Chapter Seven: Lighter, Greener, Cheaper, Smarter Infrastructure

Introduction

North American road and utility infrastructure appears to have been intentionally designed to destroy the ecological function of the land that supports it, and to bankrupt homebuyers and taxpayers through its cost to install, maintain, and replace. Since the end of WWII, the per dwelling unit costs for providing, maintaining, and replacing infrastructure (defined here as the physical means for moving people, goods, energy, and liquids through the city) has increased by nearly 400% according to some estimates.[1] Most of this per capita increase has been the consequence of ever more demanding engineering standards for residential roads, coupled with the gradual increase in per capita land demand over the decades prior to 1990, a necessary consequence of universally applied sprawl patterns throughout the North American continent. The first costs of these ever more odious engineering standards and ever more exclusive zoning regulations was often invisible to the taxpayer, buried as it is within the costs of the original home purchase. These costs become more obvious to the taxpayer after two generations, when the costs associated with the necessary replacement of infrastructure fall not on the home purchaser, but on the property tax payer.[2] First ring suburbs built during the 50s and 60s, now face major costs for overhauling an overextended system of roads and pipes, and because of low density development, have an inadequate number of taxpayers to pay for it.[3] Faced with rising property taxes and falling level of services, residents of first and second ring suburbs are often simply opting out, leaving behind these communities for the greener fields of the third and fourth ring suburbs, or even exurbia, where these impacts lie a still comfortable two generations away. The crushing liability for oversized infrastructure falling on too few taxpayers is another element of the “doughnut hole cities” phenomenon (freeway oversupply is the other). It provides strong financial incentives for residents to move further and further away from the geographic core of the region and further and further away from jobs and services.[4]

Beyond the cost consequences, there are the environmental impacts. Every dollar’s worth of pavement produces a measurable increase in environmental impact, not because pavement is inherently polluting, but rather because it so fundamentally alters how water is delivered to receiving waters when it rains: water that should go into the ground goes into a pipe instead, utterly transforming watershed performance. The cure for the sickness inflicted on watersheds consequent to urban

---

[1] By compiling the various costs associated with infrastructure construction, operation and maintenance, Condon and Teed (1998) estimated that the total per dwelling unit infrastructure costs for a Status Quo Development scenario were $23,520 while the Sustainable Alternative Development was only $4,408, a fifth of the cost of the Status Quo Development. Savings in the Sustainable Alternative Development came primarily from reducing road widths, allowing gravel lanes with utility poles and efficiencies in placement and utilization of utility hookups (for more information see: http://www.jtc.sala.ubc.ca/projects/ADS.html). CMHC (1995) found similar infrastructure savings between a conventional suburban development pattern and a mixed use, more compact development planned according to the principles of “New Urbanism.” They found that initial capital costs of infrastructure were approximately $5,300 cheaper per dwelling unit in the alternative plan, operating and maintenance costs were $3,700 less, and infrastructure replacement was over $2,000 less totalling $11,000 life-cycle savings (CMHC 1995).

[2] Sprawling development increases the cost of building and maintaining roads, sewers, schools and other public facilities for a number of reasons, including: the initial capital costs of new infrastructure in greenfield developments, the increased distance between developments increases the length of roads, water pipes and sewer lines and facilities must be more dispersed in the landscape without being able to take advantage of efficiencies from economies of scale (Meredith 2003). In Canada, more emphasis has been placed on building new infrastructure rather than maintaining existing facilities (Vanier and Danylo 1998). In a report released in 2007 the Federation of Canadian Municipalities (FCM) found that close to 80% of Canada’s infrastructure is past its service life and the price of eliminating the municipal infrastructure deficit is $123 billion (Globe and Mail 2007). In the city of Memphis, urban sprawl has contributed to the increased costs of operating basic infrastructure in real dollars from $466 per capita in 1990 to $637 per capita in 1999 (Ciscel 2000). As urban centres are left with aging and deteriorating infrastructure properties are abandoned and property values and tax revenues go down depriving the municipality of the money needed to maintain, repair or replace existing infrastructure (Hirschhorn 2001).

[3] Although the total infrastructure costs for the entire site were greater, the per dwelling unit costs in the sustainable alternative ($4,408) were significantly lower than the per unit infrastructure costs in the status quo development ($23,520) (Condon and Teed, 1998). These cost savings are attributable to a more compact urban form and higher residential density (Sustainable Alternative Development 17.7 du/acre; Status Quo Development 3.9 du/acre).

[4] In Hirschhorn’s Traditional Circular Model of Sprawl (2001) higher taxes and decaying infrastructure do as much to push the nonpoor out of urban centres as the cheap outlying land, new infrastructure, low property taxes and attractive open space pull them to the suburbs. Urban centers are left with aging and deteriorating properties, facilities and infrastructure as property values and tax revenues decline (Hirschhorn 2001).

Change in Total Population by Census Tract
Neighbourhood Areas, 1990-2000

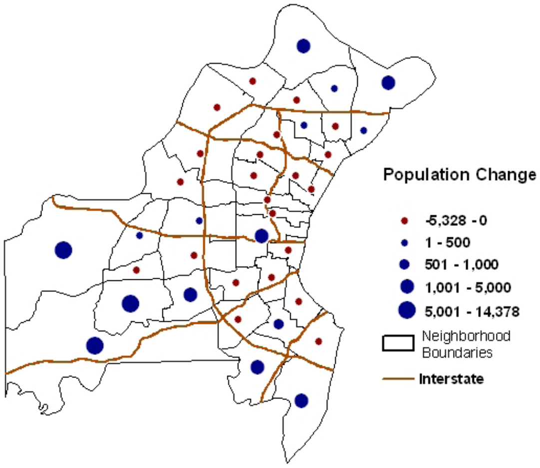


Figure X. Shows the doughnut hole effect in St. Louis as the population moves from the centre city to the suburbs. Source: USDC Bureau of the Census, Census of Population and Housing [1990 STF3; 2000 SF3] Prepared by: Office of Social and Economic Data Analysis

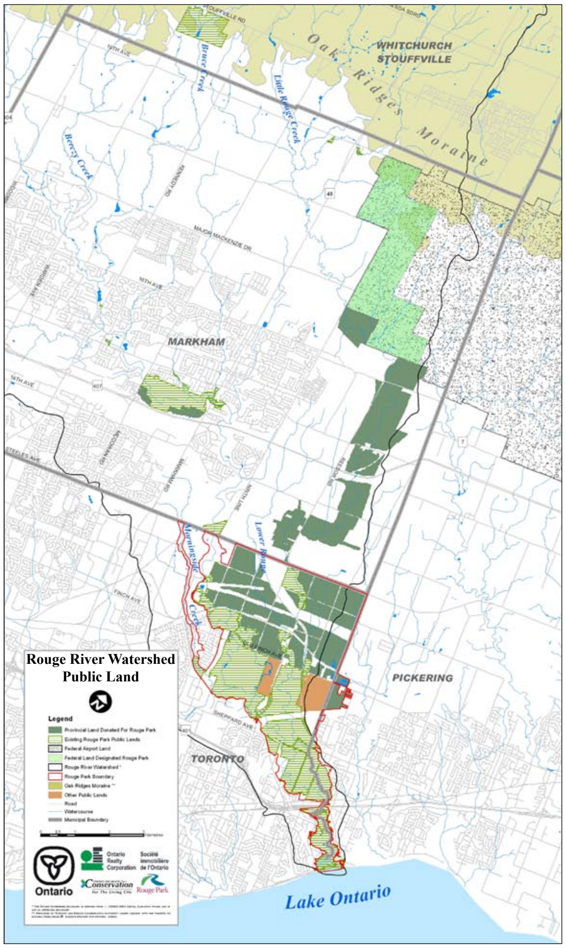


Figure X. Shows the extent of an urban watershed in Ontario, Canada.

development is to spend *less* on infrastructure not more – less pavement, fewer pipes, fewer gutters. The idea of spending less money not more is a crucial one. Environmentalists often demand costly government responses to environmental problems, be it the purchase of a nature reserve on the one hand, or a new storm water treatment facility on the other. They also often call on regulators to reduce project density or eliminate large areas of subject sites from development reducing yield and thus reducing economic return to proponents. This zero sum game allows development proponents to argue that preserving natural systems will add cost to the project, costs that must be ultimately passed on to families struggling to purchase a home. The environmental arguments leveled most often against new development are in many cases counterproductive. Arguments to keep density low simply shifts the demands for those housing units to other sites on similarly sensitive lands further away from jobs and services. The demand for natural preserve areas salvages fragmented pieces of a disintegrated natural system, cut off from the natural connections necessary to maintain ecological integrity. There are practical alternatives to unproductive pitting of environmentalists against development. Infrastructure exists that costs less than what we are currently requiring and that works with Nature's systems not against them. This is infrastructure that capitalizes on nature's services while minimizing the weight, extent, and cost of the "hardscape", the streets, walks, lanes and drainage ways of the site. Such infrastructure can significantly reduce cost while dramatically shrinking environmental impacts. How this can be accomplished is described below.

The Site is to the Region what the Cell is to the Body.

It seems obvious but bears repeating. *The site is to the region what the cell is to the body, and just as the health of the individual human cell has everything to do with the health of the human body, so too does the ecological function of the individual site have everything to do with the ecological health of the region.* Site scale elements, when multiplied thousands and even millions of times throughout vast metropolitan regions, do more than *influence* regional environmental systems, they *constitute* regional environmental systems. The most obvious and important regional environmental system is the watershed. Of all the varied influences of the city on environmental function, the influence of urbanization on watershed function is the most profound.

Natural Watershed Function

In most North American natural landscapes, the vast majority of rain water that falls on the ground is infiltrated by the soil or absorbed into plants. Plant roots draw rain water from shallow soils, then send it back up into the sky through the leaves (a

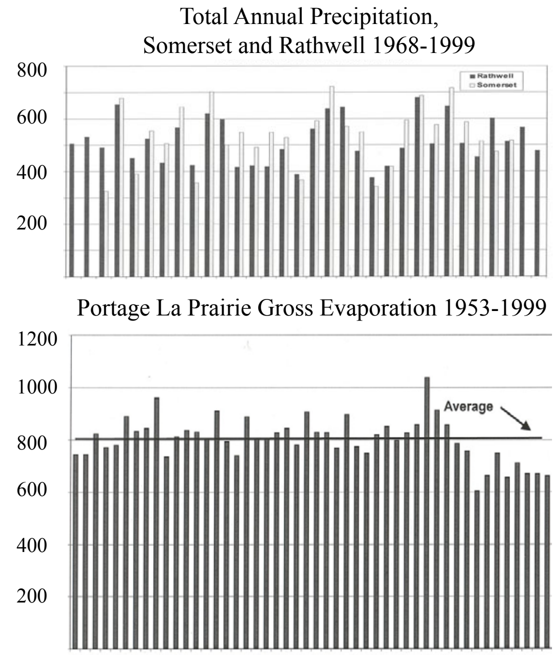


Figure X. The two charts above show the annual precipitation and evaporation for a prairie region in Manitoba, Canada. The average annual gross evaporation is approximately 800 mm (31.5 in.) while the annual precipitation is closer to 500 mm (19.5 in.).

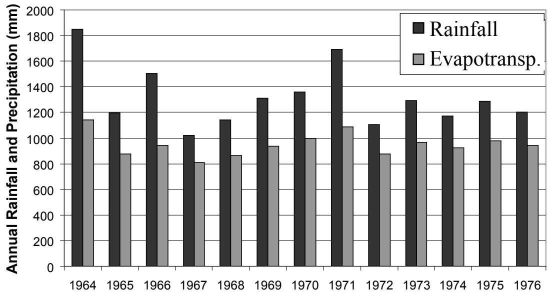


Figure X. Shows the total annual precipitation and evapotranspiration of a mostly forested watershed in the Pacific Northwest. Here, precipitation is significantly greater than evapotranspiration.
Source: Amatya and Trettin 2007

Figure X. The extent of glaciation in North America during the Pleistocent times (Minnesota University)

process called transpiration). The water that the plants don't need or can't absorb flows through the soil to be stored in the water table or drained from the soil via a nearby stream. The relative ratio of water transpired vs. water absorbed varies from place to place and from season to season. For example, during the dry season in certain prairie landscapes, plants can commonly transpire more water than they receive. Thus the plants draw not only from the supply of new rain but also from moisture stored in soil over the winter and early spring. Conversely, in coastal Pacific Northwest temperate rainforests, the average percentage of rainwater that is returned to the atmosphere as evaporation and transpiration throughout the year is about 45% while infiltration accounts for the rest. However, during the winter when it rains the most it is too cold for much photosynthesis and thus transpiration to occur. Consequently, during winter nearly 100% of the winter rain that falls on the forest floor is absorbed by the tree detritus and the soils below. As more water falls, soaking the soils, some of the excess seeps into deep water aquifers where it might be stored for an indefinite, or almost infinite, amount of time; however the majority of this water seeps a few inches or a few feet below the surface until blocked by a harder soil, called glacial hardpan, the legacy of the most recent period of glaciations. The importance of this impeded flow is discussed below.

Ten thousand years ago, all of Canada and many parts of the US were covered by a sheet of ice many miles thick. The motion and weight of this ice mixed and compressed soils and rocks to form an unstratified (all mixed up) concretized (very hard) layer that is often quite close to the surface. All of Canada, Minnesota, Iowa, Illinois, New England, New York State, and Michigan were covered by the glacier and thus have soils who's characteristics derive from this event. Parts of Wisconsin, Pennsylvania, Ohio, Indiana, and Washington State including the Puget sound were also covered and were left with "hardpan" soils in the glaciers wake. When rain water hits the hardpan layer it most often migrates horizontally over the surface of the hardpan but still underground, until it emerges in the banks of a nearby stream. The characteristic dense and fine grained lacework of streams common to these landscapes is the consequence of this relatively recent glacial event. Aquatic creatures that inhabit these streams, particularly spawning and rearing salmon, have acclimated themselves to this hydrological framework during the ten millennia since the glacial recession. Water that falls on these watersheds is absorbed by the soils and delivered to nearby streams, seeping slowly horizontally over the surface of the hardpan. A drop of rain can take weeks, or in some cases months, to get to the stream. When this water arrives at the stream it trickles down the stream banks, scrubbed clean by the filtering particles of soil and cooled by the constant temperature of the earth. The heavier the soil the cleaner is the water and the more gradual it is delivered.

What of the other parts of the continent? Soils in other parts of the continent have a more complex and older genesis, some the result of wild volcanic events so far in the distant past that the glaciations occurred only yesterday in comparison. Nevertheless, it is fair to say that in any landscape where there are frequent streams which tend to flow consistently even during periods of extended drought you are in an area of impeded flow to deepwater aquifers, resulting in horizontal interflow which feeds streams a steady supply of clean and cool waters.[5]

The capacity of soils to deliver water to deep aquifers and water tables vs. trapping it as interflow is unevenly distributed over locations. The performance of any acre of land can vary wildly from the acre next to it, particularly in glaciated landscapes. Because of the highly erratic actions of the glacier during its various stages of melt and advance, one acre of land can be the locus of a deep lens of sand left by a particular kind of outwash off the surface of a melting ice sheet, while on the acre immediately next door the soils are a dense and almost completely impervious concretized mass of very heavy clayey soils. Thus infiltration devices installed for even a very small subdivision can work splendidly in one yard and fail in the next. Nevertheless, as a general rule these averages hold true enough to form a useful assumption for planning sites, prior to more detailed investigations as part of any building program.

Streamside vegetation also plays an important role in preserving fish habitat. Streamside vegetation holds soils in place, retains nutrients in the channel, prevents water from overheating and ensures a steady food supply of insects and forest detritus for fish. Some studies indicate that at least thirty meters of streamside vegetation on both sides of any given watercourse is required in order to maintain a healthy riparian corridor.[6] Such a canopy cover of riparian vegetation shades streams and helps to maintain cold water in streams. Insects that reside in this vegetation also provide a constant source of food for fish. Fallen trees and branches provide cool resting places for fish as well as protection from predators. Roots and fallen trees reduce the energy of flowing water, which in turn helps to secure stream flow and to stabilize stream banks. Riparian plants bind soils in place and trap moving sediment, actually replenishing healthy soil and reducing erosion. During times of rising floodwater, vegetation filters surface runoff and slows overland flow. Slow-moving water then has more time to soak into the soil. In healthy, well managed watersheds, stored groundwater is released back into the stream during periods of dry weather.

Figure X. The fine lacework of streams in Tennessee shows interflow at work in an unglaciated landscape..

5. During and after a rain event on glaciated soils precipitation infiltrates the soil, percolating downward until it reaches a layer of less-permeable soil or rock material that restricts the downward flow causing the water to move laterally along this layer, eventually discharging into a surface water body (Ward et al. 2004). This lateral movement, called interflow, maintains the streams baseflow during the sometimes-lengthy period between storms (Ward et al. 2004). In the glaciated midwestern United States most present-day groundwater flow is restricted to shallow aquifers that help to maintain this baseflow (Person, et al. 2007).

6. Erman et al. 1977; Steinblums 1977; Rudolph and Dickson 1990; Chen 1991; Spackman and Hughes 1994 and Ledwith 1996 found that a minimum buffer of 30 meters (100 feet) is necessary to avoid significantly impacting riparian environments. To maintain processes such as sediment flow and contribution of large woody debris this 30 meter buffer may be increased to 60 to 80 meters, or the average height of one site-potential (ie. maximum height of native riparian forest trees) tree (Broderson 1973; Beschta et al. 1993; Thomas et al. 1993).

Even the riparian vegetation of non-fish-bearing parts of a stream system plays a role in fish habitat. Upstream areas and their intermittent streams (streams with flowing water only during wet seasons or during the period after rains) provide food for fish in the form of insects and forest detritus. They also help to maintain the quality and quantity of water flowing downstream.[7] These intermittent portions of streams are extensive throughout any stream laced watershed, which makes them impossible to completely protect when development occurs. To do so would so reduce project yield as to make development impossibly expensive while encouraging low density sprawl. Some have suggested that the solution is to build very few but very tall buildings widely spaced. While this might meet the performance criteria for stream protection it would contradict other principles for healthy sustainable communities. Fortunately there are ways to protect and recreate upstream function by incorporating an understanding of natural processes into the design strategies for site development infrastructure.

Water Quality and Water Quantity

Water Quantity, not Water Quality!

Throughout North America the conversation about watershed health has been inordinately focused on water quality, the degree to which water discharged into receiving waters carries pollutants, as opposed to water quantity, the degree to which urbanization alters the rate and amount of water discharged into receiving waters. This is a legacy of the first North American environmental movement when national concerns about polluted water and air (sparked by many notable events including the combustion of the Cuyahoga River, Cleveland Ohio, in 1969) led the US to pass the "Clean Water Act of 1972".[8] Thirty five years later, the Clean Water Act is still the only regulation governing US waters, and all 50 states have to a greater or lesser extent aligned their policies with it in the intervening decades. The original act clearly obligates states and lower levels of government to protect America's waterways, with a goal of keeping all US waters "swimmable and fishable" if not drinkable. But the Act was mute about the damage wrought on American waterways by alterations in the quantity of water that moved through its rivers and streams. At the time the act was passed very little was known about the devastating consequences to streams consequent to alterations of the rate, amount, and temperature of urban water discharged into them.[9] In the decades since the original act was passed it has been updated but its essential focus on "water quality" has never changed.

Only recently have we learned that streams, the waterway type that covers and drains the lions share of most North American

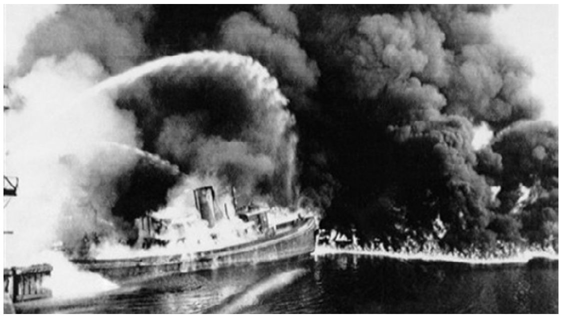


Figure X. The Cuyahoga river caught fire several times, once in 1936 and again in 1952 (shown above)
Photo credit: United Press International

---

[7] The United States Environmental Protection Agency and Environment Canada define benthic invertebrates as "animals with no backbone or internal skeleton that live on the bottom of lakes, ponds, wetland, rivers, and streams, and among aquatic plants." Many benthic invertebrates are actually the larvae of insects such as stoneflies, mayflies and caddisflies that live on land as adults but lay their eggs in aquatic environments (Yukon Place Secretariat 2007). These species, in both their larval and adult forms, are an important food source for aquatic and terrestrial vertebrate consumers such as fish, turtles and birds (Covich et al. 1999). In addition, they transform organic detritus from sedimentary storage into dissolved nutrients that can be mixed into overlying waters and used by rooted plants and algae to enhance primary productivity (Covich et al. 1999).

[8] For more information on Water Legislation in the United States visit: http://www.epa.gov/water/laws.html

[9] Much like the United States, Canada's water legislation has focused primarily on issues of water quality and the control of pollutants rather than issues of water quantity and changes to the hydrological cycle. During the 1970s Canada's management approach could be characterized as reactive and while it arguably had some successes with highly visible forms of pollution and other conventional water issues it failed to tackle more complex and pervasive forms of water degradation (Environment Canada, 1987). Federally, the Canadian Environmental Protection Act establishes a regime for identifying, assessing and controlling toxic substances and is administered largely by Environment Canada. Environment Canada also administers the Canada Water Act, enacted in 1970, which provides the framework for joint federal-provincial management of Canada's water resources. For the most part, waters that lie solely within a province's boundaries fall within the authority of that province whose legislative powers cover flow regulation, authorization of water use development, water supply, pollution control, and energy development. Although BC recently passed its Ground Water Protection Regulation in 2004, the focus was on groundwater quality not quantity (Douglas, 2006). The BC Liberal's new Riparian Areas Regulation (RAR) significantly weakens the Streamside Protection Regulation (SPR) enacted under the NDP. For example, the SPR set minimum standards for building setbacks on fish-bearing streams while RAR allows the developer to hire a professional to determine the setback while giving local governments more flexibility in choosing whether or not to implement protective measures for Streamside Protection and Enhancement Areas (SPEAs) (WCEL).

watersheds, are far more susceptible to water quantity changes than to water quality changes.[10]

Where We're Doing Wrong

In the Pacific Northwest of the US and Pacific Canada, the water quantity changes brought about by urbanization have produced a crisis. By 1999, the US Fish and Wildlife service, acting in conformance with Endangered Species Act of 1973 mandates, listed five species of Pacific salmon as endangered.[11] This triggered a requirement for other jurisdictions in the states of California, Idaho, Oregon, and Washington to respond in a way that ensured no further harm to these species. Unfortunately among the harmful activities that impacted fish, urbanization was second only to forestry on the list.

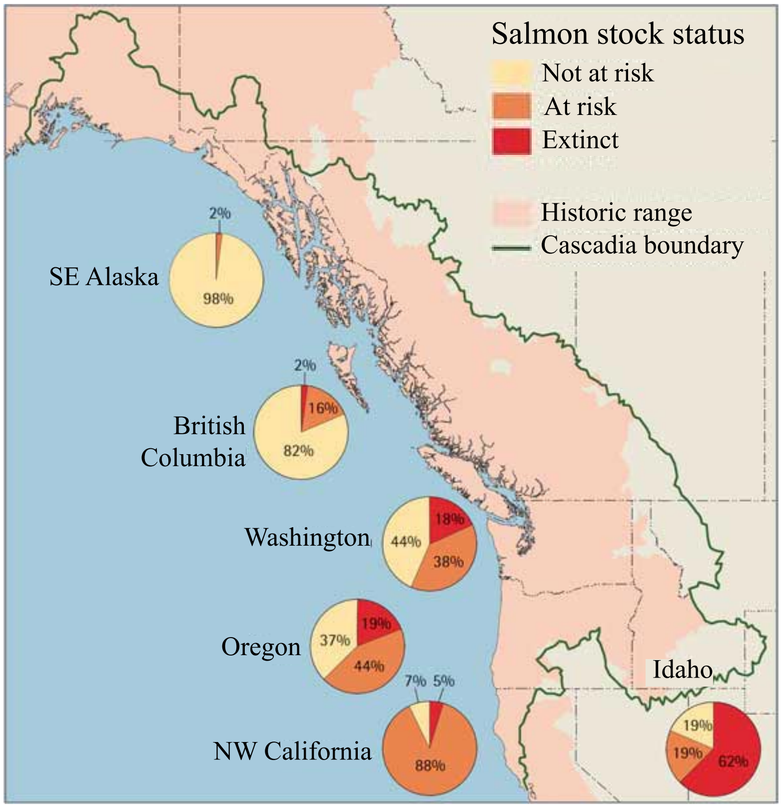


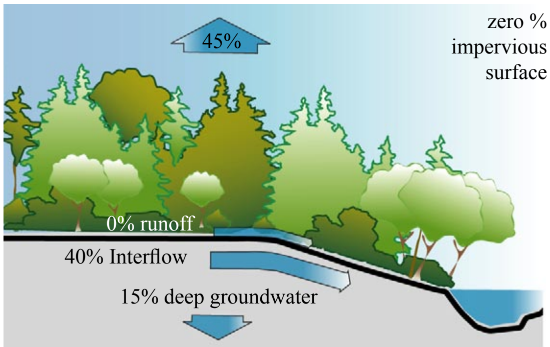
Figure X. This map shows how the percentage of threatened or extinct wild fish stocks increases towards the Cascadia's southern tip where human impacts are greatest (Source: Ecotrust)

How is it that a land use that covers less than ten percent of these states could be so damaging? One reason is that when people build cities they tend to choose the same places that salmon spawn and rear. Spawning and rearing occur on stream runs that are between 2% and 5% gradient. These gradually sloping but not entirely flat streams occur in gradually sloping but not entirely flat landscapes: exactly the landscapes that are appropriate for building cities. The second reason is how profoundly urbanization, even at suburban densities, alters

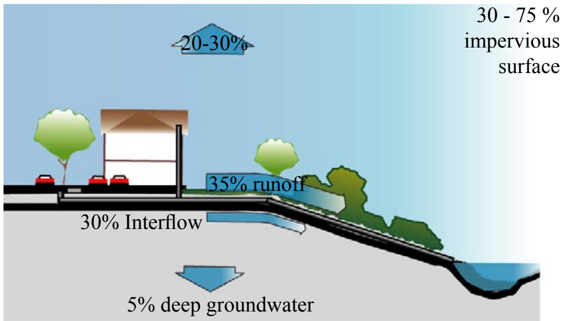
---

[10] The increase in impervious surfaces associated with development together with traditional channel and pipe stormwater management systems deliver stormwater to receiving waters much faster and in far greater volumes than under natural conditions. Water that under natural conditions would have infiltrated into the soil and traveled slowly to receiving waters via interflow, significantly contributing to stream baseflow during dry periods, is instead delivered all at once via pipes in the period immediately following the rain event. This increase in flow volume and peak flow rates erodes stream channels and increases the risk of flooding (Stormwater Planning 2002). Eroded material creates turbidity which degrades aquatic ecosystems and is harmful for fish health and reproduction (Stormwater Planning 2002). According to Booth (1991), increased runoff associated with urbanization is responsible for catastrophic expansion of stream channels, increased flooding, erosion and sedimentation in low-lying areas, and the subsequent decimation of aquatic organisms. Modifications of the land surface, specifically the elimination of vegetation and the proliferation of impervious surfaces, results in the loss of water storage in the soil column and drastically alters flow patterns so that the largest flood peaks double or more and frequent storm discharges can increase by as much as ten-fold (Booth 2000). The high velocities associated with increased peak flows increase erosion and can wash salmonid eggs from their beds, displace newly emergent alevins and fry and limit the migration of adult fish. Increased erosion leads to increased sedimentation that clogs salmonid spawning gravel, depriving oxygen to the fish eggs (Vronskii and Leman, 1991) and the removal of metabolic wastes (Havis et al., 1993). Impervious surfaces reduce the retention of water in the soil and the amount of groundwater recharge resulting in low summer base flows that can cause fish mortalities due to reduced velocity, cross-sectional area and water depth (Williamson et al. 1993). Water quality is impacted when stormwater containing hydrocarbons, heavy metals, nutrients, pesticides and bacteria is delivered directly to the stream via pipes instead of being cleaned by infiltration and delivered to the stream via interflow through the soil column. Stormwater flowing over large paved surfaces on a warm day raises the temperature of the water to levels that can be harmful for cold-water fish like salmon and trout. Finally, the capital costs of land development with traditional piped systems can be a significant cost to local government and developers and ultimately can undermine the affordability of housing (Stormwater Planning 2002).

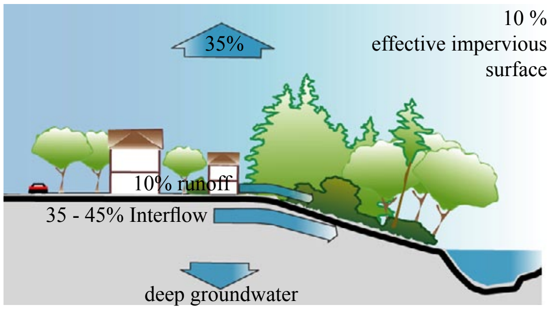
[11] Between November 1991 and October 1999, 20 distinct population segments of five salmonid species were listed as endangered under the Endangered Species Act (Buck and Dandelski 1999).



Pre-development hydrology: In a naturally functioning watershed in the Pacific Northwest, 45% of rainfall is lost to evapotranspiration, and 55% infiltrates the soil, feeding streams through subsurface interflow and replenishing the deeper groundwater aquifer. There is essentially no runoff.



Post-development (Conventional): Here runoff imcreases dramatically from close to 0% to 35% while evapotranspiration drops from 45% to between 20 and 30%. Only 35% of rainfall infiltrates the soil to replenish streams and deeper groundwater aquifers.



Post Development (Alternative): Development that limits impervious surface area achieves a much higher rate of infiltration than conventional development. Narrower streets, smaller building footprints, and riparian vegetation with continuous tree cover work together to mimic the natural hydrology of the site. Runoff is limited to 10% of the total rainfall.
Source: Site Design Manual for BC Communities (2003) http://www.jtc.sala.ubc.ca/projects/DesignManual.html

watershed performance. When an area urbanizes, conventional storm water practices require the installation of a storm water infrastructure over potentially vast percentages of salmon habitat. This storm water infrastructure functions in a way that is 180 degrees contrary to the way natural landscapes perform. Rather than holding water in the soil where it can be cleaned and delivered via interflow over days, weeks, or even months, a network of pipes is installed to insure that the same amount of water is delivered to the stream within a few hours or even within minutes of a rain event. Thus water that was previously slowly metered out by the soil, clean and at the temperature required for fish health, is flushed in amounts that can be tens of times more gallons per minute then pre development rates. This “fast flush” off urbanized landscape produces many serious consequences; destruction of stream banks is the most damaging of these, precipitated by these sudden unaccustomed deluges. Stream banks that have taken 10,000 years since the recession of the glacier to stabilize are suddenly asked to accept ten or twenty times more water than they can accommodate. The result, unsurprisingly, is erosion of the stream channel, and the delivery of those silts to lower parts of the watershed. Unfortunately it is these very places that the salmon favor for spawning and rearing - gravel beds in stream locations with gradients between 2% and 5% - that all that unstratified glacial muck gets dumped.

Figure X. A typical stormwater outfall seen here at a time of low flow. During high precipitation events the force of the water is enough to move boulders.

Figure X. Shows the consequence of urbanization on stream banks. Larger volumes of water delivered to streams in the hours immediately after storms can devastate stream banks and effectively sterilize stream ecology.

As a consequence of the disruption to urbanized watersheds, the fish-bearing capability of virtually all of our urbanized stream systems has been destroyed. In the City of Vancouver alone, only two of the original sixty salmon-bearing streams still provide habitat.[12]

---

12. In Vancouver, BC there were once over 50 salmon and trout bearing streams but today that number has dwindled to only two: the Musqueam Creek and its tributary, Cutthroat Creek, both of which run through Pacific Spirit Regional Park (Kirkby 1997). Recently efforts have been made to restore salmon habitat to waterways such as Spanish Banks Creek where coho and chum salmon fry are have been released in an attempt to develop a viable population of returning fish (Urban Streams).

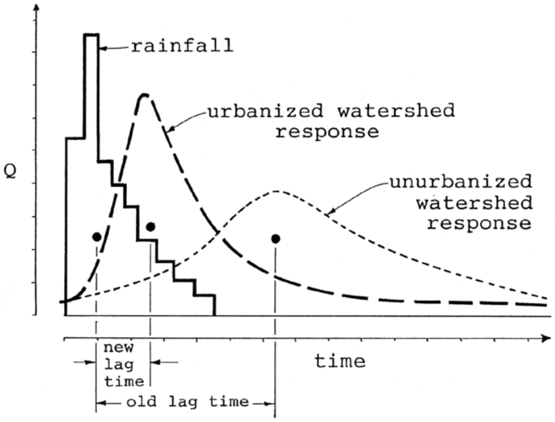


Figure X. Shows a schematic representation of changes in peak stream flow due to urbanization. The lag time between rainfall and peak flow can be significantly reduced as the watershed run-off characteristics are changed by urbanization (Source: J. David Rogers 1997)

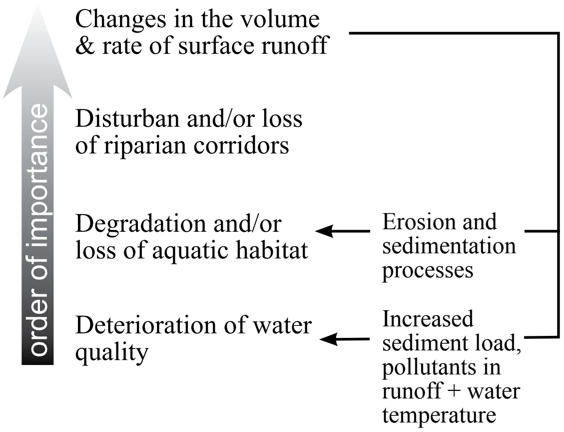


Figure X. Shows the factors that limit the ecological values of urban streams. In addition to being the most important factor in the degradation of aquatic ecosystem values, changes in the volume and rate of surface runoff also contributes significantly to the degradation of aquatic habitat and the deterioration of water quality.

Impervious Surfaces

Impervious surfaces don't kill fish. Pipes kill fish.

It's not the impervious surfaces that kill fish, it's all the pipes that drain them. Under conventional circumstances, every hard surface in the city is directly connected to the stream with a hard pipe connection. Many municipalities require that roof drains be connected from residential structures via hard pipe connections to street storm drains. This is true even when there is ample yard area to more cheaply accept roof drainage via downspouts. Similarly driveways and sidewalks are drained directly to streets where their discharge is gathered in storm drain inlets that lead to pipes. These pipes in turn lead to bigger pipes and eventually into streams. What this creates is a watershed where in what are usually considered low density and relatively green suburban locations, every other foot of land is directly piped to streams. Since most of this water drains from exposed surfaces that may have been heated by sunlight in the hours before the rains, water draining from these surfaces can be tens of degrees warmer than waters entering streams from more natural avenues.

It can be surprising to discover that even in low density developments of 4 dwelling units per acre, between rooftops, driveways, patios, sidewalks, and most importantly streets, over 50% of the surface area can be covered with impervious surfaces.[13] Note that 35% of all water that falls on such a low density site is channeled as "runoff" directly and quickly to streams via hard pipe connections to storm drain systems. Runoff is a category of drainage that does not even exist in natural forested landscapes.[14] As areas urbanize runoff suddenly emerges as the dominant way that water leaves the site. Evapotranspiration rates while still significant fall to between 20 and 30% from over 45% in pre development landscapes, while interflow and deep infiltration drops to 30% from over 50% in the forest. This change may not seem extreme until you consider that all of the 35% of total rainfall that is drained as runoff is directed to the stream in the hour or two immediately after the storm event, delivering tens of times more water to the stream during those hours than it can comfortably manage, often at temperatures many degrees too hot, and carrying varying amounts of suspended solids (dirt in layman's terms, often seen as a grey fog in stream waters).

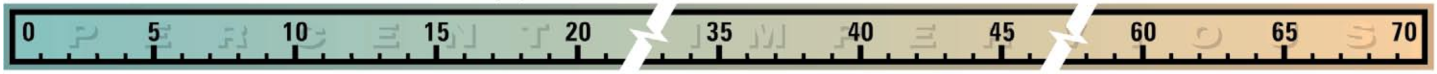
[13] To see the breakdown of impervious surfaces for low density residential developments visit: http://www.jtc.sala.ubc.ca/projects/ADS/HTML_Files/ChapterTwo/matrix_us_2.htm. Status quo development with a density of 4.4 dwelling units per acre was found to have 54% Total Impermeable Surface (TIA) while traditional development with a density of 13.4 dwelling units per acre had 51% TIA (Condon et al. 1998).

[14] Horton overland flow (HOF), commonly known as runoff, occurs when precipitation falls on soil faster than the soil can absorb it. It is most common in regions with periodic, intense rainfall, limited vegetation, and thin soils. Where rainfall intensities are generally lower than the rate at which soil can absorb it, all of the precipitation is infiltrated where it first lands, resulting in surface runoff rates of essentially 0%. The coastal regions of the Pacific Northwest, with their gentle rainfall and lush vegetation, provide an excellent example of these conditions. In these regions rainfall is infiltrated into the soil and moves downslope below the ground surface at substantially slower rates than HOF. [Summarized from Booth 2000]

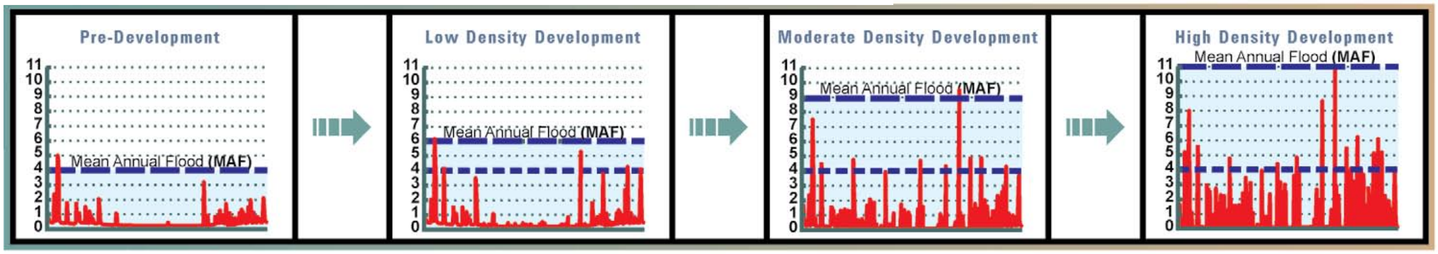
Relationship between impervious surfaces and fish kill

Increasing Urbanization (No Best Management Practices)

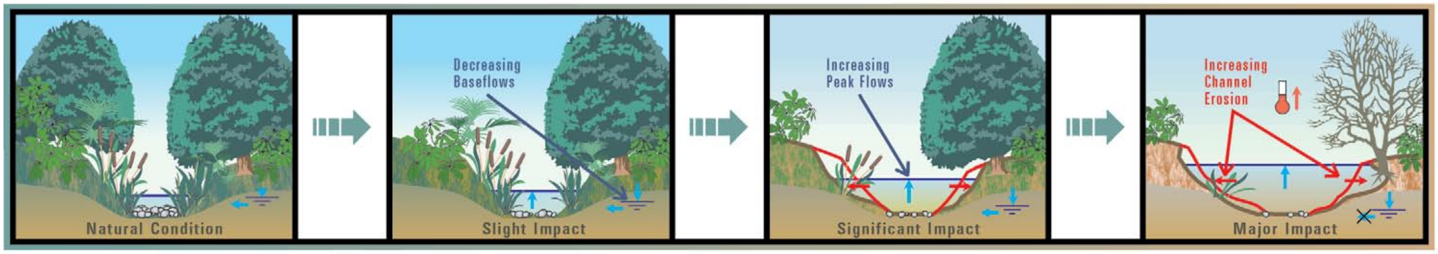
Proportion of Impervious Land Area (%)



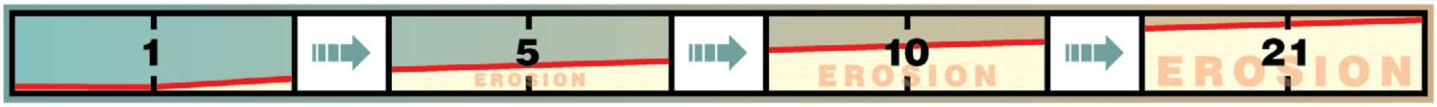
Effect on Typical Year Hydrograph



Effect on Watercourse Erosion



Number of Storm Events at or Above Predevelopment Mean Annual Flood



Ratio of Mean Annual Flood to Winter Base Flow

Figure X. Shows the impact of changes in hydrology on watercourse erosion and base flow relationships (without best management practices). It illustrates the progressive changes in hydrology that result when land use change alters the water balance and replacement of natural vegetation and soil with impervious surfaces reduces infiltration and evapotranspiration. Total runoff volume increases (as shown in red in the hydrographs) and so does the Mean Annual Flood (MAF).

Source: Graphics for Figure X and X were a collaborative effort of Kim Stephens, Bill Derry and Chris Johnston for the purposes of communicating scientific findings; and translated research done by Richard Horner and Chris May of the Center for Urban Water Resources Management at the University of Washington.

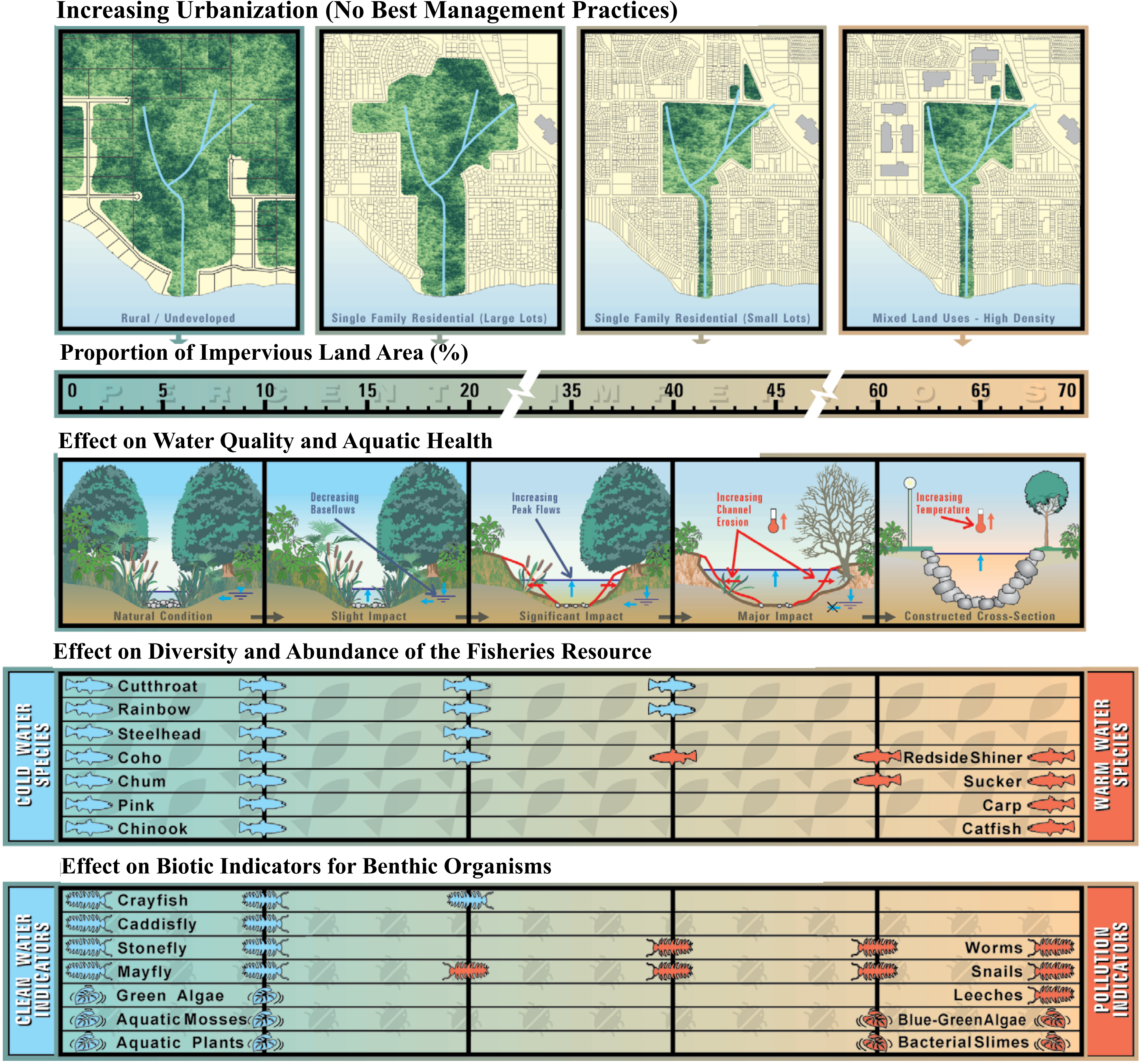


Figure X. Shows the impact of increasing urbanization on stream corridor ecology (without best management practices). Increasing impervious area and decreasing riparian corridor integrity increases runoff volume resulting in watercourse erosion, degradation of the stream channel and ultimately the progressive decline in stream corridor biodiversity and abundance of cold-water fish and clear water indicators.

It only takes a small amount of pavement in the watershed to kill fish. In the Pacific Northwest, an analysis of a multitude of urban streams revealed that fish counts in urban streams began to fall off when only 10% of the urban watershed was covered in pavement and rooftops.[15] When reaching impervious surface rates of 30% and above, the minimum coverage conceivable for even low density suburban development the news is even worse. At this level in most cases fish populations have collapsed and salmon runs have been extinguished. At streetcar city densities of 10 to 20 dwelling units per acre gross density you can, with

[15] As a watershed nears, or exceeds, 10% impervious cover stream health deteriorates rapidly. Studies have found that there is a decrease in large woody debris (Booth and Jackson 1997), a decline in channel stability and fish habitat quality (Booth 1991), a significant decline in wetland aquatic macroinvertebrate community health (Hicks and Larson 1997), sharply lower insect (Jones and Clark 1987), macroinvertebrate and fish diversity (Klein 1979), higher rates of fish egg and larvae mortality (Limburg and Schmidt 1990) and steep decline of biotic integrity (Steedman 1988). To protect sensitive stream ecosystems, such as those supporting fish populations, watershed imperviousness should not exceed 10% (Limburg and Schmidt 1990).

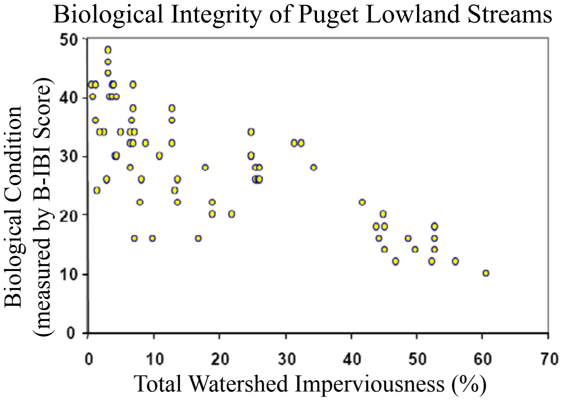


Figure X. The chart above, (from Booth 2000) shows a compilation of biological data on Puget Lowland watersheds reported by Kleindl (1995), May (1996), and Morley (2000). "The pattern of progressive decline with increasing imperviousness is evident only in the upper bound of the data; significant degradation can occur at any level of human disturbance (at least as measured by impervious cover)" (Booth 2000).

substantial effort, keep up to 50% of the site pervious; but these statistics suggest that such effort is for naught. Judging by this work, at 50% impervious levels no fish have survived. And it is not the pollutants in the streams that kill the fish. Chemical pollution in streams becomes a serious problem at impervious levels over 50% of the watershed. At this level enough chemical and particulate matter flows in streams to clog and poison the gills of the crustiest Coho. But in fact Mr. Crusty is long gone by this point; killed years before when the disruptions caused by development in his watershed had altered water quantities, temperatures, and flow rates enough to utterly destroy his habitat. But it is not the pavement that kills the fish it is the drains that drain it, as discussed below.

Storm Sewers

Storm sewer history and cultural tradition

The basic architecture of storm drain systems has not changed since the Cretan Minoans installed the first system over 4,000 years ago. For all but the last fifty years of that history the storm systems have carried both rainwater and sanitary discharge from toilets (known as black water) in the same pipe. Treating storm water as "waste" equivalent to human waste has developed a cultural ethos and a storm water technology focused entirely on removing this "hazard" as quickly and completely as possible, and not at all on understanding and working with natural processes. With storm and sanitary waters mixed in the same pipe these mixed waters were indeed dangerous and needed to be kept separate from humans.[16] Only in the last 50 years have the storm and sanitary systems been separated, and thus only recently can we consider these systems and the water they contain appropriately. Of all the impediments in the way of change the tendency to see storm water in terms of its potential for disaster is the worst. Methods used for sizing storm water pipes have not changed in the hundred plus years since the "Manning Formula" came into common use. This formula calculates the amount of water that might fall in the various parts of a drainage area and how long it will take it to reach a discharge point. The volumes assumed are derived from an assumed extreme storm event, typically the largest storm you might expect in any five year period, called the design storm return frequency. Storms that dump 10 inches of water on a site during 24 hours are commonly used as a basis for this in many parts of North America. Some jurisdictions use even more conservative design requirements, applying the 100 year design storm return frequency – typically a few inches per day more than the 5 year return storm. It follows of course that systems designed solely to quickly move waters from catastrophically large storms to off site streams will move waters from smaller more frequents storms to receiving streams

---

[16] A Combined Sewer System (CSS) is a wastewater collection system that collects and conveys sanitary wastewater (domestic sewage from homes as well as industrial and commercial wastewater) and storm water through a single pipe (EPA 2004). During times of low, or no, precipitation wastewater can be pumped to treatment facilities however when collection system capacity is exceeded during precipitation events the systems are designed to overflow, discharging sanitary wastes directly to surface waters (EPA 2004). In the United States there are 746 communities with combined sewer systems, these communities are regionally concentrated in older communities in the Northeast and Great Lakes regions and are responsible for the release of an estimated 850 billion gallons of untreated wastewater and storm water (EPA 2004). This wastewater contains raw sewage, pathogens, solids, debris, and toxic pollutants (EPA 2004). The major causes of water quality impairment are associated with pathogens, organic enrichment leading to low dissolved oxygen, and sedimentation and siltation (EPA 2004). Catchments with combined sewer overflow effluent usually exhibit high coliform bacteria densities, especially after a storm (Gibson et al. 1998, Young and Thackston 1999). To mitigate combined sewer overflows municipalities can attempt to maximize the flow to the treatment plant and expand their existing facilities to accommodate these increased flows but expansion comes with a high cost as seen in the City of Tacoma, Washington where a partial upgrade of their activated sludge process would have cost $130 million (EPA 2004). Other options include reducing the inflow of rainwater into the system, separating the storm and sanitary systems and/or rehabilitating the sewer system components (EPA 2004).

with equal or greater rapidity, with great damage to receiving streams.

It's the small storms stupid

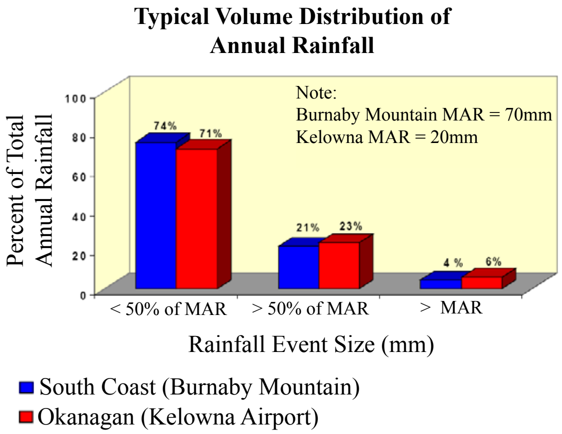
Four thousand years of focusing on the big storms prevents us from seeing the problem differently. From the point of view of the fish, it's not the big storms that matter it's the small ones. Fish can survive the rare cataclysm, it's the day to day disruption caused by the way small storms are treated that kills them. In all but a few parts of North America, the vast majority of storm events are small, generally under one inch per day. In most zones, storms under one inch in 24 hours (or one mm per hour) account for over 70% of all water that falls during the year.[17] The devastating consequences of stream health wrought by our storm drain systems can be fairly ascribed to our fixation, understandable but still a fixation, on the cataclysmic storm, and the design of our systems entirely around that rare event.[18]

Retention ponds

Some jurisdictions require retention ponds be installed just upstream of discharge points into streams, hoping thereby to mitigate the worst effects of conventional storm drain systems on receiving waters. Retention ponds were originally required to mitigate the potential floods caused by urbanization. In this function they are only partially successful and in some cases actually make floods worse by releasing waters during periods of crest when an earlier release might have been better. As for pollution benefits their efficacy is quite limited. It is generally assumed that retention ponds remove 50% of pollutants that would otherwise enter streams. Removing 50% of pollutants is like cutting your poison dose in half: instead of dying right away you die slowly and painfully. But this is not bad enough. Research suggests that in some cases retention ponds can even add pollutants to storm water, such that water emerging from the downstream side of the pond is more polluted than water on the upstream side (turbulence in the pond that stirs up previously settled pollutants appears to be the answer to this mystery).[19] Perhaps of more importance, retention ponds do nothing to enhance infiltration and thus very little to mitigate the distortions to the stream hydrograph consequent to urbanization. This is because it is physically impossible, or if not impossible incredibly expensive and space consumptive, to have a retention pond large enough and deep enough to hold the volume of water you would need in order to meter it out, not over 48 hours which is typically the maximum residence time in retention ponds post storm events, but over weeks and months to approximate the discharge rate of native soils. And even if you were willing to entertain the construction of a pond so large, you would still need

---

17. Small rainfall events are generally described as less than ½ the size of the Mean Annual Rainfall. This volume varies from region to region but in general accounts for approximately 75% of the total rainfall events in a given year. Water from small rainfall events should be captured from rooftops and paved surfaces and infiltrated, evapotranspirated or re-used at the source. Maintaining the natural water balance at the source is crucial for volume control which maintains baseflows, reduces erosion and flood risk and filters/cleans water. During large rainfall events (greater than ½ the size of the Mean Annual Rainfall) runoff from impervious surfaces should be stored onsite and released at a controlled rate. Only for extreme rainfall events (those that exceed the Mean Annual Rainfall) should it be necessary to provide escape routes for runoff with sufficient capacity to contain and convey flood flows. Generally extreme rainfall events happen only once and year, making up a very small portion of the annual rainfall volume. [Summarized from "Stormwater Planning: A Guidebook for British Columbia", May 2002 http://www.env.gov.bc.ca/epd/epdpa/mpp/stormwater/stormwater.html]



18. Kunkel and Andsager (1999) studied extreme precipitation events of 1-7 day duration with recurrence intervals of 1 or 5 years. They found that precipitation from 7 day, 1-yr events (with thresholds ranging from less than 4mm/day in desert regions to more than 21mm/day along the coast) accounted for only 15% of the total annual precipitation in the United States. The contribution of 1- and 3-day 5-yr events accounted for an even smaller percentage (Kunkel and Andsager 1999).

19. Need work from research committee (Patrick)

to provide a filtering mechanism that would emulate the cleaning function of soils, and a refrigerator to cool sun baked surface water to the temperature expected by aquatic stream species.[20]

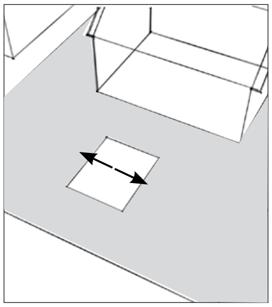
"Total impervious surface" versus "effective impervious surface".

The recently discovered direct correlation between the amount of impervious surfaces in the watershed and the collapse of fish stocks in the streams has been important but depressing discovery. Unfortunately it has often provoked responses among some researchers, environmentalists, and policy experts that lead to more sprawl not less. The 10% total watershed impervious threshold, where fish stocks begin their steep collapse, has led many to suggest that new urban developments should not exceed a total maximum impervious surface level of 10% of the entire watershed. This would give you a maximum density of about one dwelling unit per two acres or less (possibly far less depending on the presence of commercial areas and major roadways in the watershed). Some, like Tom Holz of Lacey, Washington, have even gone so far as to suggest that no single family zones should be approved at densities higher than one dwelling unit per five acres accessed on a gravel road, with most new density absorbed by isolated tall towers linked by low impact elevated transit lines.[21] Faced with such extreme solutions many have despaired and concluded that healthy watersheds and walkable affordable communities are incompatible. When a choice is made in these stark terms certainly the fish will lose. Fortunately this does not have to be the case.

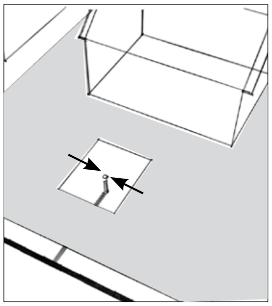
---

20. Water temperature determines the distribution, growth rate and survival of fish and other aquatic organisms through its influence on migration patterns, egg mutation, incubation success competitive ability and resistance to parasites, diseases, and pollutants (Armour 1991; LeBlanc et al. 1997). In addition, it influences rates of in-stream chemical reactions, the self purification capacity of streams and their aesthetic and sanitary qualities (Feller 1981). The highest average mean weekly temperature for coldwater, such as rainbow trout, book trout and salmon, coolwater, such as northern pike and yellow perch, and warmwater, such as catfish and bass, species are approximately 22°C, 29°C and 30°C respectively (Armour 1991). Mehner and Wieser (1994) found that on a restricted diet average metabolic expenditures were 1.56 times higher for perch at 20°C as opposed to 15°C and at 15°C, 47% of metabolizable energy was converted to body mass whereas at 20°C only 21% was available for growth (Mehner and Wieser 1994). The Q10 law states that the metabolic response of all organisms follows a general law of doubling with each 10°C increase in temperature but this is a conservative estimate for salmon where a decrease in internal temperature of 2.5°C was found to produce a 12-20% decrease in basal metabolic rate (Berman 1990). To put this in perspective, Pluhowski (1970) found that modifications of the hydrologic environment as a result of urbanization increased the average stream temperature in summer by 5-8°C.

21. Tom Holz chaired the *Salmon in the City* Conference held May 20-21, 1998 in Mount Vernon, Washington where he presented a paper with Tom Liptan and Tom Schueler, 'Beyond Innovative Development: Site Design Techniques to Minimize Impacts to Salmon Habitat,' available online at http://depts.washington.edu/cuwrm/research/sitc.pdf. More recently he has presented the concept of zero impact development to various City Councils throughout Washington State including Lacey, Sammamish, Tumwater and Shoreline.



runoff directed to lawn
Patio EIA 0%



runoff directed to drain
Patio EIA 100%

TIA and EIA

Much of the research that led to these depressing conclusions was conducted in watersheds where streets and rooftops were directly piped into streams, with great damage to the receiving waters. But it is conceivable for pavement to have little or no impact on receiving waters. For example, if you have a backyard of 1000 sq feet with a 100 sq foot paved patio, the impervious area of that backyard is 10%. This ratio of hard space to soft space is known as “total impervious area” or TIA, expressed in percentage terms. Presumably this patio contributes, when combined with all the other roads and rooftops and driveways in the area, to the destruction of the watershed. But what if the water that falls on this patio runs off into the soft grass around it, and what if the soil around the patio is porous enough to always accept this discharge. In this instance the influence of the patio on the watershed is zero. Conversely, what if the patio is equipped with a center drain, and that drain is connected to the street storm drain system, either by a hard pipe connection or via a drain that discharges at the curb or on the driveway or some other hard channel. In this instance the patio is “hydrologically connected” to the storm system. Water that falls on it has no opportunity to be absorbed by site soils. In this instance, 100% of the patio surface contributes to the decline of the watershed.

How can we then distinguish between the paved surfaces that are harmless, like the patio that drains into the grass, from the paved surfaces that are harmful, like the patio with the drain connected to the street drains? We can do so by distinguishing between the *total impervious area*, or the TIA, from the *effective impervious area*, or the EIA, of the site. In both cases described above the TIA of the yard is the same: 10% (total impervious area is a measure of pavement and rooftops and makes no distinction consequent to drainage method). But the patio that drained into the surrounding grass had no *effect* on the watershed. It therefore had an “effective impervious area”, or EIA, of zero. If all of the water shed by this patio infiltrates into the ground, then as far as the fish are concerned the pavement does not exist. It is this condition that we can and should shoot for. The following four rules provide the means.

Four Rules for Infiltration

Rule 1: Infiltrate, Infiltrate, Infiltrate

As in the business of real estate, when urbanizing or retrofitting existing urban areas for low impact on streams, there are only three rules: *infiltrate, infiltrate, and infiltrate.*[22] If all the rain or most of the water that falls on the site could go into the ground the pre development hydrograph is emulated. If this

22. An integrated stormwater management system seeks to maintain a site’s natural water balance by capturing rainfall at the source and returning it to natural hydologic pathways (which in the vast majority of landscapes are predominantly infiltration and evapotranspiration). This can be achieved through the adoption of Low Impact Development (LID) practices and source control. In addition to maintaining natural vegetation and reducing the compaction of soils, LID practices minimize the creation of impervious surfaces by building compact communities with reduced road width, building footprints and parking requirements. Source control involves preserving natural vegetation and stormwater features such as wetlands and riparian forests, preserving natural infiltration and evapotranspiration capacity through absorbent landscaping, infiltration facilities and green roofs and re-using rainwater for irrigation and indoor uses. Absorbent landscaping should provide 10-25% organic content in the soil and surface vegetation such as shrubs, grasses and trees that improve the infiltration capacity of the soil. Forests are generally the most effective landscapes for infiltration and evapotranspiration due to their deep rooting zones and high leaf density. Infiltration facilities provide on-site storage capacity through absorbent soil, sand or gravel, ponding, infiltration chambers or storage structures such as cisterns. The effectiveness of infiltration facilities depends on land use (impervious surfaces), soil type (infiltration capacity), the size of the infiltration area (as a percentage of the total site), rainfall characteristics, depth and type of the infiltration facility, and the water table depth. Green roofs can significantly reduce the volume and rate of runoff from buildings by using absorbent soil and vegetation to retain rainfall and facilitate evapotranspiration. Re-using rainwater at the source, especially for indoor greywater uses, not only reduces the volume and rate of runoff but also reduces the amount of water drawn from resevoirs and the cost of water supply infrastructure. [Summarized from “Stormwater Planning: A Guidebook for British Columbia”, May 2002 http://www.env.gov.bc.ca/epd/epdpa/mpp/stormwater/stormwater.html]

can be fortified by a robust planting strategy for streets, yards, and, at certain densities, rooftops, then the pre development hydrograph can be nearly matched.[23] This is true no matter how much impervious surface there is. For example, it is possible to design a landscape where 100% of the site is covered with sidewalks, streets and rooftops. Such a site would have a TIA of one hundred percent but would also have an EIA of zero! This would be accomplished through holding water on rooftops and then infiltrating it under foundations and street sections. It would be costly to infiltrate all this water, requiring expensive infiltration chambers under all streets and walks, and high performance green roofs on all buildings; but it could be done. Of course infiltrating water on sites with less than 100% TIA is easier. Streetcar city districts at 10 - 20 du per acre are often still 50% pervious, providing ample soft areas to work with. The soft portions are largely the lawn and landscaped surfaces of yards and roadside tree boulevards.[24]

23. Research suggests that establishing urban forests that mimic native forests is key to more sustainable stormwater management. Although each region will have different sustainable design considerations relating to its particular hydrological and vegetative characteristics, some general guiding principles should still apply. Although the degree is variable between sites and seasons, most of the above-ground, surface and below-ground effects of urban trees and forests tend to reduce stormwater runoff amounts and peak runoff rates. The interception of precipitation by leaves delays precipitation reaching the ground and allows for some evaporation and absorption of this precipitation from the leaves or stem of the tree. When the leaf surface area exposed to the sun and wind is high, water loss from the leaves is high (Watson 1989). Leaf litter and soil with high organic content under vegetation can retain rainfall, reducing the amount and/or peak rates of runoff while the roots and trunk base of mature trees create depression on the ground where water can either be evaporated or infiltrated into the soil. Older trees generally generate more leaf litter and their roots create more and larger depressions. Organic material from leaf litter and other tree detritus tends to increase infiltration rates by increasing pore space and moisture holding capacity of most soils (Lee 1980). The overall effects of urban forests on stormwater runoff tend to be greatest during the growing season when most trees are in leaf and transpiration and evaporation rates are highest and have a relatively greater effect on small rather than extreme rainfall events. For example, a study in Sacramento, CA found that runoff reduction from interception alone averaged 15.2% for small storms (< 5mm/day) but only half that for large storms (>25mm/day) (Xiao 1998).

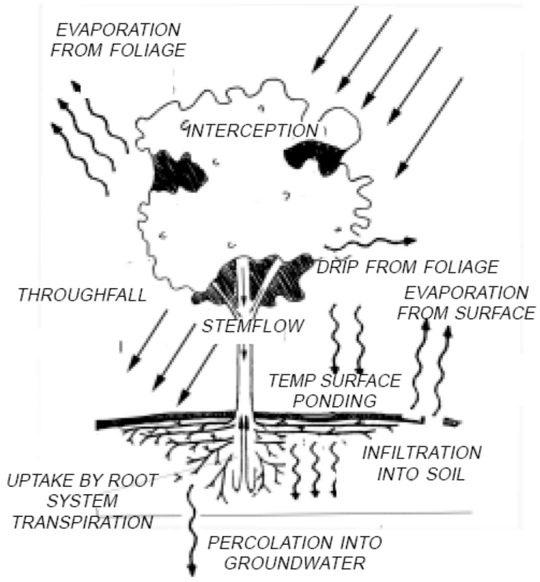


Figure X. Effects of urban forest on hydrological processes
Source: James Taylor Chair, Technical Bulletin 6, 2000

24. Condon, Patrick M. and Jackie M. Teed. 1998. Alternative Development Standards for Sustainable Communities. Available online at: http://www.jtc.sala.ubc.ca/projects/ADS.html

Rule 2: One inch per day

But how much of the rain must we infiltrate? Obviously infiltrating all of the rain should be the goal if we are to completely emulate pre development performance. Unfortunately in some parts of North America some storms dump more than ten inches of rain on the ground in a 24-hour period. These so called 100 year storms are the basis for storm water system design, should they be for infiltration systems? If soils are capable of infiltrating that much water in 24 hours the answer is yes, but few soils can do so. Fortunately aquatic species can manage the occasional large storm event, and for the most part so can the stream channel. The problem is not the big storm, which happens once in a while in natural environments too. The bigger problem is how urbanization fundamentally alters the behavior of streams under more ordinary circumstances - the 100 different rain events that you get during the ordinary year, not the one storm that comes every 100 years. Since the research suggests that watersheds start to degrade when impervious surfaces reach a threshold of 10% total imperious area (TIA), what if we were to design urban landscapes with a TIA of say 50% as if they were only 10% paved; i.e. design them such that the TIA is 50% but the EIA is 10%? It follows logically that if you could absorb 90% of all the water that falls on site, you would be emulating the performance of sites with a TIA of 10%.[25] If your objective

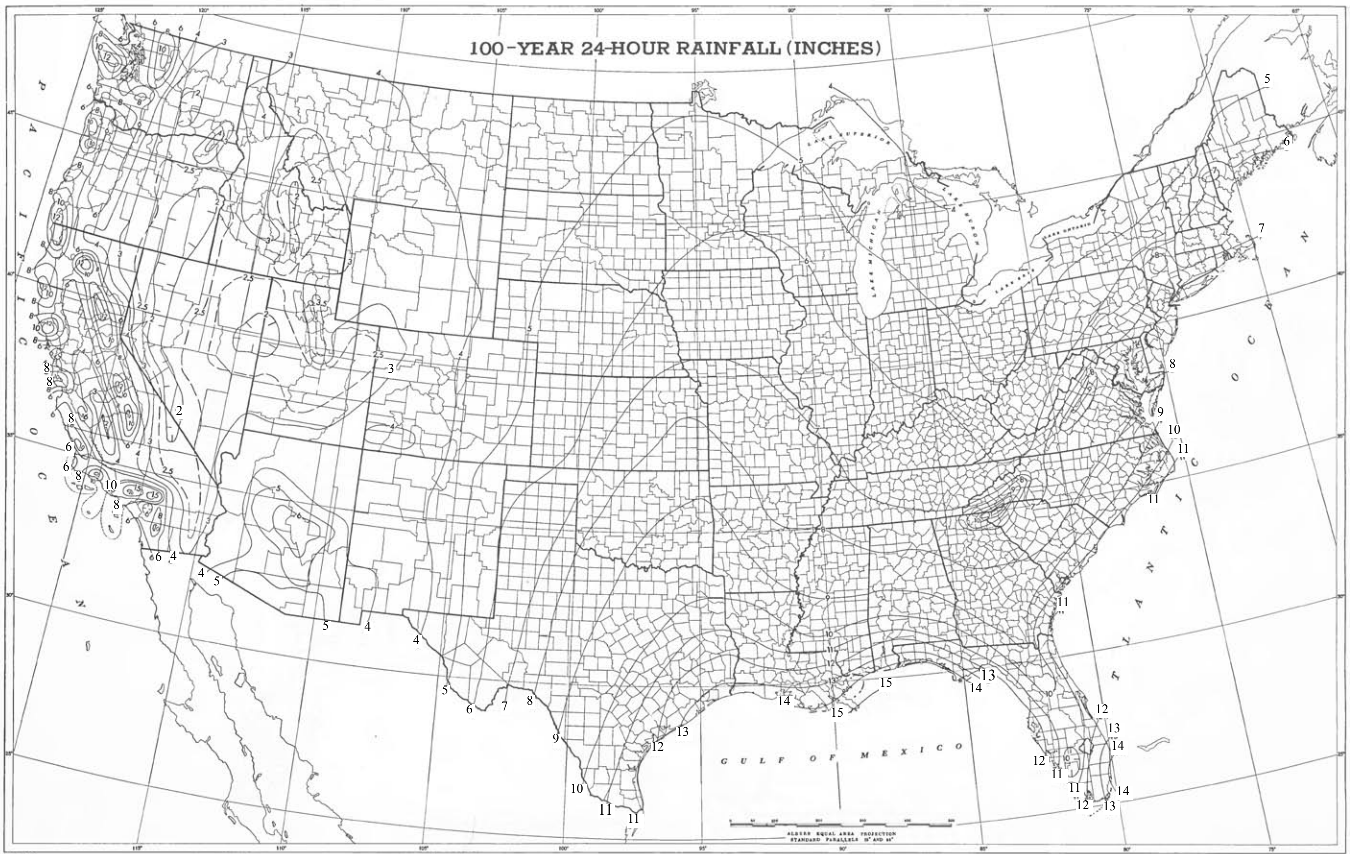


Figure X. 100 Year 24 hour rainfall (inches) in the United States. 100 year storm events range from 14 in/day in Florida to 2 in/day in Nevada. Source: Technical Paper 40 (Hershfield 1961).

[25] Limiting runoff volume to 10% of total rainfall should be sufficient to maintain baseflows, water quality and aquatic ecosystem health. Infiltrating rainfall feeds stream baseflow, removes many pollutants from stormwater and maintains the timing and volume of runoff thereby reducing the risk of flooding and stream channel instability. This can be accomplished by preserving or restoring natural vegetation along the riparian corridor and natural features such as wetlands, maintaining instream features such as channel complexity and spawning gravel and by controlling sources of water pollution from point and non-point sources. [[Summarized from "Stormwater Planning: A Guidebook for British Columbia", May 2002 http://www.env.gov.bc.ca/epd/epdpa/mpp/stormwater/stormwater.html]

is to capture not all, but most, of the rain that falls on the site then obviously your best bet is to let most of the biggest and hardest to capture events go, infiltrating all the rest. But what size storms should you always capture to meet this performance threshold? For many landscapes in North America the answer is this: *capture all storms of less than an inch and the first inch of all larger storms.*[26]

Surprisingly this amount does not vary as much form one part of North America to another (the exception appears to be thunder storm and hurricane prone Florida).[27] An in-exhaustive analysis of Midwestern, Northeastern, Southwestern, and Cascadia landscapes suggests a range between .85 and 1.25 inches per day will achieve the 90% infiltration target. It may at first seem strange that a standard for the rainy Northwest is roughly the same as for the dry Southwest, but what matters here is not the total amount of rain in a year but the percentage of rain provided by small storms versus large storms. For all but one part of the continent the small storms contribute more total rain to receiving waters than storms over one inch per day.

Of the rules listed here in this section the one inch per day rule is the most important. Negotiations around storm water performance targets can often quickly bog down in the arcane language of civil engineering, with equations for time of concentration, complex grass swale turbulence, system friction, taking on a life of their own. Most of this language reflects a view of rainwater as a nuisance to be disposed of rather than something to be retained. No flow rate or pipe size calculations are needed for putting water back in the ground. It stays where it falls. Thus part of the value of the one-inch per day rule is its simplicity. It is memorable, easy to apply, and, most importantly, correct. Insisting on the one inch a day rule helps alter the frame of reference for storm water system design. It is even a simple yet scientifically credible rapier to cut through all the regulatory underbrush that blocks our path to more sustainable communities.

[26] The majority of rainfall occurs at intensities of less than one inch per day.

Annual Rainfall Potentially Captured with a System That Can Absorb 1” (25.4mm) Every 24 Hours.

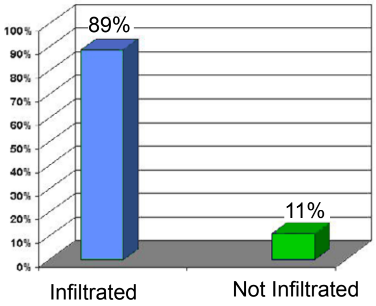
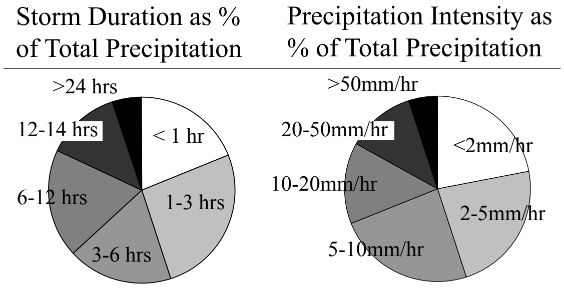


Figure X. In the Pacific Northwest a stormwater management system designed to absorb 24mm (1 inch) per day, will absorb almost 90% of all the rain that falls on a site. Source: Site Design Manual for BC Communities 2003

[27] With most areas receiving at least 50 inches of rainfall per year, Florida is one of the wettest states in the US although it exhibits great annual variation often resulting in a year of flood followed by a year of drought (Black, 1993). South Florida receives 70% of its annual rainfall between May and November while North Florida receives less than 60% (Black, 1993). Thunderstorms are the main source of rain in Florida and peak in frequency and intensity in July and August except in South Florida where the storms continue into November (Black, 1993). Storm events with a 1-year reoccurrence and 24 hour duration range from 3.5 to 5 inches/day (Hershfield, 1961) meaning that in a typical year the largest storm event would account for up to 10% of the total annual rainfall.

Figure X. 1-year isohyet for Florida (1-year storm ranges from 3.5 to 5 inches/day, among the highest in the US) Source: Hershfield, David, M. 1961.


Storm Duration as % of Total Precipitation

Precipitation Intensity as % of Total Precipitation

Figure X. Like Florida, the Southern Appalachian Mountains in North Carolina receive much of their precipitation in short term high intensity storm events (Neary and Swift, 1987).

Figure X. The Pringle Creek sustainable community in Oregon incorporates infiltration into streets, boulevards and yards.

Rule 3: Infiltrate everywhere

But the one inch a day rule only works if you can infiltrate on every inch of the site. But any developed site will have some areas that are less appropriate than others for infiltration. In our example streetcar suburb, all infiltration should occur on the soft lawn and boulevard areas that constitute fifty percent of the site. If these lawns can infiltrate the one inch per day that fall on them, and infiltrate the water that flows off of adjacent paved surfaces that constitute the other 50% of the site, then we will have met the target. Many soils can manage two inches per day without difficulty. It gets harder when you direct runoff to a more limited space. If you take the water that falls onto the impervious fifty percent of the site and for whatever reason direct it to a “rain garden” (a planted area designed to accept large amounts of water) that covers only 5 percent of the site, that rain garden will have to infiltrate the one inch that falls on it plus 10 additional inches. Eleven inches is a lot of rain. Very few un-amended soils are capable of this much. For this reason you must infiltrate everywhere: in every yard and every road verge not ignoring any opportunity to do so.

Rule 4: Heavy soils sandy soils.

Different soils have different capacities to infiltrate, but almost all soils are capable of infiltration at the 1 mm per hour or one inch per day rate. This point is key. Most civil engineers know a fair amount about soil infiltration, but they have very different performance assumption in mind when the subject is raised. For most engineers 1mm per hour is considered impervious soil, or “clay” soil.[28] The engineering community considers a soil to be porous when it has infiltration rates in the range of hundreds of mm per hour or more. This lack of common understanding between the value of ubiquitous slow infiltration for stream health, and the engineering community’s assumption that infiltration is only possible in highly porous soils, creates extremely difficult implementation barriers. Long and careful discussion is required, usually in a charrette setting, to overcome these barriers. Proponents of infiltration strategies must be wary of this language difference and difference in understanding of the minimum soil conditions necessary for infiltration. From an engineering perspective only sandy soils are capable of storm water infiltration. From a broader sustainability perspective almost all soils are capable of infiltration, even heavy soils. Watershed performance, no matter what the soil, is dependent on the soils capacity to absorb and hold water. If a watershed soil is heavy it leads to a very precise regimen of interflow where waters will be retained in the heavy soils far longer than in sandy ones, be cleaned far better than in sandy ones, and lead to a landscape more frequently incised with small productive streams than in watersheds dominated by sand. In short the same things

Soil Type	Typical Hydraulic Conductivity Range
Sands & gravels	> 50 mm/hour
Sandy loams	10 – 50 mm/hour
Silty loams	5 – 40 mm/hour
Clay loams	2 – 6 mm/hour
Clays	< 2 mm/hour

Source: Soil Texture Triangle: Hydraulic Properties Calculator, Washington State University (http://www.bsyse.wsu.edu/saxton/soilwater/)

---

[28] True clay soils are actually quite rate. Most soils that are called clay simply have a larger than usual percentage of smaller soil particles

that make heavy soils difficult in the minds of many engineers are the very things that make watersheds biologically rich.

The two elements of the urban watershed: Parcels and streets.

There are only two building blocks to the urban region, private parcels and public rights of way. Parcels can be any size but are usually small, averaging less than an acre in most regions. Occasionally they are publicly owned, as in the case of schools or parks. The two basic conditions, parcel and right of way, can be discussed separately.

Green Infrastructure for Parcels

Building footprint

For watershed protection parcels should be designed to retain water in accordance with the four rules above. This is immensely simplified if 40 to 60% of the site is still soft. In residential landscapes this is usually lawn area. At the streetcar densities of 10 to 20 du per acre this is achievable if buildings are tall rather than spread out. Vertical buildings are important for other reasons as well. They increase yield on the development parcel and provide better visual containment for the street. A more compact vertical configuration is usually better for heating and cooling as well. Here, where our focus is on infiltration, the tall house with small footprint allows medium density dwellings to be compatible with preserving yard space for play, for gardens, and for infiltration.

Rooftops

At streetcar densities rooftops can cover about over 30 of the gross development site. Rooftops can be designed to retain water and transpirate it into the atmosphere while protecting the building from excessive heat in summer and premature failure of roofing materials or roof membrane. Roofs with a layer of plant materials, however elaborate or simple, are called green roofs. Many texts exist on the topic of green roof construction so no more technical detail is required here.[29] What *is* needed is to place green roof strategies in the proper relationship with parcel and street strategies, something that is rarely if ever done. Water can be retained on roofs and transpired on roofs but it cannot be infiltrated on roofs. Water in excess of amounts that can be stored and transpired must be drained to the ground. During rainy seasons like the Pacific Northwest winter, most of the rain that falls on a green roof will somehow run off to the ground.[30] In rainy winters green roofs are useful to slow the transmission of water to the ground but this is their only real benefit. In warmer climates and in climates where rain is more evenly distributed

---

[29] For more information on green roofs see:

(1) Dunnett, Nigel and Kingsbury, Noel, Planting Green Roofs and Living Walls. Portland, OR: Timber Press, 2004;

(2) Liesecke, H.J., et al., eds., Guidelines for the Planning, Execution and Upkeep of Green-Roof Sites (English Translation). Bonn, Germany: FLL, 1995; and

(3) Scholz-Barth, Katrin, “Green on Top” Urban Land, June 2001.

[30] In 2005 a study was conducted by the Centre for the Advancement of Green Roof Technology in Vancouver, BC to “investigate the performance and practical application of extensive green roof systems in Canada’s west coast climate” (Connelly et al. 2006). Green Roof 1 (GR-1) contained 75 mm of growing medium planted with sedums while Green Roof 2 (GR-2) contained 150 mm of growing medium planted with a mix of fescues and grasses. Although both green roofs delayed the start of runoff and reduced the peak flow and amount of runoff, the extent of these effects varied with the particular rainfall event and differed for the two green roof systems. In the dry season, mid-April to the end of September, GR-1 and GR-2 both performed well, retaining 86% and 94% respectively of the 242 mm of rainfall that fell during this time (Connelly et al. 2006). During the rest of the year however, only 18% and 13% of the 1266 mm of rainfall was retained resulting in an annual retention of 29% for GR-1 and 26% for GR-2 (Connelly et al. 2006).

Figure X. An industrial area in Seattle, Washington where rooftops cover the vast majority of the site with paved roads consuming the rest.

throughout the year green roofs have greater benefit. In North America green roofs are probably most useful in Gulf Coast areas and Florida where rain is reasonably well distributed throughout the year. Consequently in these areas irrigation is not required to maintain the cooling benefits of transpiring plants . As you move north and west from here their inherent value is reduced but not eliminated.

However, green roofs become more important for *storm water* control as building coverage rates increase increase. In certain industrial areas rooftops can cover 70% of the gross area (with paved roads consuming the rest). Absent significant vegetated ground areas to infiltrate on, robustly functioning green roofs can be crucial – especially if they are located in sensitive watersheds.

These cautions are provided to counteract the overly enthusiastic claims of many green roof proponents. Green roofs are in and of themselves of limited value unless integrated into a system of green infrastructure. When integrated into a system the relative costs and benefits of green roofs must be weighed against the costs and benefits of strategies applicable to the ground of the parcel, the street, or other public areas within the development site or neighbourhood. This contextualization of the green roof strategy is seldom done. Some jurisdictions are calling for a blanket requirement for green roofs while not requiring mitigation strategies for runoff from paved areas of the parcels. This constitutes a failure at the policy level to understand how the whole urban watershed system operates and where mitigation strategies might be most cost effective.

Parcels

From roof to yard

Once water comes off of roofs it should be spread out into soft surfaces as quickly as possible. For most types of residential structures this can be done at little or reduced cost by eliminating gutters in favor of long overhangs (cruelly overhangs are often impeded by setback requirements that count overhangs as part of he structure, disincentivizing this strategy). A drip line of crushed stone at the fall line will help distribute the water into lawn and underling soil.

Parcel grading is also significant. It has become traditional for lawn parcels to be graded fairly steeply out of fear of water returning to basements. Yet grades of greater than 2% can send water over lawns too quickly depending on storm event or soil conditions. Grades between 1% and 2% or even flat depressions are therefore recommended. Yards should be graded to avoid channeling flow but rather should spread flow as much as possible across all yard space. The obvious intention is to maximize the opportunity for roof drainage to come in sustained contact with lawn and landscaped areas and their underlying absorbent soils.[31]

The soils below

Ordinary site development practice destroys the capacity of site soils to infiltrate water. If development sites contain good topsoil it is often stripped and sold when ground is broken. One year later when construction is complete a much smaller amount is returned to the site to be thinly spread over severely compacted native subsoil, compacted by a year of heavy equipment traversing the construction site. Severe compaction crushes the void spaces from the parent soil, making it impossible for water to penetrate and rendering these soils incapable of supporting root growth. Lawn areas over such soils will not infiltrate water and after drenching rains will send most rainwater into adjacent streets as runoff, performing only slightly better than the concrete it abuts. We suggest a simple remedy comprised of two parts. Part one: Insure that soils around buildings remain uncompacted, then deep till this soil when construction is done. Part two: return at least as much topsoil to the site as was stripped and possibly more. As mentioned above, about 50% of a site will remain soft after construction is complete. If the site has six inches of decent topsoil pre construction then this stockpile should contain enough soil to return a foot of soil to all of the soft portions of the site. For many sites where subsurface soils are heavy this is likely the most effective strategy of all. Such a thick layer of highly porous and organically rich soil makes an ideal sponge to absorb and slowly release water into parent soils below. At

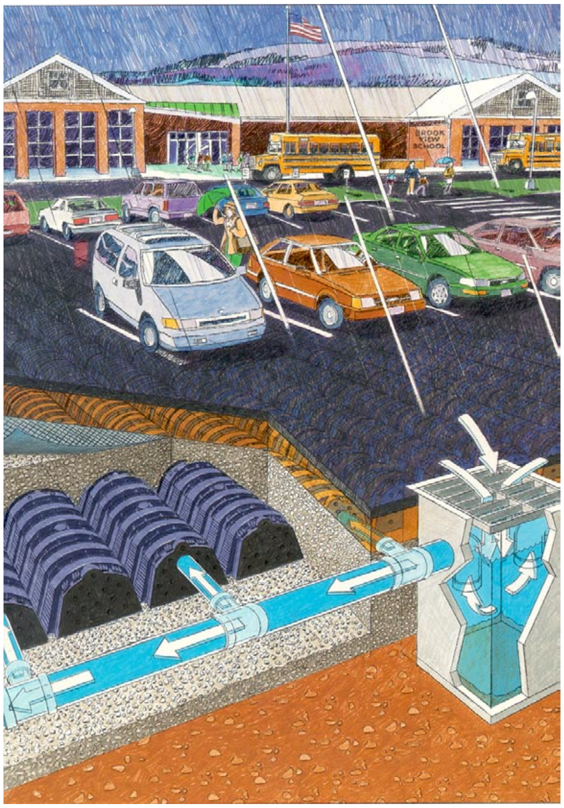


Figure X. Shows an infiltration gallery, similar to the one used for the Reebok headquarters described above, connected to a large, impervious parking lot.

---

[31] In Massachusetts it is required that on-site infiltration measures be used to handle stormwater where suitable soils exist. The stormwater management system for the new Reebok headquarters in Canton, Massachusetts uses source control, structural and non-structural treatment methods, proper maintenance regimes, and stormwater Best Management Practices (BMPs) to maintain water quality and infiltration rates during construction and post-development. To date the Reebok stormwater system has successfully achieved 'zero net runoff' and natural drainage patterns have been retained and now act as natural stormwater management strategies onsite. The total system cost was $65,000 US dollars providing an effective, easy to install and economically feasible choice for infiltrating stormwater onsite. [Summarized from Technical Bulletin No.3 (August 2000), James Taylor Chair in Landscape and Liveable Environments http://www.jtc.sala.ubc.ca/bulletbody.html]

Figure X. Topsoil, preserved from the initial site grading, is returned to residential lots at the East Clayton development in Surrey, BC.

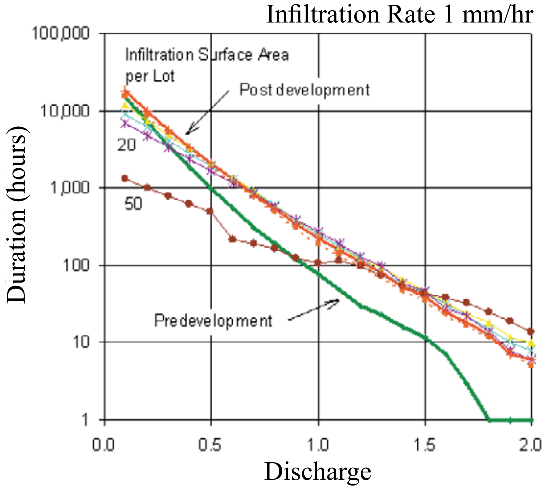
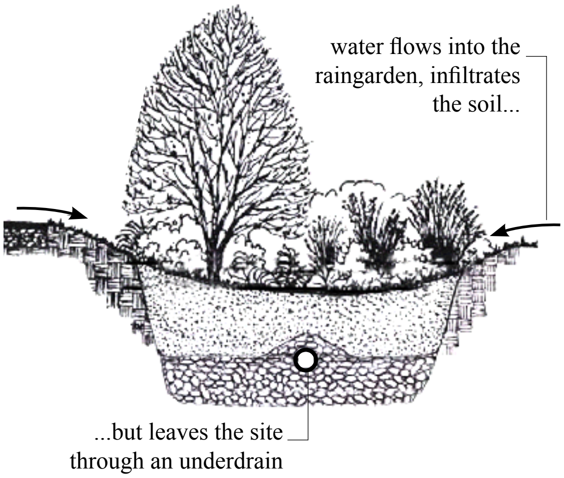


Figure X. Initial results of the 50 acre East Clayton demonstration development indicate that permeable areas and on-site infiltration devices are viable for stormwater management.
Source: ACT Phase E: Final Report (Headwaters Project)



the East Clayton project[32] it was these extra deep topsoil layers that performed far better than expected. A requirement to double backfill the soft portions of the site up to a depth of 12 – 16 inches is therefore reasonable and far more cost effective than a green roof requirement in most locales. One foot of topsoil, assuming it is reasonably dry, can absorb approximately 3 full inches of rain, far in excess of the two inches required (remember that the overall target is 1 inch a day but that the site is only 50% pervious so each soft part of the site must absorb 2 inches in 24 hours).

Raingardens

Raingardens have become increasingly popular as a low impact strategy. In a raingarden, water is directed over grass or directly from down spouts to planted areas designed to accept large amounts of water. These areas are often set an inch or two lower than surrounding grade to trap and hold water. Deep areas of amended soils are provided to absorb water and to provide rich areas for root growth. At their most elaborate they are equipped with underdrains and overflows connected to off site drains. Raingardens are inherently less effective than broad lawn areas for infiltration as they violate the infiltrate everywhere rule. When site water is concentrated in one place it puts an extreme burden on surrounding soils to absorb proportionately greater amounts of water. Heavy soils have a difficult time performing this way and thus the rain garden can get waterlogged, killing the plants if they are not resistant to constant flooding. Underdrains are often proposed as a solution but the drains compromise the original purpose of the rain garden. This is not to say they should not be employed, only that they should be secondary to ubiquitous infiltration on broad lawn areas. Hedge lines on the property line are of course the most effective rain garden design. It is necessarily long and thus covers a substantial percentage of the soft area of the parcel boundary, and are most commonly situated at the edge of large lawn areas they can capture any roof water that the lawn has been unable to infiltrate. Hedge lines on the property line are of course the most effective rain garden design. It is necessarily long and thus covers a substantial percentage of the soft area of the side, and situated at the edge of large lawn areas they can capture any roof water that the lawn has been unable to infiltrate.

Walkways

In many parts of North America, directing roof drainage across lawns will mean squishy conditions on grassy areas for many weeks in the year. This likelihood has impeded implementation of these recommendations in more than one jurisdiction.
The solution is to include paved walkways where needed. Unfortunately this can add to the TIA and possibly to the EIA

---

[32] The East Clayton Neighbourhood Concept Plan is the first phase of the Headwaters Project, a real-life demonstration of sustainable development principles and performance standards in a community neighbourhood environment. For more information on the project visit: http://www.jtc.sala.ubc.ca/projects/Headwaters.html

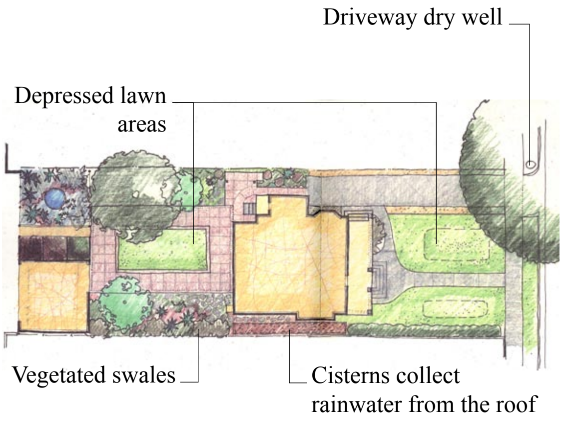
as well. Stepping stones are an effective low impact solution for occasionally used backyard paths. Stepping stones, like the patio solution discussed above, are by definition surrounded by soft pervious areas. In most soils it is likely that stepping stones will have an EIA of zero. Stepping stones flush with surrounding lawn or crushed stone beds are considered accessible under Americans with Disabilities act (ADA) rules where and when compliance is required.

For walkways that are more frequently used, such as the walkway from the front door to the sidewalk or from the back door to garage or lane, a continuous paved surface is required. Pervious pavement is an effective means to reduce EIA to zero for these surfaces, but it is often equally effective to simply cross pitch (slope slightly to the side) impervious concrete or asphalt into adjacent grass or hedges. These same rules apply to driveways, if and when required. Adjacent yard areas can be subtly dished with minor depressions to capture storm water, allowing puddles to form for short periods after severe storms.[33] This ephemeral feature is an enormously effective infiltration practice, and adds visual delight to the yard. Unfortunately allowing "standing water" on lawns for even a few hours defies most current conventions and biases against retaining rain water on site; in other words, we are afraid of puddles. This cost free strategy is therefore often difficult to implement.

Parking and Service Areas

At streetcar city densities of 10 to 20 du/acre parking lots should not be required. All recent city of Vancouver projects, commercial projects or residential projects over a gross DU per acre of 25 now have underground parking. Below this density parking is provided on streets, on lanes, or in garages. In consequence, there is generally no need for surface parking lots. However, if provided they too can meet the 10% EIA target in the following ways. Pavements can be pervious concrete or asphalt as described under roadways below. Alternatively parking lots can discharge into specially designed rain garden planters at parking lot edges or between bays. This second strategy requires highly permeable soils as the rain garden features will probably cover less than ten percent of the total surface area of the lot, and thus will be required to infiltrate ten or more inches per day to meet the overall target of one inch per day infiltration. If soil conditions are not this forgiving or if performance targets are high then infiltration under the lot via drain tiles or infiltration chambers may be required. This last strategy is especially effective when combined with rain gardens, as they clean silts out prior to delivering storm water to drain tiles. Unfortunately and obviously this is the most expensive strategy of the three discussed.

33. In the site plan below a single family residence in Los Angeles, California uses the landscape to work with, rather than against, natural cycles of water and waste. Rain falling on the building's roof is directed to depressed lawn areas or "sunken gardens" that retain rainwater until it can be absorbed into the ground. Only during rainfall events exceeding the 100-year storm does overflow need to be directed into the existing storm drain system. Rain that isn't directed into the lawn is collected and stored in two 1800 gallon cisterns that capture rain during the wet season and gradually release it for irrigation during the wet season. A roof wash unit collects the "first flush" water and sequesters it long enough to settle out the summer-long build up of dust and bird feces before the clean water decants into the cistern. These cisterns can also be used to regulate the flow of water during storms and reduce the risk of flooding. Vegetated/mulched swales slow the flow of stormwater, increases infiltration and filter pollutants while also providing an attractive and functional space that recycles greenwaste from the property. Runoff from the driveway is intercepted by a dry well which retains and cleans rainwater, giving water time to percolate into ground instead of carrying pollutants into the storm drain system. [Summarized from *Second Nature*, Condon & Moriarty 1999]



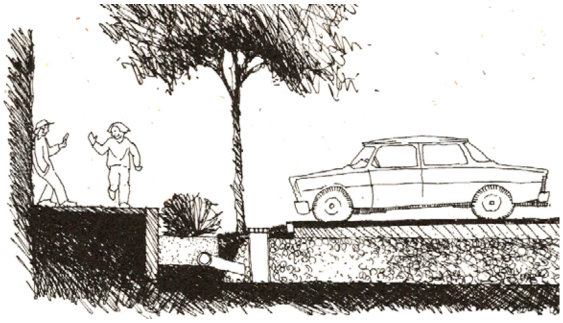


Figure X. Shows how the filter bed and the subsurface infiltratio basin work to treat and hold stormwater runoff from the large impervious parking area. The filter beds allow space for side-walks, trees and shrubs near the building whlie the plants contribute to the treatment of stormwater and reduce the energy-use for cooling during hot summer months (Condon & Moriarty 1999).

Figure X. This view of 6th Ave in Vancouver, BC shows one of four Traditional Pattern residential street types. The right-of-way is 20m (66’). Note the above ground location of joint utility lines as indicated by wooden power poles, and the occurance of on-street parking. Also note the street trees which are commonly found lining the boulevarded streets of the Traditional Pattern. Parking is allowed on both sides of the 8.2m (27’) wide paved way, which requires oncoming cars to take truns or “cue” on the residential cuing street. Sidewalks are provided on both sides of the street separated from the paved street by a 2.3m (7.5’) grass and tree boulevard.
Source: Alternative Development Standards for Sustainable Communities, Condon & Teed 1998

Figure X. Pervious asphalt (top) and pervious concrete (bottom) are cheaper and more effective than pavers, allowing water to infiltrate through voids left in the paving when small aggregates and fines are eliminated from the mix.

Right of Ways

Introduction

Rights of way are any publicly owned or publically accessible lands. In North America Rights of way are almost all streets and highways. Thus most of this discussion concerns these ubiquitous features of the urban landscape.

A street right of way (ROW) usually includes a paved street with verge areas astride it. Verge areas usually include some combination of sidewalks, tree boulevards, and/or road shoulder. ROWs are often much wider than the paved surfaces in them. For instance, the traditional streetcar city residential street ROW is 60 feet. Of this ROW less than half, or roughly 28 feet, is consumed by the paved street, measured from curb line to curb line. The remaining 32 feet is most often allotted to sidewalks and tree boulevards for both sides of the street. In most urban areas street right of ways consume between 25% and 40% of all land (depending on district street network type, existence or absence of rear lanes, and land use), making them far and away the most extensive and ubiquitous of all urban public land types. With so much of the site covered in public ROW it follows that street ROWs generate 40%, 50% or even more of the total district wide impact of impervious surfaces and storm drainage on receiving waters.

Pervious or impervious

As discussed above, it’s not pavement that kills fish, it’s the pipes that drain it. If we want to save watersheds the key is abandoning our dependence on pipes to take water off the roads, and to find ways to get the water into the ground near or under the road instead. There are two basic ways to accomplish this: you can make all of the pavement in the road pervious so the water goes right down through it, or you can find a way to infiltrate the water in the soft surfaces of the verge. We discuss fundamental strategies for pervious pavements below, followed by a discussion of impervious streets that eliminate impact to receiving waters by absorbing water in verges.

Pervious Pavements

Much confusion exists about pervious pavements. For applications in North America there are really only two hard surface options that are both affordable and effective: pervious asphalt and pervious concrete. These pavements are fully capable of allowing 100% of even the largest storms to penetrate into the structural base below. What happens then is a different matter, discussed separately below.

Impervious unit pavers are often sold as a pervious pavement solution, with infiltration presumably occurring in the joints. They are not recommended for most applications. They are many times more expensive than pervious asphalt or concrete, and due to the limited area between pavers available for infiltration, tend to clog with silts (this occurs unless the units themselves are pervious, or the joints between the pavers are extremely wide). Unfortunately the unit pavers industry is well organized and markets its products extensively making strong claims to the contrary, while no industry exists to advance the use of simpler pervious asphalt and pervious concrete.

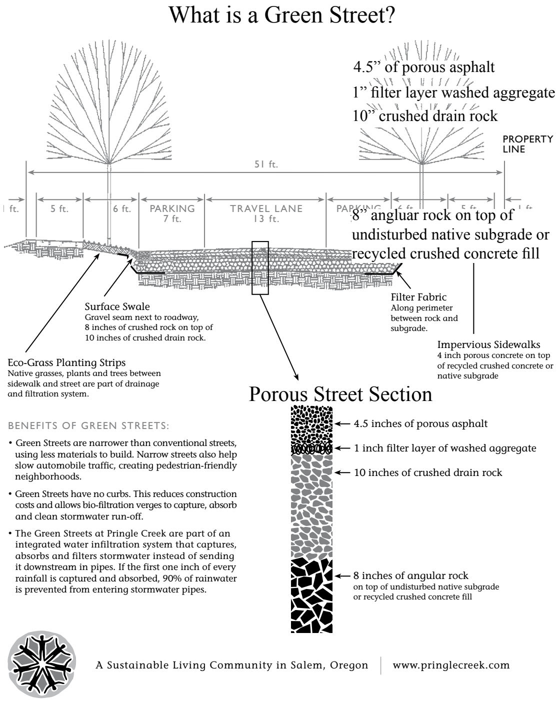
Pervious Pavement - Types and Characteristics

The two surface types, pervious asphalt and concrete, are very similar. Both pavements are identical to ordinary asphalt or concrete, except that the smaller aggregates (rocks in laymans terms) and fines (sands), which constitute a large part of mixes for impervious pavements, are absent. A typical size for aggregates in pervious pavements is ¾ “. Absent the smaller aggregates and fines, the liquid asphaltic binders of asphalt pavement or the cement of concrete pavements glues the large aggregates together, leaving ample void spaces between the ¾” rocks for water flow. Because pervious and impervious asphalt and concrete are virtually identical, costs and application techniques are similar as well. Visually the pervious surfaces have a somewhat rougher appearance but are as smooth or smoother than unit pavers and therefore do not pose a barrier or hazard to the handicapped. In short, anywhere that you can install ordinary impervious asphalt or concrete, you can install pervious asphalt or concrete for the same money, or close to.

Insuring that pervious pavements function well and last a long time is a somewhat different matter. Details of the road section below the paved surface must be reconsidered for enhanced infiltration, and care must be exercised during construction to insure that infiltration is not compromised.

Pervious pavement roadway structural section

Any roadway, or any paved surface for that matter, has two parts: The hard surface or pavement, and the earth below that holds it up. All well engineered and installed roadways need earth below that that is stable over time and structurally capable of holding up the pavement. Not all soils are. Clayey soils are particularly prone to deforming during freeze thaw cycles and thus are not used under pavements. “Gravel” is usually used instead, a mixture of fine and course sand particles and small and medium sized stones. This mixture does not deform or flow when weight is applied from above, as clay is prone to do, nor does it retain water long enough after rains for it to freeze solid, lifting and



BENEFITS OF GREEN STREETS:

- Green Streets are narrower than conventional streets, using less materials to build. Narrow streets also help slow automobile traffic, creating pedestrian-friendly neighborhoods.
- Green Streets have no curbs. This reduces construction costs and allows bio-filtration verges to capture, absorb and clean stormwater run-off.
- The Green Streets at Pringle Creek are part of an integrated water infiltration system that captures, absorbs and filters stormwater instead of sending it downstream in pipes. If the first one inch of every rainfall is captured and absorbed, 90% of rainwater is prevented from entering stormwater pipes.

Figure X. A Porous Street Section
Source: Pringlecreek.com

cracking the pavements above. These structural soils are more important in pervious pavement applications than in impervious applications because they have an additional requirement: they must store, infiltrate, and deliver rainwater within them.

Figure X. The pervious paving used at the Pringle Creek Sustainable Community in Salem, Oregon uses crushed basalt aggregates as a structural base which also acts as water storage.

Storing water in the section.

As discussed above, a useful rule of thumb is to infiltrate one inch per day of water over the whole site or 1mm per hour. If a roadway has no surcharge on it (i.e. no water directed to it from adjacent rooftops, driveways, or walks) then it must accept one inch of water somehow and infiltrate it into surrounding soils. If the roadway is accepting water from surrounding areas the amount of water it must store and infiltrate must be recalibrated up accordingly. Structural soils all have some capacity to store and infiltrate water, some more so than others. Ordinary gravel has tiny voids between the particles such that 10 to 15% of its total volume is available for storing water. Thus, to store one inch of water in the gravel would require a total cross section area of 7.5 to 10 inches. Other structurally suitable materials have even more void space. Crushed basalt aggregates of a uniform size can also be used as a structural base. Graded and washed stones commonly between ¾ inch and 1 ½ inches, used in place of gravel, have between 30 and 35% void space. Thus, to store one inch of water in a structural base of crushed basalt would only require three inches of area.

Residence time

Storing the one or more inches of water in the base may not be required if the surrounding soils are extremely porous. In such cases water will flow immediately into parent soils, requiring no residence time and no reservoir function in the base. However, such soils are rare. More commonly there will be a need to hold rain water in the section for a certain amount of time, allowing it to gradually seep into surrounding parent soils. The heavier the surrounding soils the longer this might take, and the larger the required reservoir space might become.

Figure X. The standing water seen here is actually the high water table revealed during the winter. The finished road surface is only a few inches above this point yet stays dry as water travels through the street section and surrounding soils via interflow, emerging in the banks of pringle creek almost visible in the distnce beside the trees. The surface of the creek is only a foot or two lower than the water table, but sufficient to draw down the water if interflow is not impeded.

Flow within the Section

Highly pervious structural sections will also allow water stored in the reservoir to flow along the section under the pavements. This can be a good thing, allowing rainwater to use the structural section below the pavement like an intermittent stream, facilitating the distribution of water on the site from saturated acres to acres that have better soils or more favorable water table conditions. If streets are steeply sloping this flow can be too fast, reducing the opportunity for rainwater to infiltrate into surrounding soils. In such instances various adjustments can be made. Installing a somewhat less pervious structural base intermittently along the street for example, or simply using impervious pavements for the parts of the site with steep roads, directing that water to the more shallow road gradients below.

What is not a problem

As in all things pertaining to sustainable communities, while the principles are easily accepted, the specific applications of these principles are controversial. No agreement yet exists in the engineering community about the practicality and durability of pervious pavements. These concerns are more extreme in the parts of the continent where winters are cold and freezes are frequent. The vast majority of these concerns are ill founded. The seminal collection of the research on this topic is contained in Bruce Ferguson's book, Pervious Pavements, and the reader is therefore directed to it for elaboration. Here suffice it to say that pervious pavements, if properly installed, do not crumble, and are safe. The first applications of pervious pavements are now over thirty years old and working fine, even in wintery New England. What prevents their use is an inertia built into the industry of paving roads and a fear of assuming liability for changes from accepted norms. Impervious pavement is the accepted norm, and municipal engineers are loath to depart from it for fear of something going wrong. Conventional pavements fail all the time, but because they are accepted "best practices" they are not freighted with risk to approving agents. Fear of risk is the single most intractable implementation barrier to more widespread use of pervious pavements.

Water Pollution

Pervious pavements clean pollutants out of urban environments better than pipe systems. The majority of pollutants found in urban environments adhere to dust particles and get trapped in the structural layers below the pavement. In pipe systems all of these pollutants are concentrated and delivered to the fish. Organic pollutants (largely those that come from hydrocarbons like dripping crankcase oil) are particularly well handled by pervious pavements.[34] It appears that the honeycombed structural base/reservoir is an ideal habitat for the bacteria that feed on hydrocarbons, converting them into benign discharges. The exceptions are the completely dissolved pollutants like salt and phosphate. These are not mitigated by the structural base or by surrounding soils, but neither are they more effectively handled by pipe systems. But another warning is in order here. In the US water that is considered "ground water" is more stringently managed than water that is considered "surface waters". In short, you are allowed to do nastier stuff to streams than to soil, even though the water going into the ground is likely ending up in the same place: downstream. The fact that people often drink ground water but not stream water explains the added concern. In most jurisdictions, deep ground water must be potable; no

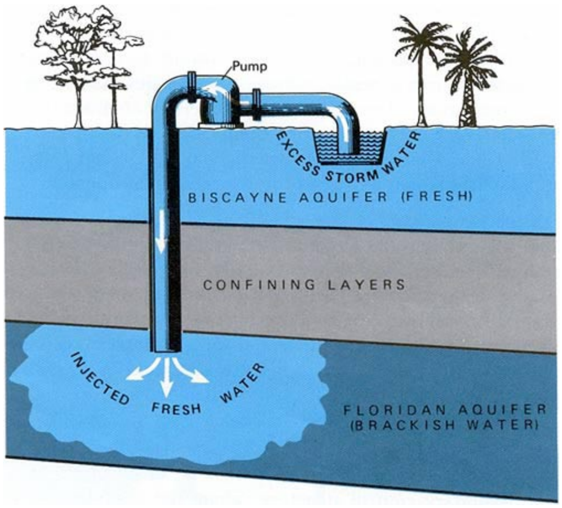


Figure X. This diagram of an injection well in Florida shows how excess stormwater is injected into the groundwater.

---

[34] Research conducted by the US Environmental Protection Agency found that the risks for groundwater contamination are significantly higher with subsurface injection than with surface infiltration (Pitt 2000). This seems to stem from the fact that most stormwater pollutants are more mobile in water than in soil. A large number of studies (see Bulletin No. 13 at http://www.jtc.sala.ubc.ca/bulletbody.html for details) have shown that shallow surface infiltration systems such as bioretention swales, vegetated buffers, and permeable paving are an effective means of removing the vast majority of residential-source stormwater pollutants, preventing their entry into groundwater sources (Condon & Jackson 2006: Bulletin No. 13 http://www.jtc.sala.ubc.ca/bulletbody.html).

such requirement applies to streams. Ironically and tragically, it is for this reason that preserving watershed function using the strategies discussed herein is disincentivized in many jurisdictions. Happily, in many locations the ground water regulations are being reconsidered for the reasons discussed above; but the changes are slow in coming and geographically spotty. Infiltrating water at the surface is usually acceptable, but there is a grey line between surface infiltration devices and what many regulators call "injection wells". The deeper an infiltration device goes in the ground and the more elaborate is its engineering the more likely it will be declared an "injection well". At the Pringle Creek Community project, State of Oregon regulators approved the infiltration streets, but only after declaring that they could be considered injection wells. If they had been so declared it would have required all water entering them to be "pre-treated". Absurdly this could only be done by capturing and scrubbing rain water before it fell on the pavement. Happily agreement was reached when it was shown that the reservoir layer was relatively shallow and well above the seasonal high water table. This example is provided as a warning of what to watch out for when entering this regulatory maze.

Figure X. The photo above was taken during the construction phase at Pringle Creek when pervious streets were covered with filter fabric to avoid excess soil filling the voids in the pavement.

Protection During Construction

There is however one very serious potential weakness with pervious pavements. They can get clogged. If massive amounts of heavy soils are dumped onto the pavements they can fill up and block all the voids in the pavement, impeding or blocking rainwater from flowing through it. In worst case scenarios they can also fill in the voids in the structural base, compromising the storage and infiltration functions as well. The amount of soil required to induce this catastrophic failure is so massive as to constitute a relatively minor concern, except of course during one period: construction. During construction new development sites are notoriously dirty, with silts pouring off torn up landscapes by the ton. If this dirt makes its way to new pervious pavement sections, the storm drainage system function will be compromised. To avoid this consequence requires extra care during site construction. This extra care translates into extra staff hours and consequently into additional cost. At the Salem, Oregon Pringle Creek Community, the contractors, who were contractually responsible for keeping the pervious pavement clean during construction, decided that it was safer to wrap all of the completed streets with filter fabric during the site construction phase, unwrapping them only when the dirtiest parts of the job were done – a very expensive proposition indeed.

Two factors make the added time and expense more acceptable: 1) developers are increasingly required to keep all construction generated silts on site anyway, so the costs for silt containment are already very high, and 2) pervious pavement systems should eliminate the need for any drainage inlet basins, pipes, curbs and other expensive elements of conventional storm systems. Savings from these items can be applied to the cost of the extra care required.[35]

Conveyance

In most cases, pervious pavements do not eliminate the need for conveyance systems. In most parts of North America, if the infiltration target is one inch per day, there will be 10 or 20 days a year when this amount is exceeded. On those days excess water that cannot be absorbed directly through the pervious pavement section must be conveyed to a receiving location. There are two ways to do this, one expensive, one cheap. The expensive way is to include a system of drain inlets in boulevards or street edges to accept and deliver these flows. The cheaper option is to allow these occasional flows to traverse the site overland. On the thirty-acre Pringle Creek site there are no storm water pipes at all. Large flows are conveyed at the edges of pavements, then across the surface of intersections, eventually to find their way to on site artificial wetlands and eventually, and very infrequently, overland to streams. Conveyance systems will be discussed in detail in the next chapter as they are rightfully considered as part of a system or network of human made features intended to emulate the natural network of tributaries in natural watersheds.

Impervious Paved Infiltration Streets.

You can use impervious pavement on travel ways and still have pervious streets; in these instances rainwater is directing to street verges, verges specifically designed to accept and infiltrate rainwater. There are many ways to perform this trick but the following three illustrate the range of options.

Example 1. Amble Greene Community, Surrey B.C.
Most typical residential streets trap water between vertical curbs. Trapped like this, water that should be allowed to infiltrate collects in gutters and flows downhill until it reaches an inlet, leading to a pipe, leading to a bigger pipe, and finally dirty and hot, gets flushed into the stream. Any major metropolitan area contains thousands of miles of vertical curb, every inch of which contributes to the destruction of the watershed and constitute in the aggregate a bonafide environmental disaster. Removing curbs eliminates the problem. Without curbs to block it, rainwater can flow over the lip of pavement into grass or crushed stone verges/boulevards. Rural roads are still built this way, not to preserve watershed function, but because it is by far the cheapest way to build a road. By removing the curb and gently lowering the grassy tree boulevard, broad spaces are made available for infiltrating water. If verges are broad enough and soil conditions

Figure X. This photo, taken in the Amble Greene Community of Surrey, BC, shows how in the absence of curbs rainwater can be directed to depressed boulevards where it is infiltrated into the soil.

---

[35] The United States is currently converting approximately 2 million acres of land from rural to urban every year (Coffman and Clar 2003). Using a conservative estimate of $1000 to $5000/acre to installing stormwater management technologies, the new construction alone costs between $2 and $10 billion annually (Coffman and Clar 2003). When the cost of annual inspections, maintenance, replacement and the cost of retrofitting areas that were developed prior to the existence of the Clean Water Act are taken into account the annual expenditure for stormwater management technology easily surpasses a trillion dollars per year (Coffman and Clar 2003). Urbanized jurisdictions are forced to maintain, inspect, and enforce thousands of miles of pipes and gutters, and tens of thousands of structures (Coffman and Clar 2003). As this infrastructure grows and ages most jurisdictions are reaching the point where they can no longer afford to adequately pay for the upkeep of their stormwater infrastructure (Coffman and Clar 2003). Through evaluating 17 case studies, the US Environmental Protection Agency (2007) found that in most cases significant savings were realized through Low Impact Development (LID) strategies (where small-scale stormwater management practices promote the use of natural systems for infiltration, evapotranspiration, and reuse of rainwater) as opposed to conventional stormwater practices (curbs, gutters and pipes). With few exceptions, total capital cost savings ranged from 15 to 80 percent when LID methods were used. Although it is difficult to directly compare maintenance costs against those of conventional stormwater management practices, some LID site designs, such as maintaining existing sandy soils for their drainage potential, cost nothing.

favorable enough, the one inch per day infiltration target can be achieved without soil or engineering enhancements. With this system verges need to perform double duty, infiltrating any water that falls on them as well as the water shed by the nearby roadways. As with rain gardens, this becomes increasingly challenging as the percentage of the ROW devoted to soft surfaces decreases. If 20% of the site is available for infiltration this means that each square foot of verge area will have to infiltrate not 1" but 5" in 24 hours. For many soil conditions this is not possible unless engineered infiltration devices and/or soil enhancements are incorporated.

The 1974 Amble Green project in Surrey B.C. provides a good and durable example of this strategy. The curbless streets in this project infiltrate 100% of the water that falls on them. Soil conditions are forgiving but by no means ideal. Nevertheless the project infiltrates not our target of 1" per day but 4": the amount of rain associated with the 100-year storm event in this city. Project proponents were required to infiltrate all rainwater that fell on the site because of inadequate off site city storm drain interceptors. Broad grassy boulevards located between sidewalks and the curbless streets absorb most of the rainfall, with additional infiltration provided by hidden "French drain" infiltration chambers located below. Occasional "blue-green" infiltration depressions are the fail safe for the plan – large dished areas often in the middle of cul-de-sac bulbs that can hold large amounts of water long enough to eventually infiltrate into soils below. As this project demonstrates, curbless streets save money and do the job; but in the minds of many they have one problem. Without curbs what will prevent parking cars from migrating onto the grass? At Amble Greene this is largely not a problem, but in the few places where it is, owners have arrived at a simple control strategy. Hand placed rocks located at street edge provide sufficient discouragement.

Figure X. The photo above shows a traditional street in Vancouver, BC where infiltration occurs in the crushed stone parking strips straddling either side of a 15' paved two way travel section.

Example 2. Blenham Street, Vancouver, BC.
While not specifically designed as a green street, this road section is an even more economical and elegant solution to the problem than the one at Amble Greene. Hundreds of older streets in many streetcar cities, particularly in the Vancouver B.C. Region, were built to this standard. Most still exist. Thus there are hundreds of examples of this street type, with over 70 years of performance to assess. These extremely inexpensive streets are queuing streets as discussed in the interconnected streets chapter preceding. Measuring roughly 28' feet from the outside edge of parking bays to the other outside edge, they are comprised of two 6.5' parking bays and one 15' paved two way travel section. The two 6.5' parking strips are paved in crushed stone, which is a cheap and highly pervious surface. Infiltration occurs under

the cars, thus the tree boulevards need not dish down to accept water, but can rise higher than the road and parking portion of the section. This subtle landform provides the proper elevational superiority for pedestrian comfort and safety, while preventing cars from migrating onto the grass. It is an extremely beautiful design which should be widely used. Sadly all of the examples of this street type are a legacy of an earlier time. The streets at Pringle Creek are very close to this typology, only differing in that they employ much narrower crushed stone strips at verges with pervious pavements doing the work of infiltration across the whole section rather than in crushed stone beds under parked cars.

Figure X. The photo above, from East Clayton, Surrey, BC, shows slotted curbs that direct water into depressed boulevards

Example 3. East Clayton, East Clayton, Surrey B.C.
The East Clayton Sustainable community plan was a product of a University of British Columbia/City of Surrey design charrette held in the spring of 1998. Green Street sections agreed to at the charrettes lacked curbs and resembled in function and form the streets of Amble Greene, also located in Surrey. Concerns raised after the Charrette led to a change in the plans. Curbs were added to all streets. To allow for natural infiltration, slots were introduced into curbs to allow channeled water to escape from gutters into lowered tree boulevards. Tree boulevards allowed for infiltration and cleansing before directing excess water to drain inlets above buried infiltration chambers. These infiltration chambers were in turn tied into a subsurface system of pipes, pipes sized in this case for the 100 year storm. The hybrid system that resulted is a fairly literal combination of a green street strategy with a conventional grey street strategy. The one inch per day infiltration target is achieved through ubiquitous infiltration in tree boulevards. Otherwise, with the curbs and substantial subsurface system of pipes it operates conventionally. This approach, in the minds of its proponents, had the advantage of limited risk. Conventional systems provided as part of the plan were robust enough and their function well enough understood that approving agents were comfortable they would not fail in extreme circumstances. The down side was that this "belt and suspenders" system was substantially more costly than either a curbless green street like those at Amble Greene or a conventional street. Contractors estimated that the system cost $5,000 dollars per lot more than conventional street systems, or an additional $120 per foot of frontage.

Lanes

Lanes or rear alleys are a common and important feature of walkable streetcar cities. As discussed in previous chapters, it is almost impossible to have10 to 20 livable and attractive detached housing units per acre without them. Unfortunately they add yet another usually paved surface to contend with, and increase the percentage of land given over to ROWs appreciably. Fortunately the same strategies used to mitigate the impacts of streets can apply to lanes. If lanes are paved they can be either paved with pervious pavements as at Pringle Creek or paved down the center with a narrow band of impervious pavement crowned to shed into pervious verges as in many older parts of Vancouver. Streetcar cities usually devote 20’ to laneway ROWs. Of this 12’ can be paved leaving 4’ on each side for infiltration verges and necessary large storm conveyance. The same strategies for determining the reservoir depth discussed above come into play here. In highly sandy soils the one inch per day can be absorbed under soft verges with relative ease. If parent soils are less forgiving then soft verges need to be underlain with a reservoir that integrates with the structural support for the paved lane. Laneways at Pringle Creek are designed to do this, albeit with the added benefit of pervious pavement for the travel way. Laneways, given that they are where cars are stored off the lane in garages or drives, include many places where verges must be paved. The denser the project and the more garages, the more soft verge will be lost. As the soft verge disappears increasingly heroic strategies for infiltration are required. For this reason, a switch to pervious pavements for lanes may be even more compelling than it is for roads in some projects.

Finally there is the option to not pave at all. In Vancouver and other North American streetcar cities, lanes were never paved. They were simply resurfaced with a structurally sound granular material, usually crushed basalt or granite. Depending on the minimum size of fines and maintenance protocols, paving lanes with crushed granite or basalt is a low cost highly effective infiltration strategy for laneways. Implementation barriers in the way of this low cost solution include fears about what children might do with the stones, and the need for city maintenance protocols for refreshing and re-grading crushed stone lanes.

Figure X. The streets in the foreground are actually lanes paved with 13 ft (for fire access reasons) pervious pavement and crushed stone verges as described in the text.

Figure X. The photo above shows a traditional lane of crushed stone in Vancouver, BC that has eventually grown over. This provides an excellent context for urban forests which can uptake water through the soils surrounding the crushed gravel.