this part of Seattle's north end where SPU planners and engineers first applied the SEA Streets NDS strategy.

A pilot project: The first SEA Street

Seattle Public Utilities drainage planners and engineers set a high standard. They wanted their new system (it didn't have a name yet!) to recreate the natural drainage performance of a pre-development pasture, mixed grassland and trees, not the roofs and streets of a city. Rain falling on pasture lands would naturally soak in, with very little surface flow, recharging groundwater and only gradually reaching nearby creeks. Under those conditions creek flow remained relatively constant year-round, perfect for fish. In contrast, runoff from developed neighborhoods is fast and strong and laden with pollutants during winter rains but relatively little rain soaks in to recharge groundwater. Summer creek flows dwindle below their natural levels, harming fish - if any remain. The new system, SPU staff decided, would mimic pre-development pasture conditions. This goal was more stringent than the City's drainage code, which at the time required developers to reduce but not eliminate peak runoff from a two-year, 24-hour storm (equal to 1.68 inches of rain in 24 hours) and a 25-year, 24-hour storm (equal to 3.13 inches of rain in 24 hours).

In the late 1990s, as part of the city's Urban Creeks Legacy Millennium Project, creek restoration work was underway in all four corners of the city where creeks form part of the drainage system. Of the four - Piper's Creek, Thornton Creek, Taylor Creek and Longfellow Creek - Piper's Creek was the best location for the pilot drainage project. The Piper's Creek watershed drains large areas of the Broadview and Greenwood neighborhoods through Carkeek Park into Puget Sound. A crude ditch and culvert systems in the north part of the watershed and underground storm drains in the south prevent localized on-street flooding and speed water into the creek. Community activism played a role, too. A neighborhood group, the Carkeek Watershed Community Action Project, had been the most active in the city in promoting creek and salmon habitat restoration, and had developed a Watershed Action Plan.

SPU staff went to the public with their drawings of streets with drainage swales and shrubbery on either side, areas where water would form temporary ponds in heavy rains and then slowly drain or disappear into specially engineered absorbent soils. On one long block in the Broadview area, this new design would replace the gravel shoulder and surface drainage in front of everyone's home. A sidewalk would be added on one side of the street and parking areas matching residents' use would be provided.

Based on preliminary criteria (not a steep grade, houses set above street level), SPU identified more than two dozen blocks that would work. At a public meeting for those whose streets qualified, the staff asked neighbors to get together and send in a simple petition if they, as a group, wanted to go ahead. Along with the specific characteristics of the petitioners' block, the highest level of interest would determine the choice of the project street. There would be no cost to homeowners.

SPU chose the block between NW 117th and NW120th streets on Second Ave. NW as the best candidate from among several groups that applied, and began a series of meetings with the homeowners to talk through design issues (assuring that sufficient parking would remain was key). They explained how the new drainage system would work and that homeowners would in the end be responsible for maintaining the landscape elements, including more than 100 new evergreen trees and 1,100 shrubs along the swales. SPU staff believe this complete involvement of residents from beginning to end was essential to SEA Street's success.

Looking north along Second Avenue NW from NW 117th Street, before and after

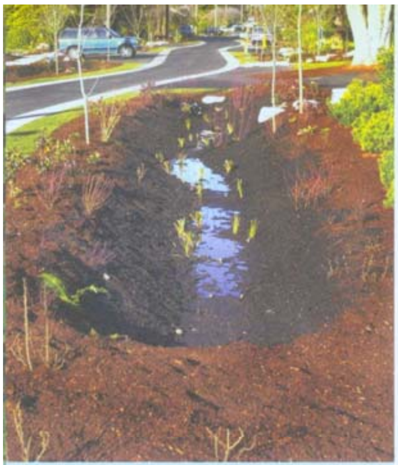
Key requirements for project success

- Involve neighborhood residents in all phases of the project, from earliest concepts through all phases of design and construction. In the end, it's their street and they'll be responsible for maintenance in the years to come.
- Provide the residents with easy to understand graphics to show the proposed final design, so they understand the design before construction begins.
- Approach each project with a comprehensive, interdepartmental project team. The team should be staffed with problem-solvers representing every concern.

Obstacles in the early going

Now, just six years after completion of the first SEA Street in 2001, public acceptance of Natural Drainage Systems makes it easy to forget what a radical departure the design was. There was a lot of skepticism among residents and from professionals in other city departments with time-honored ways of doing things.

Even community members had in mind something different before seeing the SEA Street designs. They wanted - and had wanted since their neighborhoods were annexed to Seattle in the early 1950s - the same curbs, gutters, sidewalks and concrete paving with piped storm drainage (underneath, out of sight) that they saw in neighborhoods closer to the city center. Furthermore, many residents treated significant



How do we know it works?

For the winter prior to construction of the first SEA Street, SPU consultants from the University of Washington (see References) monitored runoff from the block. The monitoring was continued after construction and showed that in the first year the SEA Street NDS reduced flow from the block to only 2% of pre-project runoff. The subsequent years of monitoring showed even better performance, with only 1% of pre-project runoff leaving the street. This high level of stormwater control continues today.

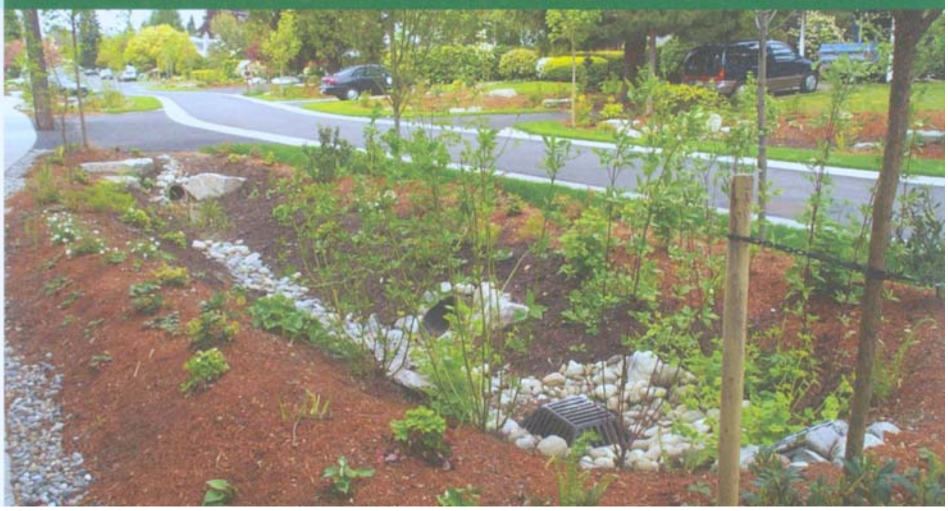
sections of the right-of-way in front of their homes as private property, considering the parking there to be their own, and often landscaping the public areas as continuations of their front yards. More than 15 feet on either side of the existing pavement was "reclaimed" by the SEA Street design which used the full 60-foot right-of-way. Through a series of public meetings, residents of the project street came to understand and accept this and work with the designers on the finished product. It's a testament to the power of NDS designs that most residents on SEA Streets now believe their streets are more interesting and look better than traditional neighborhood streets. SPU and residents also believe SEA Streets have enhanced property values. However, research to validate this is a future project that will require a larger sample of property sales on SEA Streets and, for comparison, on nearby unimproved streets.

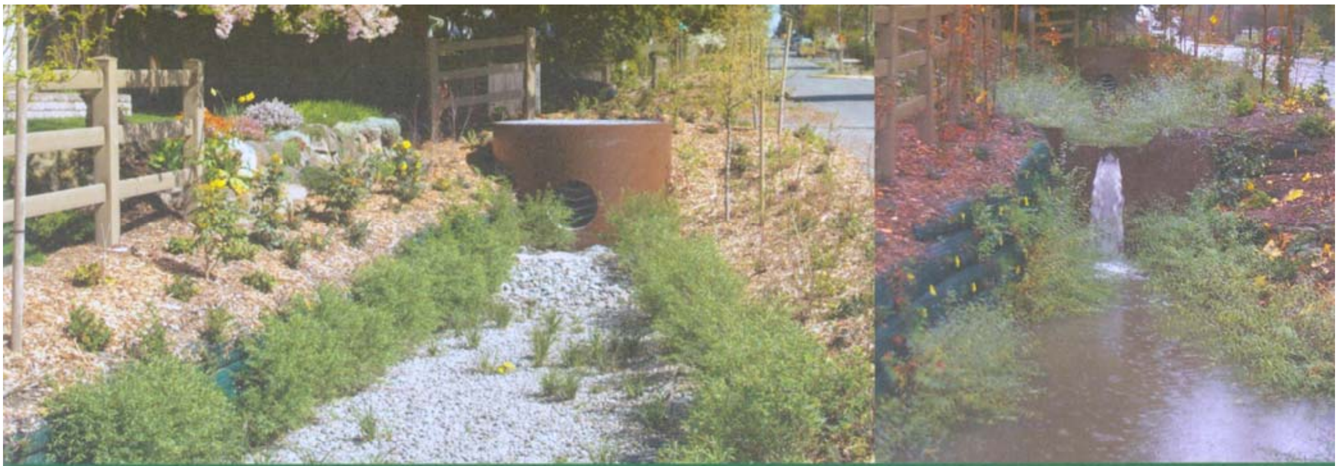
Other obstacles came from within the city family. SPU's own staff was trained and proficient in designing and building stormwater conveyance and detention systems. Those things work. Would planted swales perform as hoped? Could the runoff from acres of development really be controlled and infiltrated by streetside "swales?" Skepticism prevailed.

Other departments also had their doubts and brought those to the table. Before agreeing to design the street, the Seattle Department of Transportation (SDOT) took a long, hard look at SPU's proposals to narrow the pavement and introduce graceful curves on the first SEA Street. Curving the street allowed different widths and depths for the drainage swales on either side of the roadway. (Altogether, departures from typical roadway and sidewalk design cut by 11 percent the amount of hard surface on the project block.) The roadway width - a narrow 14 feet with 18-foot flares at intersections - and locating a sidewalk on only one side of the street were among the most debated issues. Importantly, the Seattle Fire Department had to be satisfied that emergency vehicles could get through without problems.

The solution was collaboration. SPU assembled a broad-based interdepartmental project team that worked closely together and with SEA Street residents throughout the design and construction process. SPU believes that a collaborative approach remains essential to the use of NDS and other low-impact development technologies in the solution of urban drainage problems.

Infiltration swales along the first SEA Street





The NW 110th Street Cascade, first year

Cloning success: SEA Streets & Cascades in other neighborhoods

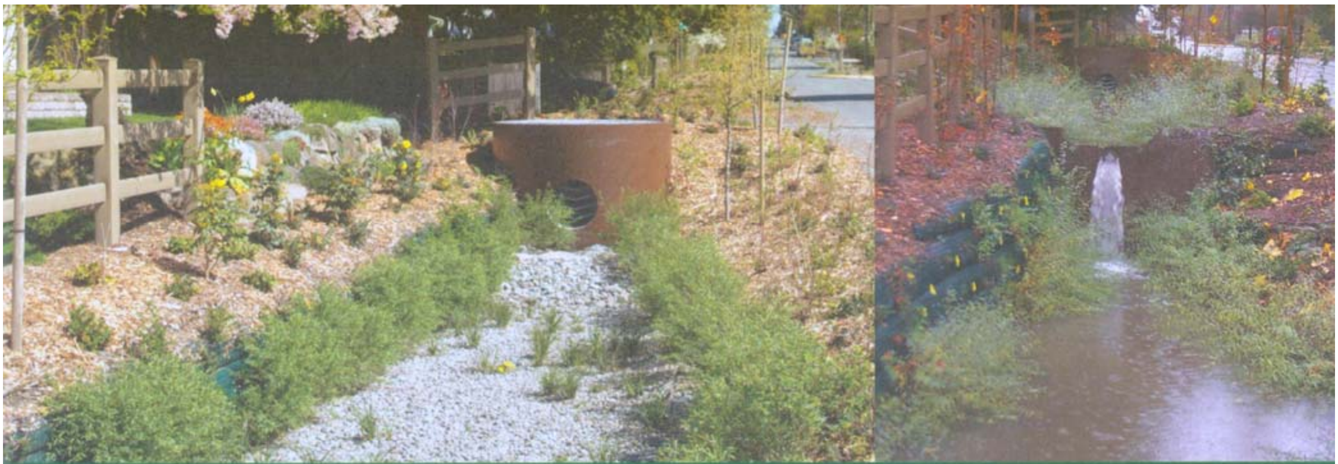
Carkeek Cascade at NW 110th Street

Not far from the original SEA Street, large volumes of storm runoff pour down from Greenwood Avenue North, an arterial lined with apartment buildings and condominiums. The runoff courses through the ditches along neighborhood streets and into Piper's Creek. The ditch and culverts along N/NW 110th Street, overloaded with the runoff generated by 21 acres along Greenwood Ave and the adjacent residential neighborhood, were the next challenge for SPU drainage planners.

Controlling the heavy flows that came down the slope (varying from 1% to a reasonably steep 8%) called for a more robust system. The ditch that the new system would replace had been asphalt-lined to prevent erosion, and heavy storms filled the culvert at the bottom and sent sheets of water across Third Ave. NW, a north-south arterial. To deal with this powerful flow, the natural model would turn out to be a mountain stream.

To slow water from a two-year, 24-hour storm and lesser rainfall, the 110th Street Cascade uses a series of shallow, rock-bottomed pools which step gradually down the slope behind a series of check dams designed as weirs to temporarily detain flow within each swale. In addition, the Cascade provides water quality treatment per City code for the 6-month, 24-hour storm. First, the slowing of the stormwater allows solids and the pollutants that bind to them to settle out. Infiltration of the 3 inches of water held in each pool then causes pollutants to be trapped in the soil. The Cascade extends from Greenwood Ave. N west for four blocks (about 1,300 feet) to Third Ave. NW, just two blocks outside Carkeek Park. Extensive plantings have grown to almost obscure the flow control features of the Cascade since its completion in late 2002.

A series of shallow, rock-bottomed pools which step gradually down the slope behind a series of check dams designed as weirs temporarily detain flow within each swale.



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A series of shallow, rock-bottomed pools which step gradually down the slope behind a series of check dams designed as weirs temporarily detain flow within each swale.

110th Cascade - How do we know it works?

SPU again contracted the University of Washington to conduct project monitoring, comparing flow volumes and water quality from an upstream station to a downstream station. Monitoring shows that the system infiltrates at least 48% of all inflows from the upstream station and likely up to 74% of all inflows when modeling is used to predict inflow from streets downstream of the inflow monitoring location. The system released water in only 49 of 235 storms between October 2003 and March 2006. Water quality monitoring of total suspended solids, total nitrogen, total phosphorus, copper, zinc, lead and motor oil found the following removal rates based on mass loading: total suspended solids (TSS), 84%; total nitrogen, 63%; total phosphorus, 63%; total copper, 83%; dissolved copper, 67%; total zinc, 76%; dissolved zinc, 55%; total lead, 90%; and motor oil, 92%. (See References.)

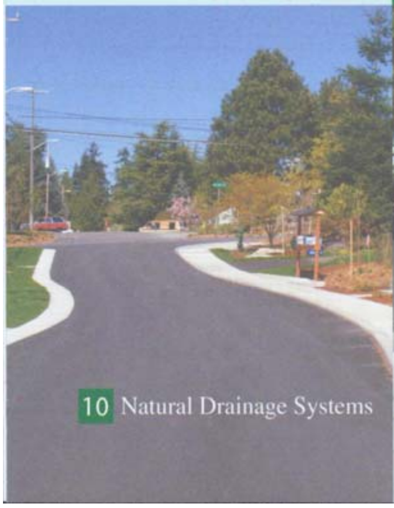
Broadview Green Grid

The Broadview Green Grid, also in the Piper's Creek watershed, was built to demonstrate the NDS techniques of SEA Streets and the 110th Street Cascade on a relatively large scale, and to provide scientific monitoring on a project-basin scale. The 15-block* Green Grid includes four parallel SEA Streets between the Cascade on N/NW 110th Street and a new, six-block Cascade on N/NW 107th Street. The 107th Cascade collects runoff from the Green Grid's SEA Streets, a 10-acre area. In addition, like the first Cascade on 110th, it slows and infiltrates stormwater from an additional 22 acres along heavily developed Greenwood Avenue North.

The Green Grid SEA Streets swales and Cascade pools were designed to provide decentralized stormwater flow attenuation and water quality treatment through the swales using surface storage in combination with healthy soils and plants. The water quality treatment standard is the same as required for any development with new impervious surfaces by the city of Seattle's drainage code - complete treatment of the runoff from a six-month, 24-hour storm- but here it is done by natural means. The swales and Cascade pools also reduce the peak and duration of flows from two-year flood events as well as all storms of lesser intensity. Built with soils specified to have varying degrees of organic matter to control infiltration depending on location and purpose, the Green Grid swales absorb water at rates between 0.5 and 1.5 inches per hour. All ponded water in the swales must - and does - disappear through infiltration within 72 hours of the end of a rainstorm to prevent mosquito breeding.

Just west of Fourth Ave. NW, flow from the 107th Cascade enters a pipe which carries it down the hillside and discharges into Piper's Creek. Construction was completed in 2004 and landscaping in 2005.

* The street grid in the Broadview area of Seattle has long blocks of approximately 630 linear feet oriented north-south, the direction of flow of the SEA Streets, and shorter blocks of approximately 315 linear feet running east-west, the direction of flow of the Cascades. In the Green Grid, a "block" is considered approximately 315 linear feet on one side of a project street so that a SEA Street is two blocks long.



Broadview SEA Streets just after planting

High Point photos by Anthony Harris

High Point: An immense opportunity

Built as temporary workforce housing during World War II, the 750 single- and two-story duplexes of West Seattle's High Point housing project were more than ready for replacement when the federal government created the HOPE VI program to raze out-moded low-income housing. As it had with two similar HOPE VI projects completed earlier, the Seattle Housing Authority (SHA) planned a mixed-income development that included rent-subsidized townhouses and multiplexes, a low-income apartment building for seniors, and market-rate townhouses and single-family homes. The first half of the project, 419 rental units and 411 market rate homes, was opened in phases during 2005 - 2007. By 2010, the completed project will consist of 1,600 units.

Streets throughout the 129-acre project, many originally ending in suburban-style

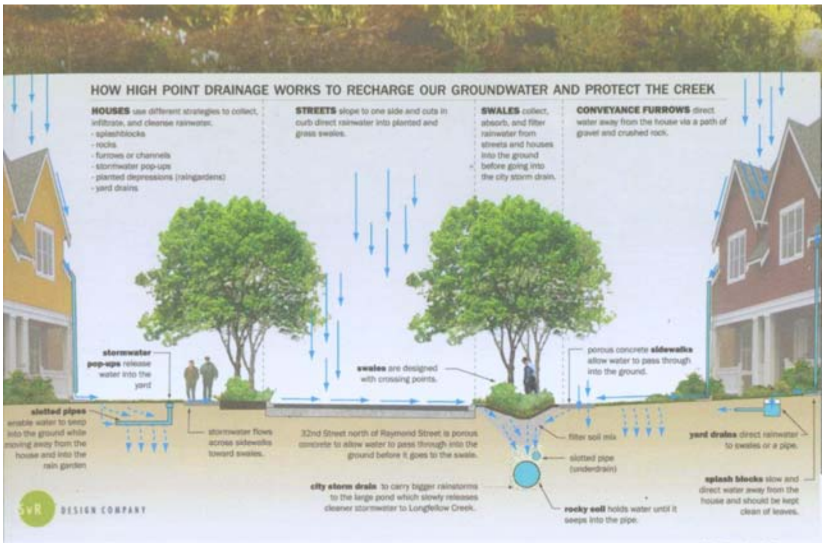
Grassy and vegetated swales at High Point

cul-de-sacs, were relocated, reconnecting them to the city's street grid and ending the physical isolation of the community. Most important from Seattle Public Utilities' point of view, High Point and its bordering green belt make up 8 percent of the Longfellow Creek watershed. The redevelopment provided a chance to apply Natural Drainage Systems on a large scale - properties of High Point's size are rarely available in urban areas - and to significantly effect flow volumes and water quality in the largest creek remaining in southwest Seattle. To this end, in 2004 SPU and SHA entered into a Memorandum of Agreement that NDS strategies would be incorporated into the project. To meet SHA's need to minimize expense, SPU agreed to pay costs above the estimate for a traditional drainage system, about $2.7 million. The funding included a low-interest loan from Department of Ecology's Centennial Clean Water Fund which sought to promote the NDS approach. Requirements were also placed on the drainage covenant and plat agreement establishing impervious surface coverage limitations, designated discharge points and roof area drainage discharge limits. Low-impact development (LID) technologies, the building blocks of Natural Drainage Systems, were required as mitigation for deviation from these standards or increases in impervious surface.

The High Point NDS was designed to a standard higher than the Seattle drainage code, requirements expected to reduce runoff to pre-development levels. With drainage code revisions planned for the near future, SPU saw that High Point provided the opportunity to see if these higher standards could be met using a combination of NDS technologies and a traditional detention pond. This was a significant challenge. At High Point, 65 to 70 percent of the project acreage - roofs, streets and sidewalks - would be impervious surface, compared to 45 percent or less in the Broadview and first SEA Street NDS areas.

Remarkably, but not really surprising to the SPU planners and engineers who were becoming steadily more confident in their new technologies, the High Point NDS design reached the targeted runoff-reduction levels and reduced the size of the detention pond. To achieve the same stormwater benefit with a traditional piped street drainage system would have required a detention pond with five times the volume.

After six years of planning and construction, the Natural Drainage System at High Point is meeting its goals of stormwater flow attenuation, filtration, and bioremediation of pollutants by healthy soils and plants. The design also reduced impervious surface and



SvR Design Company

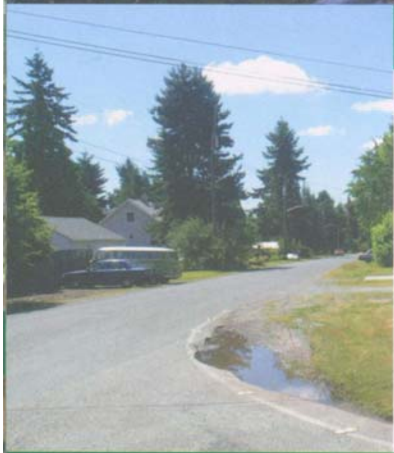
increased vegetation along streets and in public areas. The project preserved 107 decades-old "legacy trees" for their drainage and aesthetic benefits and, at completion of Phase II, more than 3,000 new trees will have been planted at High Point. In the end, Longfellow Creek will receive no more flow from High Point during and after a two-year, 24-hour storm than it would if the 129-acre site were still a grassy pasture.

Among the NDS techniques that work together at High Point:

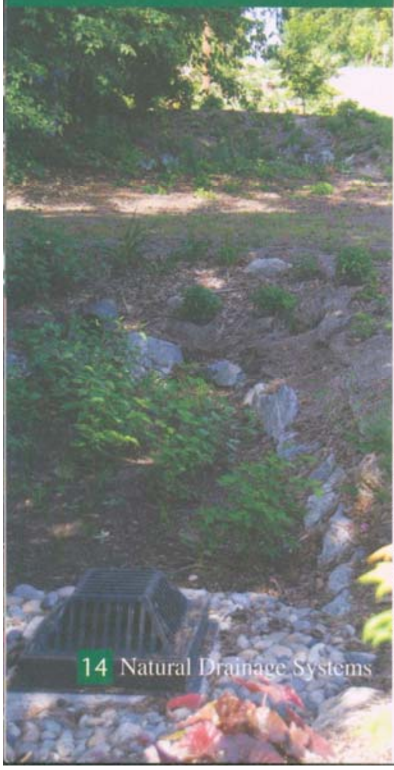
- Vegetated bioretention swales with under-drains on one side of most streets provide filtration and bioremediation of pollutants. They also delay the time it takes water to reach the detention pond and hence Longfellow Creek. From the streets, water enters the swales through curb cuts. From adjacent properties, water not absorbed by rain gardens or compost-amended lawns also flows into the swales.
- The system meets water quality standards by treating runoff from a six-month, 24-hour storm.
- The majority of downspouts are disconnected. Artist-designed splash blocks disperse roof water for infiltration through rain gardens, infiltration zones or composted amended gardens and lawns. Excess water flows into the streetside swales.
- Among the denser housing, grassy play areas store stormwater underneath as needed.
- To minimize impervious area, one-half of sidewalks and one block of a residential street were made with porous concrete pavement, providing SDOT and SPU a chance to test the technology. Most off-street parking areas use other pervious materials such as pavers or crushed stone.
- Most of the streets are narrower than standard for similar Seattle residential areas, 25 feet, compared to 28 or 32, reducing impervious surface and calming traffic. Traditional curb and gutter construction with curb cuts to channel street drainage to 12-foot wide swales between street and sidewalk also demonstrates that this design can be applied as a retrofit to existing city streets.
- A piped conveyance system picks up overflows from 25-year and larger storms.
- The majority of drainage from the project area enters the detention pond. Peak and duration of stormwater discharge matches predevelopment pasture conditions for the two-year storm frequency. The pond also provides peak-flow control for 25-year and 100-year storms.

To achieve the same stormwater benefit with a traditional piped street drainage system would have required a detention pond with five times the volume.

The Pinehurst NDS locates large, deep swales on one side of the roadway



Above: Pinehurst before



14 Natural Drainage Systems

Photos except "Before" by Anthony Harris

Pinehurst Green Grid

The several branches of Seattle's Thornton Creek drain almost 12 square miles in northeast Seattle and the city of Shoreline north of Seattle. The area includes major commercial developments, among them Northgate Mall, where in 2007 NDS features to control parking lot drainage were just being constructed. As in the Piper's Creek watershed where the first SEA Street was built, the extensive residential areas in the Thornton Creek drainage send significant storm flows rushing into the creek. Local flooding due to the limits of the ditch and culvert system is a common problem.

In 2004, SPU began design of Pinehurst Green Grid. Building on the experience from Broadview Green Grid, designers could more confidently model flows and system performance. As a result, they were ready to try new designs for the street-side swales, merging elements from the SEA Streets model and the high volume Cascades. Here, the newly paved street was placed on one side of the right-of-way, allowing for larger swales to provide natural drainage on the other. The new, larger swales provided another benefit, too. SPU drainage designers found that the new swales could handle runoff not only from the adjacent street and houses but from an area three to five times that size. The additional capacity allowed for a system that would accept runoff from cross streets and other nearby streets that therefore did not need reconstruction for swales.

Because of these design changes, the six 660-foot long SEA Streets blocks in the Pinehurst neighborhood also control runoff from six additional blocks which received drainage improvements such as conveyance ditches and culverts but not swales and landscaping. These blocks direct flow from a total of 49-acres into the blocks with Natural Drainage Systems for treatment of pollutants and infiltration of the runoff. This again lowered costs for Green Grids.

In Pinehurst, permeable pavement was used for the first time for some of the rebuilt street-to-driveway connections. Otherwise, the NDS streets provided the same amenities developed on the first SEA Street: A new sidewalk on one side of the street (previously, there were no sidewalks at all), a new roadway which

Comparison between Pinehurst Natural Drainage System and traditional street and drainage design
Using Seattle Public Utilities' asset management life-cycle cost analysis

Project Basin Options	Number of Project Streets	Pros	Cons-	Annualized Drainage Volume Reduction (gal.)	Achievement of Conveyance Goal	Percentage of Volume Reduction Goal [1]	Percentage of Drainage Peak Reduction Goal [1]	Achievement of Water Quality Goal	Achievement of Neighborhood Goal	Average Annual Maintenance Costs	Estimated Project Cost
Option 1 Do Nothing	0	• No capital cost expenditure	• Does not meet any project goals	0	No	0%	0%	No	No	$11,000	$0
Option 2 NDS	11.5	• Achieves all project goals except peak flow reduction • Achieves the highest level of peak flow reduction • Option is the most cost-effective	• Capital expenditure • Higher maintenance costs than Do Nothing	9,700,000	Yes	100%	51%	Yes	Yes	$18,800	$4,600,000
Traditional	11.5	• Achieves same number and level of project goals as Option 2	• Highest cost option • Mid range of maintenance costs • Must acquire 6 properties	9,700,000	Yes	100%	51%	Yes	Yes	$14,000	$8,854,000

Notes

1) Volume and peak goal levels are reported at project basin outfall.
2) Goals for project set at a minimum target of replicating the pre-developed condition for the 6-month storm, but targeting the 2-year storm.
3) Goal achievement in this table reported for the 2-year storm.

was narrower to reduce impervious surface, extensive landscaping in and around the drainage and bioretention swales and new trees along the streets.

The Pinehurst Green Grid includes 12 city blocks between NE 113th St. to NE 117th St. and 16th Ave. NE and 23rd Ave NE with additional work at the intersection of NE 113th St. and 25th Ave. NE. It was constructed and landscaped between July 2005 and April 2007.

A Pinehurst swale shortly after project completion

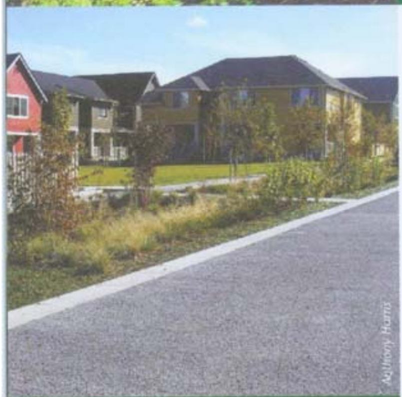
Photos by Anthony Harris

The next challenge: Adapting NDS to densely developed areas

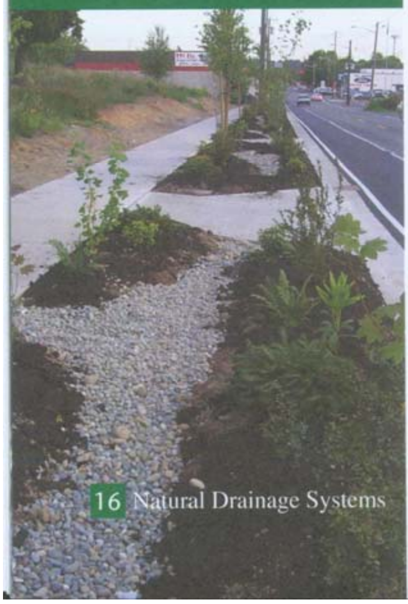
SPU's Natural Drainage Systems have been hugely successful in neighborhoods where the streets have lacked curbs, gutters and sidewalks and the piped drainage systems which accompany them. But those areas are not the only ones that present the city with drainage problems. In the areas with combined sanitary and storm sewers, combined sewer overflows (CSOs) that may occur during heavy rains send raw sewage into Lake Washington and Puget Sound. SPU is under federal and state regulatory order to reduce its CSOs. That means reducing the peak flows from rain storms. This can be accomplished, as traditionally, in large part with end of pipe detention tanks, or part of the job can be done upstream with NDS technologies.

Beginning in 2008, the city's revised drainage code plus "Rainwise" drainage rate credits will focus on reducing the impact of stormwater from private property. The Natural Drainage System program will continue to focus efforts on flows from public

Vine Street Cascade in downtown Seattle



Below: 30th Avenue NE in Seattle's Lake City neighborhood



rights-of-way (more than 25 percent of the urban area) as well as the private property that directs runoff to the right-of-way. Currently, SPU planners are looking at NDS strategies to control, clean and infiltrate storm runoff from more densely developed neighborhoods. In order of increasing effectiveness, here are a number of proposed techniques:

A. Retain existing large street trees to maintain the canopy which intercepts rainwater and facilitates evapotranspiration.

B. Construct infiltration and conveyance trenches in planting strips to provide detention and infiltration depending on design.

C. Reduce surface flow by direct infiltration through porous pavement on sidewalks or streets.

D. Build linear bioretention systems in planting strips or by interconnecting tree pits along a street. These systems use special soil mixes, sometimes in subsurface soil vaults that promote tree root growth, runoff treatment and infiltration depending on design. These systems can be built with or without curb and gutter.

E. Construct interconnected vegetated swales similar to SEA Streets using the planting strips and part of the roadway through elimination of parking on one side in residential neighborhoods. Stormwater enters the swales from the sidewalk and from the street through curb cuts. Where driveways cross planting strips, pipes connect the swales.

F. Where feasible, flows can be separated from the combined system, treated using bioretention or biofiltration as described above and discharged to large receiving water bodies.

Case study: A Natural Drainage System in a developing commercial neighborhood - the Capitol Hill Water Quality Channel or "the Swale on Yale."

Seattle Public Utilities' "Swale on Yale" applies NDS techniques to a redeveloping, high-density commercial area north of downtown. To be located on Yale Ave. N in the South Lake Union neighborhood, four blocks of interconnected swales in an extra-wide planting strip between street and sidewalk will provide treatment for one-third of the stormwater runoff from a 600 acre drainage on Capitol Hill, one of the most densely developed multi-family and commercially-zoned neighborhoods in the city.

Because of its dense development, stormwater runoff from the streets of Capitol Hill carries a heavy pollutant load directly to Lake Union. When the Swale on Yale is complete, runoff from moderate rainfall and the first 10 cubic feet per second (cfs) of flow from larger storms will be diverted from an existing storm drain into a pretreatment vault where trash and large particulates are screened or settle out. From the vault, runoff will flow into one of four swales.

Each of the four swales will be about 270 feet - one block - long and 10-ft wide at the bottom. The width and length of the large swales and short, dense vegetation to be planted throughout will act together to slow runoff and provide water quality treatment by allowing sediments and pollutants to settle out. It will take about 10 minutes for water to flow through each swale, sufficient time for pollutants to settle, meeting Washington State water quality treatment standards.

The Swale on Yale has been designed to treat a maximum amount of stormwater in the area available. Each separate block will be able to treat runoff from more than 50 acres of the Capitol Hill drainage. To achieve high-volume treatment, infiltration into the soil is not part of the design or function of the swales. Storm water flowing into Lake Union will be cleaner, but not noticeably reduced. The Swale on Yale NDS project will remove an estimated 40 tons

It will take about ten minutes for water to flow through each swale, sufficient time for pollutants to settle, meeting Washington State water quality treatment standards.

The "Swale on Yale" between street and sidewalk in a commercial area

Anthony Harris

of total suspended solids (TSS) annually. (TSS is a surrogate for pollutant loading.) The design meets the Washington Department of Ecology performance goal of 80% reduction in TSS for runoff passing through the swales.

Swales such as the connected system being build on Yale Ave. N., can fit into a typical existing 60-ft street right-of-way in place of a parking lane and with the sidewalk narrowed from eight or ten feet to six. In the South Lake Union area, one story warehouses and offices are giving way to multi-story mixed-use retail, office and residential buildings. Because Swale on Yale construction can be coordinated with new development along the four blocks, the swales will be integrated with adjacent buildings to create an exciting urban streetscape.

As of mid-2007, the Swale on Yale was in the preliminary design phase. Construction could begin as early as 2008. Completion of all four blocks is dependent on the rate of adjacent redevelopment and may take several years. The total cost of the Swale on Yale is $5 million to $6 million.

Awards for Seattle's Natural Drainage Systems projects

Kennedy School of Government, Harvard University, Innovations in American Government Award, 2004. The award included a $100,000 prize supporting expansion of SPU's NDS program.

Puget Sound Regional Council, 2020 Vision Award, 2003 and 2007.

Glossary

Biofiltration is a water pollution treatment technique using plants and living soils to filter out or enhance the chemical breakdown of pollutants. In Natural Drainage Systems this often takes place in engineered bioswales where stormwater flow is slowed to allow solids and pollutants attached to them to settle out or be captured by plants growing in the bottom and on the sides of the swales.

Design storm. A design storm is a statistical construct that is based on historical records of storm frequency and intensity of rainfall that drainage engineers use as a benchmark for designing traditional or natural-drainage stormwater control facilities. Seattle regulations require on-site water quality treatment for stormwater runoff from a six-month, 24-hour design storm, which is defined as having 1.08 inches of total rainfall in 24 hours and is statistically likely to occur once every six months. In addition to water quality treatment, Seattles regulations require on-site control of the peak discharge rate and runoff volume from storms with recurrence intervals of two years or greater. The two-year, 24-hour storm is defined as 1.68 inches of rainfall in 24 hours and is statistically likely to occur every 2 years.

Low-Impact Development (LID) is the use of building and infrastructure construction technologies that minimize the life-cycle environmental impact of constructing storm drainage and other public and private facilities. Often, as with Natural Drainage Systems which make use of healthy plants and soils for stormwater treatment, these techniques mimic or take advantage of natural processes rather than complex or mechanical systems. In buildings, examples would be increased use of natural light and opening windows to reduce lighting and ventilating equipment use and power demand.

Natural Drainage Systems - The use of low-impact development technologies to mimic the earth's natural hydraulic processes to control stormwater and remove pollution from runoff. NDS systems may include use of trees and plants and special soils in vegetated swales, cascades (a series of small dams or weirs), rain gardens (ponds that dry after a rainfall), porous pavement, disconnection of downspouts from storm drains and rainwater harvesting.

Non-point pollution is water pollution caused by stormwater runoff from streets, parking lots, roofs and other widely distributed sources carrying pollutants such as oils and metals into streams, rivers, lakes and salt water bodies in contrast to pollution arising from a specific source such as an industrial waste discharge.

Swale, bioswale - A swale is a low spot or channel, often with plantings along the sides and bottom, where storm runoff may pond temporarily for infiltration or through which runoff may slowly flow so that pollutants will settle out or be captured by the vegetation.

References, additional information and technical documents

All of the references and documents used to develop this manual and extensive additional references and technical details including plans and specifications for Natural Drainage Systems projects are available on the Seattle Public Utilities web site, www.seattle.gov/util/services. Enter Natural Drainage Systems in the search box. For telephone inquiries call the SPU media relations office at (206) 684-7688.

Credits

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Seattle Climate Action NOW

Greg Nickels, Mayor

Seattle Public Utilities, Chuck Clarke, Director

Seattle's Natural Drainage Systems were planned, developed and constructed by Seattle Public Utilities in collaboration with the Seattle Department of Transportation, Seattle Fire Department, Seattle Police Department, Seattle City Light, Seattle Department of Planning and Development, Seattle Conservation Corps, Seattle Department of Parks and Recreation, and the citizens of Seattle's neighborhoods whose community groups and watershed action teams have powered the city's environmental commitment to its urban creeks for 20 years.

At High Point

Tom Phillips, Project Manager, Seattle Housing Authority

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Bruce Myers, orca sculture and splash block design

Additional support provided by Washington State Department of Ecology Centennial Clean Water Fund

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Seattle Climate Action NOW

SeattleCAN.org

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附錄 2－獎助參與 Rain Wise 明信片

附錄 3－S.E.A. Project 簡介及配置詳圖

S.E.A. Streets Site: 2nd Avenue NW

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TTY/TTD: (206) 233-7241
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http://www.ci.seattle.wa.us/util/

Street Edge Alternatives Project

An innovative street design for the 21st Century

The Street Edge Alternative, or S.E.A. Streets, Project is part of Seattle Public Utilities (SPU) Urban Creeks Legacy program. SPU is restoring portions of Seattle's four largest creeks. These Urban Creeks Legacy projects improve drainage; prevent erosion and flooding; restore wildlife habitat and create or improve community open spaces and trails.

The City of Seattle is returning to its roots, so to speak, by designing a street and drainage system to do what used to happen naturally in uninhabited areas throughout the Puget Sound – providing more areas for water to soak into the ground and drain slowly into our creeks. Thereby, improving the quality of the water and reducing the volumes that currently impact our streets and creeks.

As more and more people moved to Seattle to enjoy the beauty of the Puget Sound, our wild areas were covered up with impervious surfaces, such as streets, driveways, and houses. Additionally, our lifestyle, for instance modes of transportation and how we take care of our lawns, impacted the quality of our creeks.

Seattle Public Utilities (SPU) is confident that the Street Edge Alternatives, or S.E.A. Streets, project in the Pipers Creek Watershed will demonstrate ways to improve both impacts on our ecosystem and the impacts on our streets.

S.E.A. Streets offers an alternative to the typical street drainage system of curbs, gutters and pipes, using innovative drainage design and plantings. (See design inside.) Using more natural systems to reduce the impacts of urbanization and storm water on the creek, the project will also show that the standard street improvements are not the only alternative to consider for a residential neighborhood. The intent is to show that an alternative design may not only minimize water quantity impacts to creeks but also increase the aesthetic appeal of the neighborhood and provide street improvements that citizens desire.

The Pipers Creek watershed area was identified for the demonstration project because of the pioneering efforts of many citizens to restore Pipers Creek in Carkeek Park. City staff from SPU, Seattle Transportation (SEATRAN), Department of Neighborhoods, and the Department of Parks and Recreation reviewed the area for potential sites. Residents from 31 potential sites were invited to an informational meeting on May 5th, 1999. Interested blocks were requested to turn in a petition demonstrating support for the project. Six blocks turned in petitions that had the 60% minimum support or more. These six sites were evaluated and the block of **2nd Avenue NW from NW 117th to NW 120th Street** was selected as the S.E.A. Streets demonstration site.

A ceremonial groundbreaking occurred on April 17, 2000, as part of SPU's Creek Week / Earth Day Celebrations. Construction is slated for the summer of 2000 and will last approximately three months.

The S.E.A. Street Project has several objectives: 1) decrease runoff peak flow and volume; 2) minimize impervious area; 3) document effects of alternative design through research studies; 4) minimize maintenance requirements through proper design and resident stewardship; 5) design a street that reduces vehicle speeds, provides a sidewalk on one side and incorporates a landscaping design that complements the drainage system; 6) change the existing paradigm that a curb/gutter/sidewalk system is necessary in residential areas.

The design process by SPU and SEATRAN evaluated several options for meeting the objectives, and addressing the needs and concerns of property owners along the block. The drainage system consists of a series of 12 swales that are connected together. The storm water flow will be regulated at structures and through infiltration into perforated pipes in order to detain water during higher flow periods. The swales will store the rain water of a 24 hour six month storm event and slowly release it to the creek. Landscaping and trees will also compliment this drainage system and provide an important element to the street design and operation. Approximately 80 new trees will be added to help soak up rain water and, will in turn, beautify the block. Impervious area on this site was reduced to 32% from the current 39%, while adding a sidewalk on one side of the street.

SPU began monitoring the volume and rate of rain water that flows off the street and into the drainage ditches that lead to Pipers Creek in the winter of 1999. Monitoring will continue for a couple of years after construction has been completed in order to evaluate the effectiveness of the new drainage design.

This project also coordinates efforts with SEATRAN to evaluate new alternatives for residential street design that meet drainage requirements and provide the appearance, amenities and safety that neighborhoods want.

If proven effective, the S.E.A. Streets design could be a more cost-effective way of managing storm water and providing street improvement options on unimproved streets throughout Seattle and serve as a model for other areas throughout the country.

For further information about the S.E.A. Streets project, please contact **John Arnesen**, Project Manager of S.E.A. Streets, at (206) **684-8921** or e-mail him at **john.arnesen@ci.seattle.wa.us**.

Seattle Public Utilities

Urban Creeks Legacy

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Street Edge Alternatives Final Design - Spring 2000

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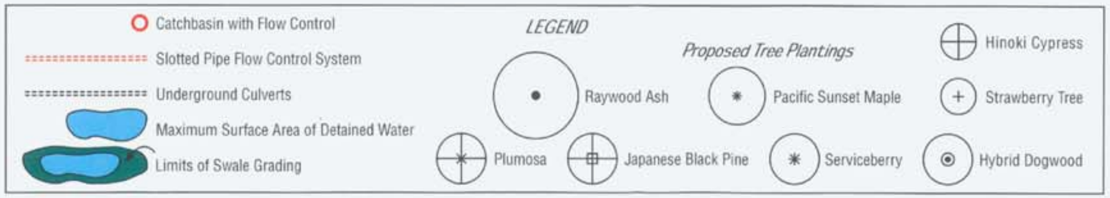

Benefits of a S.E.A. Street are:

- sidewalks and landscaping;
- traffic calming to reduce speed of cars;
- easier maintenance of swale instead of ditch;
- a more attractive street;
- reduce storm water impacts on creek.