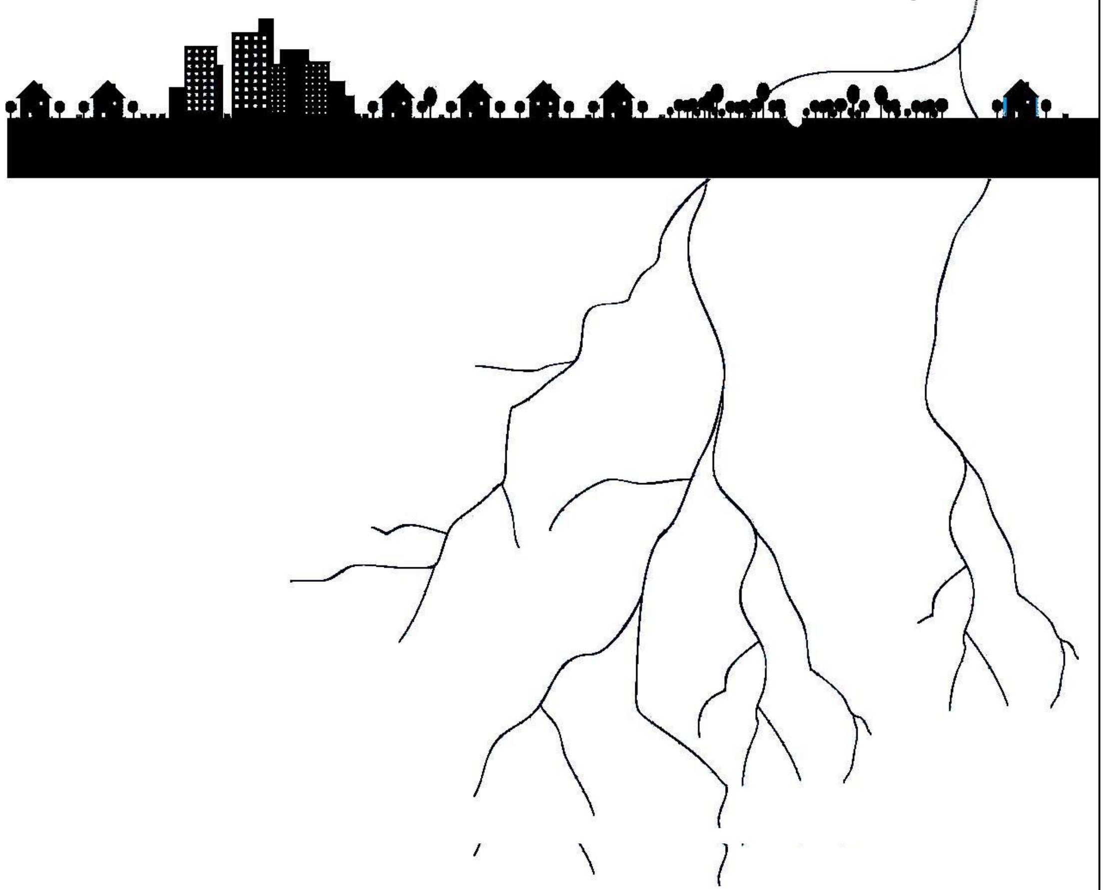
The Science Behind Integrated Stormwater Management



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2.1 Developing a Common Understanding

A science-based understanding of how land development impacts watershed hydrology and the functions of aquatic ecosystems provides a solid basis for making decisions to guide early action where it is most needed.

This chapter provides an overview of the science. It presents graphics that have helped diverse audiences reach a common understanding about hydrology and the factors limiting the ecological values of streams.

An understanding of the science is a critical underpinning of strategies to predict and manage the potential impacts of stormwater related to land use change.

Research on the Effects of Urbanization on Fish

Aquatic habitats that influence the abundance of salmon and trout are the outcome of physical, chemical and biological processes acting across various scales of time and space. The environmental conditions that result from these processes provide the habitat requirements for a variety of species and life history stages of fish and other stream organisms.

Decline of Wild Salmon

Whether in pristine or heavily urbanized watersheds, the basic requirements for survival of salmon and trout are the same. These basic requirements include: cool, flowing water free of pollutants and high in dissolved oxygen; gravel substrates low in fine sediment for reproduction; unimpeded access to and from spawning and rearing areas; adequate refuge and cover; and sufficient invertebrate organisms (insects) for food.

Over the past century, salmon have disappeared from over 40% of their historical range, and many of the remaining populations are severely depressed (Nehlsen *et al*. 1991). There is no one reason for this decline. The cumulative effects of land use practices, including timber harvesting, agriculture and urbanization have all contributed to significant declines in salmon abundance in British Columbia (Hartman *et al*. 2000)

Puget Sound Findings

In Puget Sound, a series of research projects have been underway for over 10 years to identify the factors that degrade urban streams and negatively influence aquatic productivity and fish survival. The streams and sites under examination represent a range of development intensities from nearly undisturbed watershed conditions to watersheds that are almost completely developed in residential and commercial land uses (Horner 1998).

For each watershed, detailed continuous simulation hydrologic models were prepared and calibrated to rainfall and runoff data. Physical stream habitat conditions, water quality, sediment composition, sediment contamination, and fish and benthic organism abundance and diversity were measured and documented for each site.

The studies found that stream channel instability is a result of the urbanization of watershed hydrology. The alteration of a natural stream's hydrograph is a leading cause of change in instream habitat conditions. The physical and biological measures generally changed most rapidly during the initial phase of watershed development, as total impervious area changed from 5% to 10%. With more intensive urban development in the watershed, habitat degradation and loss of biological productivity continues, but at a slower rate (Horner 1998).

The role of large woody debris in streams was recognized as a key factor in creating complex channel conditions and habitat diversity for fish. Both the prevalence and quality of large woody debris declined with increasing urbanization. In addition, development pressure has had a negative impact on streamside (riparian) forests and wetlands, which are critical to natural stream functioning.

The impacts of poor water quality and concentrations of metals in sediments did not show significant impact to aquatic biological communities until urbanization increased above approximately 50% total impervious area.

Instream habitat conditions had a significant influence on aquatic biota. Streambed quality, including fine sediment content and channel stability, affected the benthic macro invertebrate community (as measured by the multi-metric Benthic Index of Biological Integrity (B-IBI) developed by Karr (1991)). Negative impacts to fish and fish habitat from sedimentation related to urban development have been documented (Reid *et al*. 1999). The composition of the salmonid community was also influenced by a variety of instream physical and chemical attributes.

Summary of Puget Sound Findings

Alterations in the biological community of urban streams are a function of many variables representing conditions that are a result of both immediate and remote environmental conditions in a watershed. The research findings clearly demonstrate that the most important impacts of urbanization that degrade the health of streams, in order of importance, are:

- Changes in hydrology
- Changes in riparian corridor
- Changes in physical habitat within the stream, and
- Water quality

Further discussion of these impacts is contained in Section 2.4.

Georgia Basin Findings

Within the Georgia Basin, population pressures have caused urban sprawl, resulting in habitat loss (B.C. MELP 2000). Freshwater fish population declines in this region are a partial result of rapidly expanding urban development (Slaney 1996).

The aquatic ecosystems most directly affected by urbanization are the small streams and wetlands in the lowlands of the Georgia Basin and lower Fraser River Valley. These ecosystems are critical spawning and rearing habitat for several species of native salmonids (both resident and anadromous). In the Lower Fraser Valley, 71% of streams are considered threatened or endangered, and a further 15% have been lost altogether as a result of urban growth (B.C. MELP 2000).

A Science-Based Understanding

The widespread changes in thinking about stormwater impacts that began in the mid to late 1990s reflect new insights in two areas:

- Hydrology, and
- Aquatic ecology

These new insights are the result of improved understanding of the causes-and-effects of changes in hydrology brought about by urban development, and the consequences for aquatic ecology. As we gain new knowledge and understanding of what to do differently, a central issue for watershed protection becomes:

- What is the proper balance of science and policy that will ensure effective implementation and results?

King County in Washington State addressed this question in 1999 as part of the Tri-County response to the listing of chinook salmon as an endangered species in Puget Sound. A significant finding was that scientists and managers think and operate differently. This led to the following recommendations:

- An interface is needed to translate the complex products of science into achievable goals and implementable solutions for practical resource management. This interface is what we now call a science-based understanding.
- A reality for local government is that management decisions need to be made in the face of significant scientific uncertainties about how exactly ecosystems function, and the likely effectiveness of different recovery approaches.
- The best path forward is a dynamic, adaptive management approach that will allow local governments to monitor the effectiveness of their regulatory and management strategies and make adjustments as their understanding grows.
- In a co-evolving system of humans and nature, surprises are the rule, not the exception; hence, resilience and flexibility will need to be built into the management system.

Through a science-based understanding of the relationship between hydrology and aquatic ecology, this chapter derives a comprehensive set of watershed protection objectives that provide an over-arching framework for Parts B and C of this Guidebook.

2.2 The Natural versus Urban Water Balance

Rainfall landing on a site travels in four directions:

- Soaking into shallow ground and moving slowly through soils to streams - *interflow*
- Percolating vertically into *deep groundwater*
- Back up into the air – evaporation from surfaces and transpiration from leaves - *evapotranspiration*
- Flowing over the ground – *surface runoff*

Because the total volume of rainfall equals the sum of the four components, this relationship is known as the 'Water Balance'. It is a core hydrologic concept.

Urban drainage has traditionally focused on managing surface runoff**.** It is only recently that the other three components have begun to receive serious attention, with the emphasis on interflow. Although interflow was first defined in the 16th century, its significance has been largely ignored for over 400 years. It is now recognized that all four components need to be considered as part of a comprehensive and integrated approach to stormwater volume management.

Where Rainfall Goes Before and After Development

Figure 2-1 illustrates how the Water Balance changes when natural vegetated cover is replaced by suburban development. By providing example percentages, this drawing highlights the magnitude of the additional volume of water that must be handled by a drainage system after land is cleared. The actual percentages will vary from region to region, but the relationships are universal.

On an annual basis, surface runoff from a forested or naturally vegetated watershed in the Pacific Northwest is minimal as a proportion of total water volume. Before development, the flow that we observe in streams is actually interflow. After development, flow in streams typically originates as surface runoff.

As a watershed is cleared, surface runoff volume increases in proportion to the percentage of impervious surface area, defined as non-infiltrating surfaces (e.g. concrete, asphalt, rooftops, hard landscaping and exposed rock). Once a pipe system is installed to drain these impervious areas, almost every rainfall results in runoff.

Example Annual Water Balance

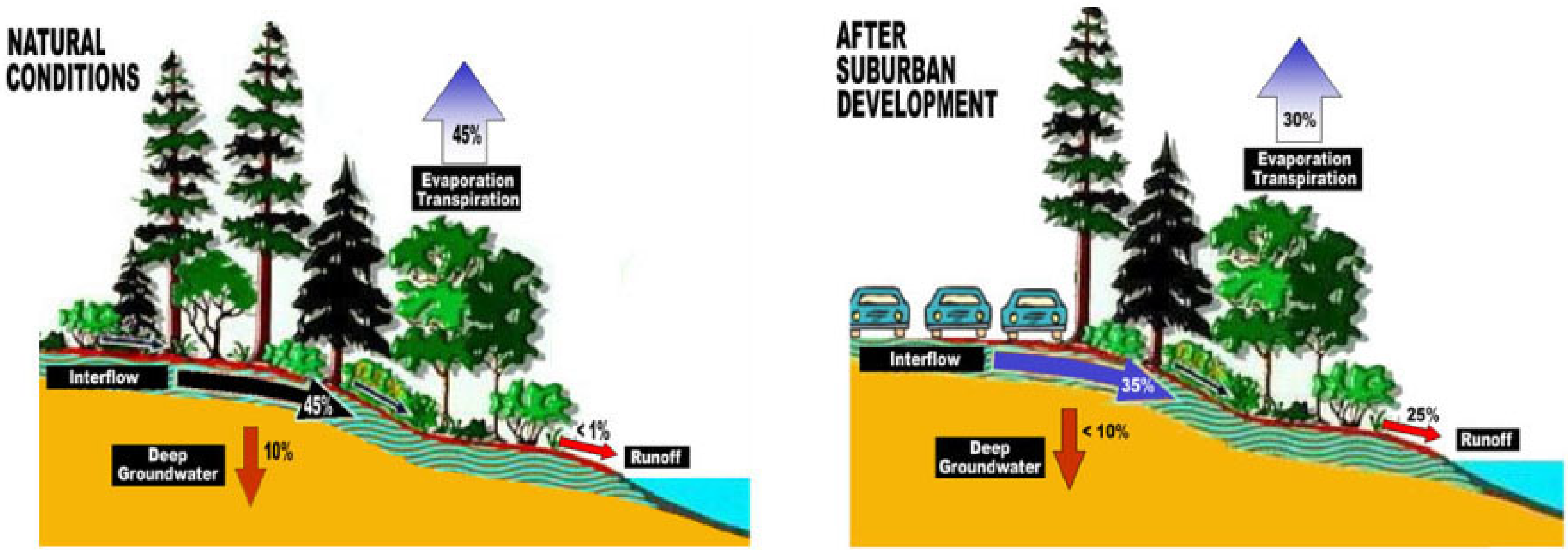


Figure 2-1

Distribution of Rainfall Over a Year

Understanding how rain falls over the course of a year is fundamental to understanding the Water Balance and how to manage its components. Figure 2-2 is an example of a typical distribution of annual rainfall volume. While total rainfall can vary significantly between regions, the distribution pattern is universal for British Columbia.

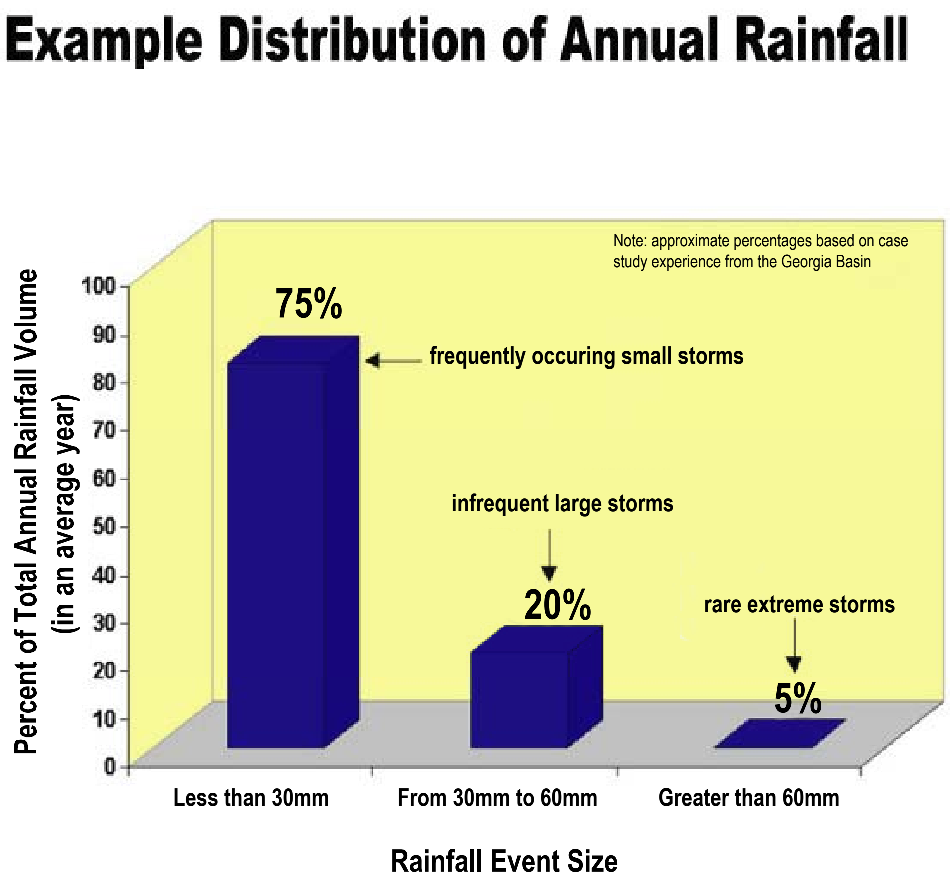


Figure 2-2

Role of Soil, Vegetation and Trees in Capturing Rainfall

The relevance of Figure 2-2 is in making the case that the frequently occurring small rainfall events hold the key to protecting the Water Balance in the urban environment. Small rainfall events typically account for 75% of the annual rainfall volume.

Because the majority of rain falls in small amounts, soil and vegetation are generally able to absorb and infiltrate it as it falls – this is why interflow and evapotranspiration are maximized and surface runoff is minimized in a forested environment.

In a natural condition, vegetated surface soil layers are highly permeable. As surface plants die and decompose, they provide a layer of organic matter which is stirred and mixed into the soil by earthworms and microbes. This soil ecosystem provides high infiltration rates and a basis for interflow.

Trees contribute to the soil ecosystem in two ways: the root zone creates a permeable environment; and the buildup of forest litter creates an absorbent layer.

In an urban situation, preservation and/or restoration of soil, vegetation and trees can help to:

- Recharge interflow
- Protect baseflow
- Minimize runoff

Water Balance Objectives for Protecting Watershed Health

In terms of preventing land development and related human settlement activities in the urban environment from impacting the Water Balance, British Columbia case study experience has resulted in identification of the following objectives for a truly healthy watershed:

- **Objective 1 -** Preserve and protect the water absorbing capabilities of soil, vegetation and trees.
- **Objective 2 -** Prevent the frequently occurring small rainfall events from becoming surface runoff.

2.3 Understanding Changes in Hydrology

Stormwater management practitioners now commonly use the phrase 'changes in hydrology'. Figure 2-3 presents a basic definition of this phrase:

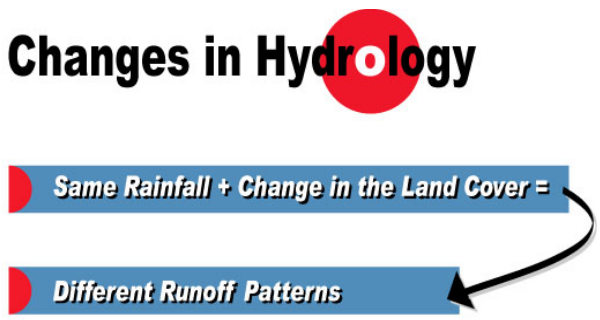


Figure 2-3

Relationship Between Impervious Area and Runoff Volume

Figure 2-4 illustrates the progressive changes in hydrology that result when land use change alters the Water Balance. Replacement of natural vegetation and soil with impervious surfaces reduces infiltration and evapotranspiration. The total runoff volume increases (as shown in red), and so does the Mean Annual Flood (MAF), a statistical rating of the annual peak flows in a creek system.

The MAF is defined as the channel-forming event because the cross-sections of stream channels tend to reach equilibrium with the MAF. When the MAF increases, the channel erodes to expand its cross-section. A critical parameter for watercourse erosion is the number of runoff events per year that equal or exceed the natural MAF. The more frequently the natural MAF is exceeded, the greater the channel instability, leading to habitat degradation as a result of erosion and sedimentation.

A second critical parameter is the ratio of the MAF to the winter baseflow. Washington State research indicates that 20:1 is a threshold ratio for coastal fisheries biodiversity and abundance.

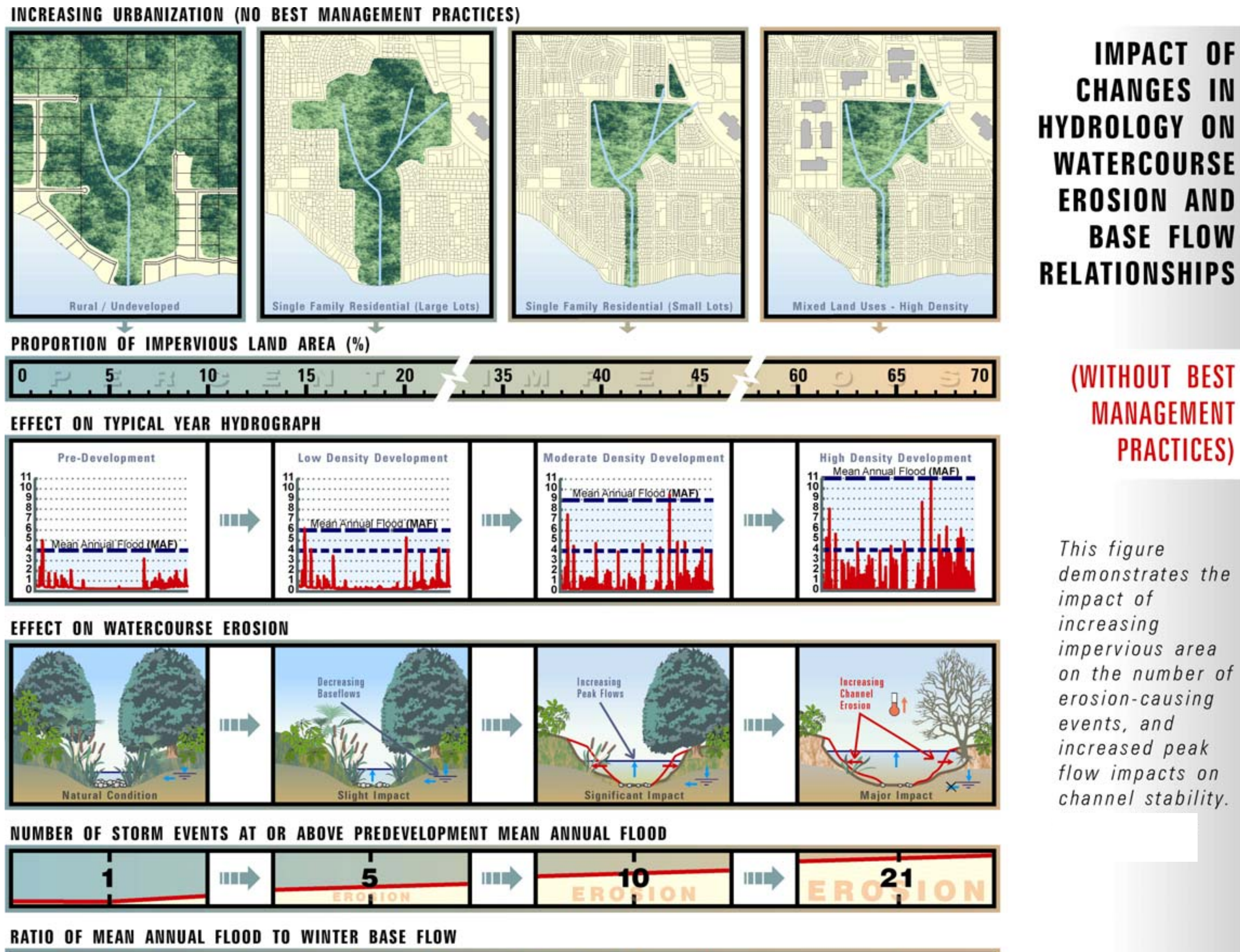

INCREASING URBANIZATION (NO BEST MANAGEMENT PRACTICES)
Rural / Undeveloped
Single Family Residential (Large Lots)
Single Family Residential (Small Lots)
Mixed Land Uses - High Density
PROPORTION OF IMPERVIOUS LAND AREA (%)
0
5
10
15
20
35
40
45
60
65
70
EFFECT ON TYPICAL YEAR HYDROGRAPH
Pre-Development
Low Density Development
Moderate Density Development
High Density Development
Mean Annual Flood (MAF)
EFFECT ON WATERCOURSE EROSION
Decreasing Baseflows
Increasing Peak Flows
Increasing Channel Erosion
Natural Condition
Slight Impact
Significant Impact
Major Impact
NUMBER OF STORM EVENTS AT OR ABOVE PREDEVELOPMENT MEAN ANNUAL FLOOD
1
5
10
21
EROSION
RATIO OF MEAN ANNUAL FLOOD TO WINTER BASE FLOW
8
14
20
30
IMPACT OF CHANGES IN HYDROLOGY ON WATERCOURSE EROSION AND BASE FLOW RELATIONSHIPS
(WITHOUT BEST MANAGEMENT PRACTICES)
This figure demonstrates the impact of increasing impervious area on the number of erosion-causing events, and increased peak flow impacts on channel stability.

Figure 2-4

Other Hydrology-Based Relationships

Impervious Area and Water Quality

Not only does more impervious surfaces mean more runoff volume, it also means there is more surface area (e.g. roads, parking lots) available to collect pollutants which then wash off into receiving streams when it rains. Most stormwater runoff receives no treatment before it is discharged to streams.

More runoff volume also means there will be more instream erosion and more frequent turbidity (or dirty water).

Another measure of changes in hydrology is the level of total suspended solids (TSS) in a creek system. TSS comprises the direct wash-off from impervious surfaces, plus sediment that erodes from stream bottoms and sides. TSS acts as a carrier of other pollutants such as organics, hydrocarbons and metals.

Interflow and Baseflow

Yet another measure of changes in hydrology is the Mean Annual Discharge (MAD). This is the average flow over the year. MAD is applied when assessing the relative magnitude of summer baseflows.

The interflow component of the Water Balance sustains baseflow. In fact, interflow can keep creeks flowing for months after winter rainfall stops. Interflow recharge depends on the integrated hydrologic function of soil, vegetation and trees. If interflow is reduced, baseflow is reduced.

When considering both community water supply and fisheries needs during periods of prolonged dry weather, a generally accepted criterion in British Columbia for Water Balance assessment purposes is that minimum baseflows should equal 10% of MAD.

Hydrology and Water Quality Objectives for Protecting Watershed Health

In terms of mitigating the impacts of impervious area on watershed hydrology, British Columbia case study experience has resulted in identification of the following hydrology-based objectives for a truly healthy watershed:

- **Objective 3 –** Provide runoff control so that the Mean Annual Flood (MAF) approaches that for natural conditions.
- **Objective 4 –** Minimize the number of times per year that the flow rate corresponding to the natural MAF is exceeded after a watershed is urbanized.
- **Objective 5 –** Establish a total suspended solids (TSS) loading rate (i.e. kilograms per hectare per year) that matches pre-development conditions.
- **Objective 6 –** Maintain a baseflow condition equal to 10% of the Mean Annual Discharge (MAD) in fisheries-sensitive systems.

2.4 Factors that Limit the Health of Aquatic Resources

A science-based understanding of the factors that limit the health of aquatic resources leads to reference levels of impervious area for planning purposes. This understanding provides the basis for setting performance targets and developing site design criteria.

Ranking of Limiting Factors

Research by the University of Washington (Horner and May 1996) clearly demonstrated that the factors limiting the ecological values of urban streams are, in order-of-priority:

1. **Changes in Hydrology** –
   Greater volume and rate of surface runoff caused by increased impervious area and densification of the road network.

2. **Disturbance and/or Loss of Integrity of the Riparian Corridor** –
   Clearing and removal of natural vegetation in riparian (streamside) areas.

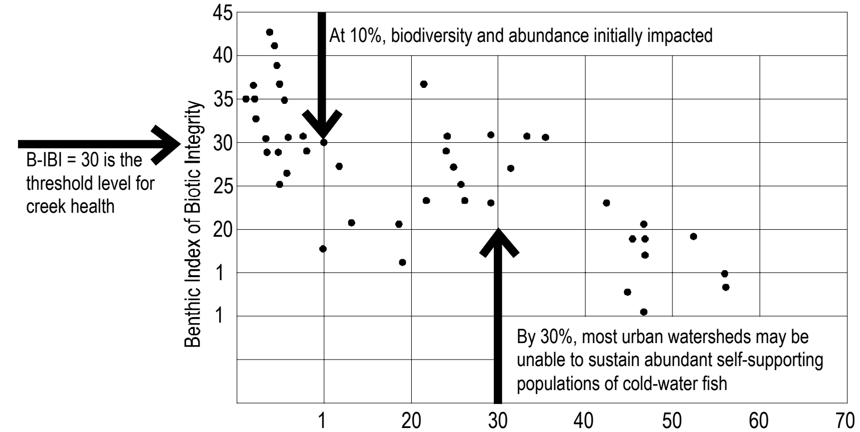
3. **Degradation and/or Loss of Aquatic Habitat within the Stream** –
   Caused by erosion and sedimentation processes, bank hardening, and removal of large organic debris; aquatic habitat degradation is a direct result of changes in hydrology (Factor #1).

4. **Deterioration of Water Quality** –
   Increased sediment load due to more runoff volume causing channel erosion. Pollutant wash-off from land uses, deliberate waste discharges and accidental spills.

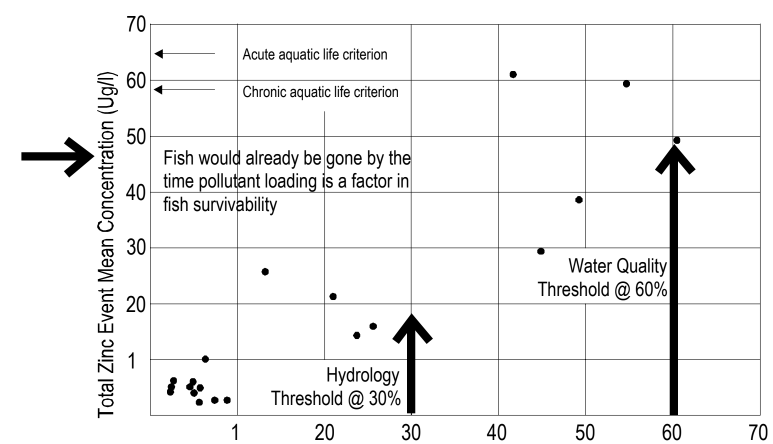
Figure 2-5 illustrates the research findings for two of these factors: changes in hydrology (#1) and deterioration in water quality (#4).

The work of Horner and May has had a profound impact in changing the way stormwater professionals view the relationship between watershed impervious area and stream health. Their work has also resulted in a science-based understanding that, in turn, has enabled the definition of reference levels for land use planning.

Reference Levels for Land Use Planning



Creek Health (B-IBI) Versus Impervious Land Cover



Water Quality Versus Watershed Impervious Land Cover

Figure 2-5

Reference Impervious Area Levels for Land use Planning

The scientific correlations presented on Figure 2-5 are simplified in the table below. The objective is to provide points of reference for integration of stormwater management with land use planning. This simplification will at least enable informed decision making. In reality, land use and stream health changes occur along a continuum.

Impervious Percentage	Biophysical Significance of the Reference Level
10%	Fisheries biodiversity and abundance are initially and significantly impacted
30%	Most urban watersheds in the Pacific Northwest may be unable to sustain abundant self-supporting populations of cold-water fish
60%	Pollutant loading would theoretically be a significant factor in fish survival, except cold-water fish would likely already have been extirpated because of hydrological changes and related degradation of the aquatic habitat

Measuring the Environmental Health of Creek Systems

Figure 2-5 refers to a Benthic Index of Biological Integrity (B-IBI) score as an indicator of creek health. B-IBI is a multimetric benthic macroinvertebrate index designed and calibrated for use in the Pacific Northwest. Each of the metrics it incorporates (e.g. total number of taxa, number of pollution tolerant taxa) was chosen for its consistency in responding to several types of human disturbance, including urbanization, forestry, agriculture and recreation. B-IBI is also useful because it is very sensitive to slight changes in a watershed.

Benthic invertebrates are used because anadromous fish species in the Pacific Northwest are subject to significant environmental pressures unrelated to their home watershed. These outside influences affect their distribution, diversity and abundance, making it difficult to use fish population measures as indicators of stream health.

Other Washington State Research Findings

Riparian Corridor Integrity

In any given watershed or at any given site, any one of the four factors can limit biologic health. Research by the University of Washington (Karr and Morley 1999) as well as a series of studies summarized by Millar (1997) demonstrate the importance of healthy riparian corridors. The presence or absence of healthy riparian forest greatly affects a stream's biologic integrity in otherwise similar watersheds with similar total imperviousness.

A healthy, forested riparian corridor can partially compensate for impervious surfaces in a watershed. In contrast, a cleared riparian corridor results in a damaged stream even in a watershed with low impervious area.

Density of Road Networks

Another significant finding is that the density of road networks also provides an excellent way to closely track total impervious area and associated impacts. This is because of the drainage system pattern associated with nearly all roads.

Drainage ditches collect surface water and interflow and transport it immediately to streams. Resulting changes in stream-system hydrology are similar to the effects of increased impervious surfaces.

Biophysical Objectives for Protecting Watershed Health

In terms of preventing changes in hydrology from impacting aquatic resources, Washington State research has resulted in identification of four objectives for defining a truly healthy watershed – that is, one that can support self-sustaining populations of wild salmon:

- **Objective 7 -** Limit impervious area to less than 10% of total watershed area.
- **Objective 8 -** Retain 65% forest cover across the watershed.

2.5 Managing Complexity

There is a logical link between changes in hydrology and impacts on watershed health, whether those impacts are in the form of flooding or aquatic habitat degradation. The link is the volume of surface runoff that is created by human activities as the result of alteration of the natural landscape (i.e. through removal of soils, vegetation and trees).

Eliminate the Source of Problems

The key to protecting watershed health is to maintain the Water Balance as close to the natural condition as is achievable and feasible. But protecting the interflow and evapo-transpiration components requires major changes in the way we develop land (i.e. if we are to preserve and/or restore soils, vegetation and trees). Understanding the cause-and-effect relationship between hydrology and biology provides credibility for a change in approach from only dealing with consequences, to also eliminating the source of problems. This shift in thinking is illustrated by Figure 2-6 below.

Science-based credibility helps people accept new ways of thinking. But to maintain credibility, it is important to apply common sense to the science.

Figure 2-6

What the Science is Telling Us

The science is explicitly telling us that major biophysical changes occur once the impervious percentage of a watershed reaches about 10%. Beyond this threshold, the change in the Water Balance triggers watercourse erosion, which in turn degrades and/or eliminates aquatic habitat.

The science is implicitly telling us that where urban land use densities are produced, the focus should be on what needs to be done at the site level to effectively mimic a watershed with only 10% impervious area, and in doing so reduce runoff volume to the same 10% level.

The science is also implicitly telling us that capturing rainfall at the source for the frequent small events will in large part maintain or restore the natural Water Balance.

What Can be Done at the Site Level to Protect Watershed Health

The financial and staff resources of local government are limited. Therefore, those resources must be invested wisely to maximize the return-on-effort. Common sense says that the best return will be at the site level where local government exerts the most influence, and can therefore make a cumulative difference at the watershed scale.

A Starting Point for Early Action

Common sense says that we now have sufficient science-based knowledge and understanding for local government to make some decisions, and to get on with implementing early action in at-risk areas. More data to refine the science is desirable when there is time and resources, however, there will be situations where excessive data collection becomes a barrier to effective action in the face of an immediate risk.

Strategic data collection required is to understand the historic Water Balance, the current Water Balance if the watershed is partially developed, and the proposed changes to land use in the watershed.

Looking ahead to the discussion in Parts B and C, the objectives of most ISMPs will include trying to maintain or restore the natural Water Balance as development or re-development proceeds. Improved understanding of how to do that will evolve through demonstration projects that test and refine solutions to aquatic habitat and receiving water quality challenges.

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Objectives for Protecting Watershed Health in the Urban Environment

The three sets of objectives for a truly healthy urban watershed are brought forward from the previous sections and consolidated below. The purpose is to provide an integrated framework for guiding the actions of local governments within their sphere of responsibility and influence.

Water Balance

- **Objective 1 -** Preserve and protect the water absorbing capabilities of soil, vegetation and trees.
- **Objective 2 -** Prevent the frequently occurring small rainfall events from becoming surface runoff.

Hydrology / Water Quality

- **Objective 3 –** Provide runoff control so that the Mean Annual Flood (MAF) approaches that for natural conditions.
- **Objective 4 –** Minimize the number of times per year that the flow rate corresponding to the natural MAF is exceeded after a watershed is urbanized.
- **Objective 5 –** Establish a total suspended solids (TSS) loading rate (i.e. kilograms per hectare per year) that matches pre-development conditions.
- **Objective 6 –** Maintain a baseflow condition equal to 10% of the Mean Annual Discharge (MAD) in fisheries-sensitive systems.

Biophysical

- **Objective 7 -** Limit impervious area to less than 10% of total watershed area.
- **Objective 8 -** Retain 65% forest cover across the watershed.
- **Objective 9 -** Preserve a 30-metre wide intact riparian corridor along all streamside areas.
- **Objective 10 -** Maintain B-IBI (Benthic Index of Biological Integrity) score above 30.