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BEST AVAILABLE SCIENCE

FLOOD AND CHANNEL MIGRATION HAZARD AREAS

The following summaries and excerpts from scientific literature pertain to the proposed Critical Area regulations for flood and channel migration hazard areas. The numbers in this report correspond to the footnote style numbers ([1]) in the draft regulations.

Contents:

1. Channel migration-General

There is considerable scientific literature regarding stream channel dynamics, movement, and factors affecting stream channel migration. There are few examples from scientific literature that define Channel migration zones (CMZs) with specificity or evaluate the effectiveness of various CMZ delineations in reducing channel migration hazard. Currently there is no national standard or single method of delineation identified to regulate land use within a CMZ.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW Center for Streamside Studies, July 2001, pgs 1-3: Schumm (1985) defines three major categories of stream channels: bedrock, semi-controlled, and alluvial. Bedrock channels are stable over time and do not change their position unless there are weak sections of bedrock that allow the channel to shift laterally. Semi-controlled channels have local controls that resist channel movement. Local controls can be areas of bedrock, resistant alluvium, or large wood and logjams (Abbe 2000). In areas without local controls, the channel is subject to migration. By definition, alluvial channels have substrates and banks made of material that is transported by the stream. This means that stream discharges can erode, transport, and deposit the material that shapes the channel. Alluvial channels frequently change their positions and exhibit a range of patterns that are characterized by meander and braiding features. The stability of alluvial channels is much higher when islands and bars have mature vegetation (Kondolf and Curry 1984; Hupp and Osterkamp 1996), but in some situations vegetation has only limited influence on stability and channel migration (Burckhardt and Todd 1998).

- Best Available Science, Channel Migration Zones, Draft, King County, 2/2004: A basin-scale perspective of channel migration provides an initial overview. Drainage basins can be broken into three zones in the downstream direction: the rugged headwaters dominated by erosion and sediment production; a middle zone of sediment transport; and a downstream zone of deposition (Schumm 1977). These three subdivisions of the fluvial system may seem like a simplification, because sediment is eroded, transported, and deposited in all three zones (Schumm 1977). These three zones are similar to the source, transport, and response segments of a watershed described by Montgomery and Buffington (1993), with channel changes such as channel migration most commonly occurring in the generally downstream response segments where areas of sediment deposition predominate (Montgomery and Buffington 199_).

  Channels in the steeper erosion and sediment production zone and areas dominated by sediment transport may not show significant channel migration over time scales of a few decades. Areas of deposition, especially the transition from a transport to a depositional zone, would be areas of likely channel migration (Church 1983; Montgomery and Buffington 1993). These conditions exist where channel gradient and confinement decreases markedly, such as where a steeper river emerges from foothills onto a broad, flat floodplain. In the major King County rivers, most of which flow from headwaters in the Cascades to mouths at or near sea level, the segments with a history of channel migration typically are located in just such depositional areas.

The footprint of a channel can be expressed as a percent of the total floodplain area in plan view. As the channel migrates, the composite footprint of its sequential locations will occupy an increasing percentage of the floodplain. By extension, the timeframe needed for a channel to migrate and occupy its entire floodplain can be calculated as a "floodplain turnover rate" (O'Connor et a1. 2003), which might be on the order of hundreds to thousands of years in an alluvial channel of western Washington. Given time and without obstruction, a natural, unimpeded, meandering channel can swing and shift across its valley and the entire pattern may sweep downstream, resulting in a complete reworking of the alluvial floodplain (Schumm 1977).

Hence the generally flat floor of a valley, its alluvial floodplain, was constructed by the river during lateral channel migration and by deposition of sediment. In alluvial floodplains, the river has occupied or migrated through every position of the valley floor at some point in the past (Dunne and Leopold 1978). The river channel moves laterally by erosion of one bank and simultaneous deposition on the other. As a channel migrates, there may be physical features evident in the floodplain such as progressive erosion and deposition at meander bends (Figure 4.1). Other features, such as side channels or oxbow lakes (crescent-shaped body of standing water situated in an abandoned meander) may be evidence that a channel has moved by shifting abruptly or by cutting off a meander bend. Though such field conditions provide evidence of channel migration, the actual boundary of the CMZ may not be readily evident in the field because the lateral extent of the CMZ typically depends on selection of a timeframe within which migration occurs (as described further below).

Types of Channel Movement. (A thorough description of types of channel movement is provided by Rapp and Abbe (2003)). Channel movement can occur in both vertical and horizontal directions to produce channel migration. Vertical channel movement occurs as either a raising or lowering of the channel bed. Increases in channel bed elevation result from sediment deposition and aggradation. Significant increases in bed elevation allow a given flood flow to gain greater access to side channels and overbank areas, or increase exposure to erodible banks, all of which increase the likelihood of horizontal channel movement. Decreases in channel bed elevation result from channel incision, local or general channel scour, and degradation. Significant decreases in bed elevation lead to bank collapse and channel widening.

Horizontal channel movement includes lateral channel migration, avulsions, channel widening and channel narrowing, and involves erosion of the existing floodplain and terraces (Rapp and Abbe, 2003). Lateral channel migration results from erosion of floodplain material along one bank concurrent with deposition of sediment along the other bank. Bank erosion is the primary channel process necessary for channel migration to occur (Leopold et al. 1964). Ongoing lateral channel migration typically results in development of meander bends, which themselves may migrate in a downstream direction. Rivers tend to establish secondary circulation patterns of flow that moves downstream in a generally spiraling motion, where a descending flow pattern encourages scour and an ascending flow direction favors deposition. The scour and deposition from secondary circulation is associated with development of bed forms such as pools and riffles. As pools alternate from one side of the channel to the other, they scour and undermine the outside banks, initiating meander development (Knighton 1998). If the processes of erosion and deposition are in rough equilibrium, there may be little net change in cross sectional area even as the channel meanders or migrates across the floodplain (Dunne and Leopold 1978).

An avulsion is an abrupt shift of the channel to a new location, often with little erosion of the land between the old and new channel locations. An avulsion can happen during a single flood event, e.g., if a main stem river is obstructed by a woody debris jam and reroutes the river into a side channel during high flows. Another type of avulsion is the neck cut-off of a meander bend, which can occur as a meander bend increases in sinuosity until parts of the meander loop connect and bypass the longer, circuitous path of the entire meander. Chute cutoffs cut across a point bar and may occur more commonly than a neck cutoff (Rapp and Abbe 2003). Conditions that would favor the occurrence of avulsion include the existence of side channels accessible to frequent flows, or the ongoing development of sinuous meander bends.

Channel widening and channel narrowing result in horizontal changes to the channel dimensions, although channel alignment may not change. Channel widening might occur with channel aggradation and/or channel braiding. Channel narrowing can result as a response to upstream decreases in sediment or water discharge.

Channel movement is difficult to predict with certainty on alluvial fans (W A DNR 2001). An alluvial fan is a fan-shaped feature composed of streamflow and/or debris flow sediments deposited usually at a topographic break such as the base of a mountain or a valley floor at the outlet of a steeper tributary. The alluvial fan is formed as the tributary deposits sediment to the point where its channel elevation is higher than the adjacent fan; the channel then shifts location to flow to the adjacent, lower elevation. As this ongoing process continues, the channel shifts to deposit sediment in an arc radiating from the tributary outlet. A braided channel or channel network is common on an alluvial fan. By its inherent tendency to shift channel locations, and resultant uncertainty in predicting channel migration, the entire surface of the alluvial fan is considered a channel migration zone of its source tributary (W A DNR 2001).

Natural Factors that Influence Channel Migration. (A thorough description of factors affecting channel migration is provided by Rapp and Abbe, 2003). Lateral channel migration meets a solid boundary in bedrock. In areas where the river channel is in direct contact with bedrock, bank erosion is assumed to be minimal over scales and timeframes typically used in channel migration study.

Channels confined by narrow valleys are less likely to move laterally and so may have little or no channel migration zone. The degree of channel confinement can be expressed as a ratio of valley floor width to channel width, where a ratio of less than 2: 1 indicates high confinement and lack of a CMZ (W A DNR 2001). A CMZ also is interpreted to not exist where there is a consistent lack of evidence of channel movement in the historic record, in current aerial photos, and in field observations (NMFS 2000).

A valley wall may appear to be the boundary of a CMZ as the de facto edge of a floodplain, but the greater elevation of a valley wall does not preclude channel migration. An eroding vertical bank of unconsolidated material such as a terrace of older alluvium or glacial deposits does not prevent toe erosion, transport of sediments, and lateral channel migration (Rapp and Abbe 2003). Lateral channel migration into such terraces or unconsolidated bluffs may proceed at a slower rate than through younger floodplain alluvium (Shannon and Wilson 1991).

The susceptibility of riverbanks to slope instability and mass failure depends on their geometry, structure, and material properties (Knighton 1998). Undercutting the toe of tall, steep slopes by the river decreases slope stability and can result in landslides directly into the channel, particularly in geologic units predisposed to landsliding (see Chapter 5 - Geologic Hazard Areas. At that point, hillslope delivery of sediment and fluvial sediment transport may become coupled in a "pseudo-cyclic process" of basal erosion, upper bank failure, lower bank accumulation, and removal offailed material by river transport (Knighton 1998). The river's flow may erode and remove relatively small deposits, but a landslide mass that blocks the channel and is not eroded will reroute the channel as an avulsion.

Slope failure by landslide or mass wasting introduces both sediment and woody debris to the channel. Other input sources of woody debris to the channel include wind throw, bank erosion, and fluvial transport from upstream, in both chronic and episodic time scales (Bilby and Bisson 1998). Leaching, fragmentation, decay, consumption by invertebrates, and fluvial transport all contribute to the export of wood from a channel (Keller and Swanson 1979). Studies that reconstruct historic channel conditions document prodigious amounts of woody debris in mainstem channels of the Pacific Northwest and Puget Sound lowlands (Maser and Sedell 1994, Collins et al. 2003). .

Channel migration-time frame.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW, Center for Streamside Studies, July 2001, pgs. 5-14: When trying to define a channel migration zone (CMZ) or area within which the stream is expected to move, one first needs to define a time period. The amount of channel migration will vary depending on the time frame of interest. For various reasons, <u>many authors have decided that 100 years is an appropriate time frame</u>. …Pollack and Kennard (1999) defined the channel migration zone as the area that the stream and/or its side channels could potentially occupy under existing climatic conditions. It frequently approximates the 100-year floodplain, though it also includes lower terraces and hillslopes adjacent to the floodplain where the stream is likely to meander. In contrast, Skidmore et al. (1999) found the Nooksack River, Washington 100-year floodplain to be wider than the geologic channel, historic channel or meander belt width. This is probably due to the presence of a bridge that had confined the channel for many years.

- Section 577(e) of the **National Flood Insurance Reform Act** of 1994 defined an erosion hazard area as: "Erosion hazard area means, based on erosion rate information and other historic data available, an area where erosion or avulsion is likely to result in damage to or loss of buildings and infrastructure within a 60-year period." (FEMA 1994) (It appears that the primary purpose of NFlRA 1994 was to authorize FEMA to study the feasibility of mapping REHAs, as there is no federal regulation that establishes a 60-year-based riverine erosion hazard zone.)

- The **Shoreline Management Guidelines** define CMZ: "Channel migration zone (CMZ)" means the area along a river within which the channel(s) can be reasonably predicted to migrate over time as a result of natural and normally occurring hydrological and related processes when considered with the characteristics of the river and its surroundings." Unless otherwise demonstrated through scientific and technical information, the following characteristics should be considered when establishing the extent of the CMZ for management purposes: Within incorporated municipalities and Urban Growth Areas, areas separated from the active river channel by legally existing artificial channel constraints that limit channel movement should not be considered within the channel migration zone.

- The **US Fish and Wildlife Service** (MBTSG cited in USFWS 1998) gave the following description and rationale for channel migration zones for Bull Trout: <u>The 100-year floodplain was chosen based on the need to fully incorporate the channel migration zone (CMZ) on low gradient alluvial streams.</u> These stream channels provide critical spawning and rearing habitat for bull trout. An additional 150 feet on either side of the 100-year floodplain is required for the following reasons: 1) it encompasses one site-potential tree height at most locations; 2) provides sufficient width to filter most sediment from non-channeled surface runoff from most slope classes; 3) provides some microclimate and shallow groundwater thermal buffering to protect aquatic habitats inside the channel and the channel migration zone; and 4) provides an appropriate margin of error for unanticipated channel movement, hillslope and soil stability, blowdown, wildfire, operator error, disease, and certain other events that may be difficult or impossible to foresee on a site specific basis.

  The **Tricounty** effort in Washington defines the CMZ as the area within the lateral extent of likely stream channel movement over a given stream reach due to stream bank destabilization, rapid stream incision, stream bank erosion, and shifts in location of stream channels. They intend to identify CMZ boundaries for all stream reaches where stream power, soil conditions, and valley-floor widths are sufficient to support significant potential migration. For regulatory purposes, the Tri-county CMZ will be based on available historic records of channel migration, <u>field indicators of the presence of the side channel in the last 100 years, or 100 years of calculated channel migration, whichever is greater</u>, and will generally include those areas that encompass: The limit of geologic controls, such as hillslope, bedrock outcrop, or abandoned floodplain terrace; the side channels, abandoned channels, and oxbows; and the outside edges of any signs of progressive bank erosion at the outside of meander bends.

  The **Washington Forest Practices Board** (WFPB 2000) defined CMZ as the area where the active channel of a stream is prone to move and thus results in a potential near-term loss of riparian habitat adjacent to the stream, except as modified by a permanent levee or dike. For this purpose, near-term means the time scale required to grow a mature forest (WAC 222-16-010)." (WA DNR 2001). The FPB Manual describes the channel migration zone as the area likely to be occupied by the channel based on floodplain characteristics and evidence of active movement. Evidence for potential channel movement can be provided from current and past channel movement visible on aerial photos or field observations. In addition to delineating CMZs on the valley floor, the FPB Manual calls for mapping alluvial fans as a CMZ (WDNR

2001).The WFPB manual has descriptions and illustrations of CMZs and delineation guidelines, that include CMZs that have been modified by a permanent levee or dike.

- The **National Marine Fisheries Service** (NMFS) defined CMZ as follows: "A CMZ is defined by the lateral extent of active channel movement along a stream reach over the past 100 years. Evidence of active channel movement over the 100-year time frame can be inferred from aerial photographs or from specific channel and valley bottom characteristics and it was chosen for that reason. Also, this time span typically represents the time it takes to grow mature trees that can provide functional large woody debris to streams. A CMZ is not typically present if the valley width is generally less than two bankfull widths, is confined by terraces, no current or historic aerial photographic evidence exists of significant channel movement, and there is no field evidence of secondary channels with recent scour from stream flow or progressive bank erosion at meander bends." (Federal Register, 2000, p. 42462)

  In the February 17 1998 draft proposal of Oregon Forest Practice Rules the National Marine Fisheries Service (NMFS) defined the CMZ (in Pess 1998) as…<u>the area a stream is expected to occupy in the time period it takes to grow a tree of sufficient size to geomorphically function in the channel</u>. Spatially, this area generally corresponds to the modern floodplain, but can also include river terraces subject to significant bank erosion. <u>An acceptable method for delineating the CMZ at a particular site, involves delineating either the flood-prone area or the approximate 100-year flood plain, whichever is greater</u>. <u>The objective of identifying the CMZ is to ensure that the stream has a protective buffer in the future, even if the stream were to move away from its present location.</u> (Bolton and Shellberg, 2001)

- Best Available Science, Channel Migration Zones, Draft, King County, 2/2004: There are few examples from scientific literature that define CMZs with specificity. No studies were found that identify various CMZ definitions and evaluate the adequacy of resulting CMZ delineation in protecting the affected area from channel migration hazard. Clear identification of boundaries is difficult because streams and riparian areas are not fixed in time and space" (Bolton and Shellberg 2001). Because stream channels are naturally areas of disturbance, floods, droughts, fires, and landslides can all affect the location of the wetted stream channel and adjacent riparian areas over time (Naiman et al. 1992). A time period needs to be specified when defining a channel migration zone or area through which a channel is expected to move. The extent of channel migration will vary depending on the time frame of interest (Bolton and Shellberg 2001). Delineation of a CMZ boundary identifies the area in which channel processes will occur during the selected period of time; the CMZ boundary is stationary for the design life of that CMZ delineation (Rapp and Abbe 2003).

  A <u>period of 100 years</u> often is identified as an appropriate timeframe (Bolton and Shellberg 2001). Reasons for using this timeframe may include that the 100-year floodplain is mapped to identify flood hazard due to inundation, or it may be because CMZ mapping relies on assembly of archival material and the record of relevant information often dates back about 100 years (NMFS 2000). There is evidence that <u>100 years provides sufficient time for the growth of a tree to the height that it would be functional LWD were it to fall into the channel</u> (**NMFS** 2000), which indicates a scientific basis for selecting the 100-year time period. However, most CMZ definitions that incorporate a time period do not indicate a scientific basis. For example, **FEMA** (1999) states that "there is no apparent scientific basis to choose <u>60 years</u>" as the time period used to define erosion hazard areas in the National Flood Insurance Reform Act of 1994. The same could be said about selection of any specific time period for a CMZ definition (unless it is tied to a physical process of specific duration): it is more of a policy decision than science-based determination.

- Best Available Science, Channel Migration Zones, Draft, King County, 10/2003: In general terms, a CMZ is a corridor of variable width that includes the current river channel plus the adjacent area through which the channel has migrated or is likely to migrate within a given timeframe. Within the CMZ corridor, water, sediment, and organic material are moved by fluxes between river and floodplain and are routed from headwaters to mouth on time scales of days to centuries.

  Pollack and Kennard (1999, in Bolton and Shellberg 2001) defined the channel migration zone as the area that the stream and/or its side channels could potentially occupy under existing climatic conditions. If "existing climatic conditions" includes the period since the last glaciation, then the CMZ would likely encompass the entire valley bottom, along with lower terraces and hills lopes adjacent to the floodplain where the stream is likely to meander. Such a CMZ definition, which uses a geologic timeframe, would be consistent with sweeping channel of Schumm (1977) and the river constructing its full alluvial floodplain per Dunne and Leopold (1978). <u>It also may be the most science-based CMZ definition and would render moot the selection of a time frame tied to a specific number of years</u>.

Mapping Channel Change

- A Framework for Delineating Channel Migration Zones, Cygnia Rapp and Tim Abbe, 2003: This report, prepared in light of proposed revisions to Chapter 173-26 WAC (the Shoreline Management Guidelines) and for purposes of flood hazard management, is intended as a guidance document for local governments and practitioners, based on up-to date, peer-reviewed research. While offering a thorough and systematic procedure for identifying and delineating CMZs, the approach and methods presented in this document:

  - represent only one approach to CMZ delineation;
  - are not mandated for local government use under any state law;
  - do not replace existing regulatory definitions of CMZs; and
  - are intended to be applied in areas under Shoreline jurisdiction (as defined by the Shoreline Management Act).

  The Department of Ecology believes this delineation methodology, though an intensive approach, <u>will result in optimum data upon which to make planning and resource management decisions</u>. We are aware that other methodologies exist that are not as resource-intensive; the use of these methods may be appropriate depending on the scale of application (e.g., planning vs. site-specific permitting).

  The principal goal of CMZ delineation is to predict the area of a river system that is at risk of future channel erosion due to fluvial processes. <u>The purpose of this report, therefore, is to provide the framework for evaluating how trends in channel movement, changes in boundary conditions, and the context of a channel’s disturbance history</u>

contribute to future channel behavior... How precise and accurate the determination of any of these components depends on the level of integrity of the historical and field analyses.

CMZ studies analyze historical information and field data to interpret past and current channel conditions in order to predict future channel behavior and areas at risk of channel movement. Delineation of a CMZ relies on an evaluation of channel processes that occur within a multi-dimensional context (space and time). Channels respond with horizontal movement (lateral migration, avulsion, channel widening, cannel narrowing) and vertical movement (incision and aggradation) depending on site-specific circumstances and watershed conditions. Thus, patterns and rates of channel movement must be estimated by using a combination of historical and field studies to determine future trends in channel migration (bank erosion and avulsion). The CMZ study takes into account trends in channel movement, context of disturbance history and changes in boundary conditions, as well as topography, bank erodibility, hydrology, sediment supply and woody debris loading.

The CMZ boundary delineates the area in which channel processes will occur over a specified period of time. Consequently, the timeline used for a CMZ delineation will affect the relative area included in the CMZ. For example, a CMZ intended to capture channel processes for 100 years into the future may be smaller in area than a CMZ intended to capture channel processes for 500 years. The boundary of the CMZ is stationary for the design life of the CMZ delineation; it does not change unless channel erosion hazards are not properly accounted for in the original CMZ delineation, leading to unanticipated erosion.

When delineating CMZs, it is helpful to view the river landscape as a series of identifiable components (Figure 1) that can be used collectively to define the boundaries of the CMZ:

1. The Historical Migration Zone (HMZ)—the collective area the channel occupied in the historical record.
2. The Avulsion Hazard Zone (AHZ)—the area not included in the HMZ that is at risk of avulsion over the timeline of the CMZ.
3. The Erosion Hazard Area (EHA)—the area not included in the HMZ or the AHZ that is at risk of bank erosion from stream flow or mass wasting over the timeline of the CMZ. The EHA has two components: the Erosion Setback (ES) and the Geotechnical Setback (GS). The ES is the area at risk of future bank erosion by stream flow; the GS is defined by channel and terrace banks that are at risk of mass wasting (due to erosion of the toe). The GS projects from the ES at a side slope angle that forms a stable bank configuration, thereby accounting for mass wasting processes that will promote a stable angle of repose.

The Disconnected Migration Area (DMA)—the portion of the CMZ where man-made structures physically eliminate channel migration. Accordingly, delineation of the CMZ (Figure 1) is the cumulative product of historical analysis and field interpretations, characterized by the following equation: CMZ = HMZ + AHZ + EHA – DMA (EHA = ES + GS)

Field studies are used in combination with historical studies to define the AHZ, EHA and DMA by field mapping and assessment of surficial geology, fluvial landforms, geotechnical characteristics and current physical conditions of the given area. When applied to historical data analysis, field observations (on-the-ground data) provide the means for interpreting future channel change and delineating the boundaries of the CMZ. Accordingly, the AHZ, EHA, and DMA may not apply in every CMZ study. However, in river systems susceptible to avulsion and/or erosion beyond the HMZ, accounting for these components by limiting development in geologically and geomorphically hazardous areas reduces risk.

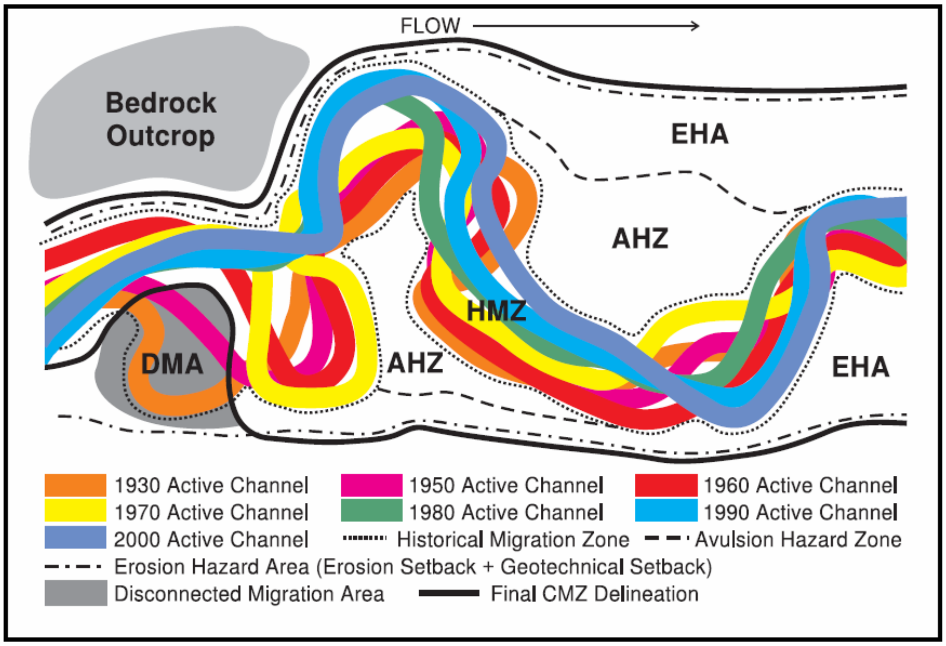

Figure 1. An example of the CMZ as the cumulative product of the Historical Migration Zone (HMZ), the Avulsion Hazard Zone (AHZ), the Erosion Hazard Area (EHA), and the Disconnected Migration Area (DMA) based on historical and field analysis and interpretation.

Before a CMZ study begins, a design life (how long into the future the CMZ is intended to account for channel processes) must be established…. In those instances where it has not already been determined, or the aims of the study do not correspond to compliance with local ordinances, the design life should be far-reaching enough to account for long-term alterations of the fluvial landscape.

In order to understand the first component—the HMZ—the analyst first maps the extent of the locations of the channel over time, identifies trends in channel movement (channel migration and avulsion) that extend beyond the HMZ, calculates rates of erosion over the CMZ design life, and calculates floodplain turnover rates for each reach. Figure 6 illustrates why further analysis is required to determine if avulsion hazards exist beyond an HMZ, depending on vegetation, topography, and factors that may cause aggradation of the channel bed (e.g., log jams and snags).

The next component—the AHZ (Section 4.3)—accounts for any avulsion hazards that may extend beyond the HMZ, and is determined by: (1) empirical observations of bank stratigraphy and the role of LWD in channel bed dynamics; (2) vegetative characteristics; (3) topography and elevation of fluvial features; (4) survey data; and (5) hydraulic modeling.

The third component—the EHA (Section 4.4)—delineates the areas outside of the HMZ and the AHZ that are at risk of channel erosion (either from stream flow and/or mass wasting) over the design life of the CMZ; the EHA includes bank erosion anticipated from the AHZ, as well as bank erosion associated with current trends in channel behavior (Figure 18). The EHA's two components—the ES and the GS—account for bank erosion that occurs along floodplain and terrace banks that are composed of erodible materials (outwash, alluvium, loess, floodplain sediments). The ES (Section 4.3.2) is determined from rates of erosion and floodplain turnover rates for banks composed of similar geologic materials, heights, and vegetative characteristics. For slopes prone to mass wasting (due to current and/or anticipated erosion of the toe from channel processes), the GS (Section 4.3.3) establishes a stable slope beyond the ES in anticipation of a stable angle of repose. The DMA is the fourth and last component, given that the field survey of bank protection is best coordinated with the other field studies that precede it. In other words, much of the information the analyst will need to delineate the DMA will already have been acquired in the process of determining the HMZ, AHZ, and EHA. The purpose of delineating a DMA is to determine the impact of man-made structures (such as levees, revetments, roads, and railroads) on channel migration and also to determine the possible impact of future channel migration on public and/or private developments and property.

The culmination of these efforts also allows the analyst to determine the relative risk of erosion hazards (Section 4.5). In the instances where probabilistic methods are used to evaluate channel movement over time, the analyst can define and map hazards by percent ranges (e.g., 100-75%, 75-50%, 50-25%, 25-0%). This approach, of course, has its limitations and should only be applied in rivers where the HMZ captures the full extent of anticipated future channel behavior. Otherwise, the analyst must rely on information that provides rates of erosion, trends in channel movement, avulsion hazards, erosion hazards, and locations of bank protection to evaluate relative risk (Figure 20). Reliance on best professional judgment emphasizes the need for qualified professionals (extensively trained in geomorphology) to make these calls.

- Best Available Science, Channel Migration Zones, Draft, King County, 2/2004: A common starting point for mapping channel movement and delineating CMZs is a compilation of archival records to document change in location from historic to contemporary channels. The floodplain turnover rates and channel and floodplain dynamics described earlier were calculated for the Quinalt and Queets Rivers by comparison of up to nine sets of channel locations dating from 1900 to the present (O'Connor et al. 2003). Methods in development in the Puget Sound area characterize historical river landscapes and aquatic habitat using a geographic information system (GIS) as well as modern topographic information, aerial photography, and field studies (Collins et al. 2003).

  Ham and Church (2000) mapped channel features for five dates between 1952 and 1991, using GIS to analyze changes in erosion and deposition volumes and relate those volumetric changes to riverbed material transport via a sediment budget approach. While the focus of Ham and Church (2000) was on sediment volumes, their characterization of plan-form changes in channel conditions through time used the same methods and tools employed in a channel migration analysis. Graf (1984) measured the change in channel locations through time with a grid framework of cells superimposed on the floodplain to calculate the probability that any given floodplain cell will be eroded. Comparison of channels over a number of time intervals from 1871 to 1978 showed that the probability of a cell being eroded within a given period of time is directly proportional to the sizes of the annual floods during the period and inversely proportional to the distance upstream and the distance lateral to the channel (Graf 1984). These studies and others suggest that at least 50 years of remote sensing data such as aerial photos (at intervals of five to 10 years) are necessary to reveal meaningful trends in channel change and bed material transport rates (Rapp and Abbe 2003).

Skidmore et al. (1999) mapped four different boundaries of the lateral extent of likely channel movement along a seven-mile stretch of the Nooksack River using four criteria: a corridor based on meander amplitude, a composite of historic channel locations, the area within geologic controls such as alluvial terraces features and geologically defined valley margins, and the 100year floodplain. The outer edge of channel movement under these four mapping approaches could each be taken to be a CMZ boundary. The four CMZ boundaries were largely coincident along one bank defined by geologic controls. There was no consistent trend in the CMZ boundaries along the other bank except that the 100-year floodplain was generally the widest. Skidmore et al. (1999) concluded that channel migration corridors are best delineated from a combination of methods.

FEMA (1999) reviewed a dozen case studies nationwide to evaluate the feasibility of mapping riverine erosion hazard areas (REHAs; assumed to be equivalent to CMZs). All of the case studies characterize riverine erosion hazard in some way; five of the 12 case studies (including King County) result in erosion hazard area delineation that is presently used to regulate land use in REHAs. FEMA concluded that it is technologically feasible to conduct riverine erosion studies and establish conclusions regarding the likelihood of future erosion (FEMA 1999).

CMZs were mapped along parts of four rivers in King County (Shannon and Wilson, 1991; Perkins 1993; Perkins 1996) using a combination of historic studies and field investigation. A compilation of historic channel locations is prepared, from which representative historic channel migration patterns and rates are characterized. The potential for avulsions is identified from maps and aerial photos and verified in the field. An unconstrained probable outer limit of future channel migration is predicted based on representative historic channel migration patterns and rates, potential avulsion sites, meander amplitudes, and the width of the historic meander belt. Relative levels of channel migration hazard are mapped as severe hazard areas, based on 100 years of predicted channel migration, and moderate hazard areas, which is the area between the severe hazard area and the predicted outer boundary of future channel migration. Lastly, constructed features such as infrastructure, levees, and revetments that pose legitimate constraints to channel migration are taken into account and the CMZ boundaries are modified accordingly (Perkins 1993, 1996).

CMZs were mapped along parts of three rivers in Pierce County (GeoEngineers 2003). The CMZ is delineated based on several factors, including the river's Historic Channel Occupation Tract (HCOT) over the observable period of record, its unconstrained character and rate of channel migration, and the locations of ancient and historic abandoned channels. The CMZ is delineated as the area through which lateral migration would proceed over 25 years landward in each direction from the edge of the HCOT, assuming that levees and revetments do not constrain channel migration. To recognize relative hazard within the CMZ, three Migration Potential Areas (MPAs) are also delineated. The severe MP A includes the HCOT plus the area through which the river could travel in five years of steady lateral migration. The moderate MP A is generally the HCOT plus 15 years of channel migration. The low MPA is the area landward of the moderate MPA to the outer boundary of the CMZ (GeoEngineers 2003).

King county approach: The primary purpose of King County CMZ regulations is to protect public safety from hazards due to channel migration, and CMZs are designated as a critical area for that reason. Two distinct areas - the moderate and severe channel migration hazard areas -- are delineated in recognition that the hazard to public safety is not the same throughout the width of the CMZ. Land that is closer to a migrating channel is at greater risk of erosion, even if it is at a higher elevation than the identified flood hazard elevation. Channel migration hazard to human habitation, structures and property generally decreases with greater distance from the migrating channel.

The severe channel migration hazard area is that area predicted to experience erosion within the next 100 years. Unlike the 100-year floodplain, its delineation is not based on a statistical analysis so it is not possible to state that there is a one-percent chance of erosion occurring in any given year throughout the entire severe hazard area. Instead, it is predicted that the channel will occupy the entire severe channel migration hazard area within the next century. There is no specific timeframe associated with the moderate channel migration hazard area, except that the channel is not predicted to migrate into the moderate hazard area until 100 years in the future.

The channel migration zone, the moderate channel migration hazard area, and the severe channel migration hazard area are defined in the proposed Critical Areas Ordinance (CAO) as follows. Channel migration zone: those areas within the lateral extent of likely stream channel movement that are subject to risk due to stream bank destabilization, rapid stream incision, stream bank erosion, and shifts in location of stream channels, as shown on King County's Channel Migration Maps. The channel migration zone is a corridor that includes the present channel, the severe channel migration hazard area and the moderate channel migration hazard area. A channel migration zone does not include those areas that lie behind an arterial road, a public road serving as a sole access route or a regional transportation corridor. A channel migration zone may be excluded from those areas that lie behind a lawfully established flood protection facility that is likely to be maintained by existing programs for public maintenance consistent with designation and classification criteria specified by public rule. When a natural geologic feature will affect channel migration, the channel migration zone width shall be modified to consider such natural constraints.

Channel migration hazard area, severe: a portion of the channel migration zone, as shown on King County's Channel Migration Zone maps, that includes the present channel. The total width of the severe channel migration hazard area equals one hundred years times the average annual channel migration rate, plus the present channel width. The average annual channel migration rate shall be as determined in the technical report that is the basis for each Channel Migration Zone map.

Channel migration hazard area, moderate: a portion of the channel migration zone, as shown on King County's Channel Migration Zone maps, that lies between the severe channel migration hazard area and the outer boundaries of the channel migration zone. Further information on designation and classification of CMZs and the component areas are provided in the channel migration public rule (King County 1999). Details on CMZ mapping methods and resultant map designations of severe and moderate channel migration hazard areas are described in the technical reports that are the basis for existing King County CMZ maps (Perkins 1993, 1996). Study methods are summarized here as relevant to the discussion of King County CMZ classification and definition, and assessments thereof, below.

King County CMZ studies and delineation include the following steps. Channel and basin-scale characteristics are described through review of existing information and field investigations. Archival and current material is reviewed, especially in the form of maps and aerial photos. A compilation of historic channel locations is prepared, from which representative historic channel migration patterns and rates are characterized. The potential for avulsions is identified. The unconstrained probable outer limits of future channel migration are predicted based on representative historic channel migration patterns and rates, meander amplitudes, and the width of the historic meander belt. Channel migration hazard is mapped to identify both severe hazard areas and moderate hazard areas. Lastly, constraints to channel migration due to infrastructure, levees, and revetments are taken into account, and the CMZ boundaries are modified accordingly (Perkins 1993, 1996).

The width of the severe channel migration hazard area equals 100 years times a representative average annual channel migration rate, plus the width of the present channel. The time period thus represented is a prediction of channel migration over the next 100 years. The severe hazard area includes the present channel at its center. The moderate hazard area is the area between the severe hazard area and the predicted outer boundary of future channel migration. The outer boundary of channel migration considers historic channel migration patterns and rates, meander bend amplitudes, the width of a composite of all historic channel locations, and abandoned channels and potential avulsion sites. The outer edge of the moderate hazard area (which is the same as the predicted outer boundary of future channel migration) is intended to accommodate future channel migration due to bank erosion and avulsion.

Sites with high potential for avulsion are identified from maps and aerial photos and verified in the field. High-potential avulsion sites include creeks, side channels, or well-defined former channels that are flooded deeply and frequently, are directly connected to the river, and diverge from the mainstem channel in a downstream direction (Perkins 1993, 1996). The river is assumed to shift to all high-potential avulsion sites, then also migrate laterally the distances to severe and moderate hazard boundaries as described in the previous two paragraphs. Delineation of CMZs using this King County definition and method results in a corridor of variable width that is comprised of severe and moderate channel migration hazard areas and the present channel. It is intended that King County channel migration studies and associated CMZ maps be updated on an approximately 20-year interval (as recommended by Shannon and Wilson 1991).

Study methods used by King County to document channel change and measure channel migration rates are consistent with methods in the literature described in the subsection on Mapping Channel Changes, and do not depart from BAS in that regard. As described previously, the selection of a timeframe upon which to base the CMZ definition appears to be primarily a policy decision. The 1O0-year time frame, chosen in many example regulations, is similar to the available period of archival record and the time it takes to grow a geomorphic ally functional tree (NMFS 2000). To the extent that CMZ regulations are based on science, the lateral extent of King County's 1O0-year-based severe channel migration hazard area is consistent with other CMZ regulatory examples in Section 3-B.l under "Existing Regulatory Definitions of CMZ." The overall King County CMZ exceeds a 1O0-year-based delineation with inclusion of the moderate channel migration hazard area, which extends beyond the severe channel migration hazard area.

Levees and revetments as CMZ boundaries

Best Available Science, Channel Migration Zones, Draft, King County, 2/2004: Regulatory CMZ definitions from some jurisdictions state that for a levee or revetment to be considered a boundary to channel migration it must have an elevation that exceeds the 100-year flood stage or it must withstand the erosional forces of a 100-year flood (W A State Department of Ecology draft 2002, W A DNR 2001, W A State Department of Ecology 1996). The 100-year flood stage and its erosional forces are determined by scientific or engineering analyses. Selecting those levels as a standard to meet is a policy decision and so not constrained by BAS criteria.

As described by FEMA (1999), no stability analysis is done in the King County CMZ mapping method to detennine how effective levees or revetments would be in preventing channel migration. However, each existing levee and revetment is evaluated against criteria to detennine whether it should be mapped as a boundary to channel migration as part of the King County CMZ mapping method. Criteria that have been considered to date include the length and continuity of the facility, its angle relative to flood flow, the likelihood of avulsion behind the facility, its erosion history, and its likelihood of resisting erosion. The subjectivity described by FEMA (1999) in the King County method of "selecting barriers to migrating channels" may refer to the use of professional judgment by King County staff in applying these criteria.

2. Flood control

- Best Available Science, Flood Hazard Areas, King County Draft, February 2004: Traditional flood control measures include widening or deepening the channel, straightening the channel, levee construction adjacent to the channel, stream bank stabilization, and clearing living and dead vegetation in and along the river. Levees that constrict the floodplain confine flood flows to the main channel, resulting in higher water velocities and depths, both of which may be harmful to habitat and fish. Over time, the higher velocities and increased potential for erosion along levee faces have resulted in levees evolving into bank stabilization projects in addition to their original containment function (Maddock 1976). The presence of levees disconnects the active channel from its overbank areas, disallowing the periodic interaction of floodwaters and sediment that are necessary for fully-functioning floodplain. Levees also have blocked flow and fish access to important side-channel habitats used by fish for spawning and rearing. Blockages to small tributary streams entering rivers also occur due to inoperative flap gates on culverts, perched outlets and pump stations having no fish passage facilities.

Clearing rivers and streams of vegetation and large woody debris increases the capacity to convey floodwaters but may increase bank erosion (Shields and Nunnally 1984). In addition, the removal of large woody debris simplifies the physical structure of the channel and affects the ability for the stream or river to form pools, which are important salmonid habitat (Montgomery and Buffington 1993). The removal of vegetation from within streams and rivers also reduces the ability to trap and store sediment and nutrients important for aquatic life (Bilby and Ward 1991; Culp, Scrimgeour, and Townsend 1996). Gippel et al. (1992, 1996) determined that the reintroduction of large woody debris into streams lacking woody debris does not significantly decrease the flood-carrying capacity nor increase the flood frequency of the stream or river. However, the re-introduction of large woody debris into streams will result in a slight rise locally in the base flood elevation. The habitat benefit derived from large woody debris has been recognized by FEMA as a reasonable compromise for this effect on base flood elevations (FEMA 2002c.). Also, FEMA allows the local floodplain administrator to exempt those encroachments necessary for addition of enhancement elements (i.e., large woody debris) that would result in an increase in base flood elevations.

- Ecological Issues in Floodplains and Riparian Corridors, Susan Bolton and Jeff Shellberg, UW Center for Streamside Studies, 2001: Channelized rivers tend to have greater fluctuations in water temperatures, less shading from trees, reduced cover for fish, less diverse aquatic habitats, and less organic matter input. These impacts result from traditional flood control techniques. Contemporary floodplain management measures use alternative design and construction practices to more fully mitigate impacts and enhance aquatic and riparian habitats.

- Best Available Science, Flood Hazard Areas, King County Draft, February 2004: Past practices for flood control involved containing the flow of water within a defined channel by constructing berms and levees along natural riverbanks and creating hard surfaces using erosion resistant materials, such as concrete slabs and large angular rock. Contemporary science of floodplain management strives to mimic natural floodplains and their flow regimes. Today's floodplain management allows floodwaters to use as much of the natural floodplain as possible during storm events so that the natural processes of river systems can occur largely unimpeded.

  Impacts from flood control projects can be minimized by first emulating nature in the design approach. Projects should revegetate or maintain vegetation and have minimal channel alterations to natural channels. Rock riprap, for erosion protection, should be used judiciously and two-stage channels should be considered when addressing control of flood elevations. Channel morphologic features, such as original meander bends, small side-channels and rifflepool complexity, should be preserved. Alternating construction on opposite sides of stream or riverbanks can minimize disturbances during construction.

In addition to preserving native vegetation, newly planted native vegetation should be installed to create habitat complexity. The re-establishment of a more naturally vegetated floodplain area can occur by creating a vegetated berm as part of a two-stage channel morphology and also by setting back a levee to allow for natural revegetation along the active channel. In-channel placement of large woody debris and the use of bioengineering techniques on stream and riverbanks can address erosion protection while increasing aquatic habitat and riparian habitat diversity. Complete or partial removal of levees and revetments can more readily provide for the restoration of floodplains and channel morphology.

Watersheds experiencing urban growth, or changes in physical conditions caused by erosion, can benefit from the use of future conditions hydrology to estimate where the boundaries of the floodplain will be after full build-out of the basin (FEMA 2001b.). Depicting a future conditions floodplain would serve to alert the public to potential, future hazards and also further the understanding of potential effects to the natural habitat and aquatic resources

- Larson and Plasencia, No Adverse Impact: A New Direction In Floodplain Management Policy, 2001: Current-day strategies in floodplain management are focused on "no net impact. A "no adverse impact floodplain" is one in which the floodplain action of one property owner or community does not adversely affect the flood risks for other properties or communities as measured by increased flood stages, increased flood velocity, increased flows, or increased potential for erosion and sedimentation, unless the impact is mitigated. Regulatory approaches to remedy the effects of floodplain alterations include compensating for lost storage volume and requiring no increase in flood elevations. Regulatory requirements serve to prevent the risk to health and human safety by protecting current floodplain conditions. They also preserve existing aquatic and riparian habitat resources.

  These types of regulatory remedies are most effective in reducing flood losses and in protecting and preserving the natural resources of the river and stream corridor when combined with structural solutions in a comprehensive flood hazard reduction plan. Structural solutions may include setting back the location of levees or re-connecting side-channels, which re-establishes flood storage areas and restores vital aquatic and riparian areas. Other actions, such as the relocation of flood-prone buildings from the floodplain, reclaim lost floodplain areas while permanently removing the risk to human safety (Conrad et al. 1998).

3. Floodplain Alteration

- Carlton et al. 1989; DeVries 1980: Floodplain encroachments increase flood elevations and flow velocities, change flood flow patterns and increase the area of flood inundation. Encroachments into the floodplain also result in a loss of storage volume of floodwaters which in turn increases the downstream flood peaks that then exacerbates flooding and erosion. By minimizing human intervention, the dynamic processes of rivers and streams and their floodplains can more naturally occur. Limitations on placement of fill material and other floodplain alterations including removal of native vegetation, can protect and maintain the natural characteristics and functions of the floodplain, as well as reduce, the impact to human life and loss of property.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW Center for Streamside Studies, 2001: Past flood control activities and land development have altered stream floodplains. These altered floodplains do not provide the same habitat benefits as a natural floodplain. Floodplain alterations are typically caused by streambank hardening intended to provide erosion protection and flow confinement through the placement of fill materials (e.g., roadway and levee construction), and channel excavation (e.g., gravel bar scalping and dredging). <u>These alterations can result in an increase in water velocities that may exacerbate channel scour, a reduction of floodwater storage that would increase peak flood flows, and the loss of the physical, biological and chemical connectivity between the river or stream and its riparian vegetation, side channels, and floodplain wetlands</u>.

- USDA 1998 Stream Corridor Restoration: Principles, Processes, and Practices. National Engineering Handbook 210- VI; Poff et al., The Natural Flow Regime -A Paradigm For River Conservation And Restoration, 1997: <u>If the storage capacity of floodplains is retained, downstream peak flood volumes and flood velocities and associated velocities will be reduced. Protecting, restoring, and managing floodplain areas provides for a more natural flow regime by minimizing floodplain modification and limiting development within floodplains</u>. This not only reduces the potential for flood damages but also provides an improved condition for the fish and wildlife species dependent upon viable riverine corridors.
- Best Available Science, Flood Hazard Areas, King County Draft, February 2004: Zero-Rise in Base Flood Elevation**:** No rise is allowed in the base flood elevation in the zero-rise floodway except when amendments to FEMA maps are adopted and all the affected property owners agree to the rise. There is a presumption in the zero-rise floodway that there is no increase in base flood elevation for new residential structures that meet specific standards, but only if post and piling construction techniques are used. In the FEMA floodway, development cannot increase the base flood elevation. Substantial improvements of existing structures in the FEMA floodway is assumed to not produce an increase in base flood elevation only if the existing footprint is not increased.

  The application of the zero-rise standard usually results in a wider computed floodway than the NFIP standard, which means less development could occur in the floodplain (Federal Emergency Management Agency 200Ia.). With less development occurring in the floodplain, there is a lesser impact to aquatic habitats and more habitat is preserved. In addition, fewer people and less property are placed at risk from flooding.

4. Habitat value of floodplains/channel migration zones.

- Best Available Science, Flood Hazard Areas, King County Draft, February 2004: The relative importance of floodplains to stream ecology increases with the regularity, duration, and extent of inundation. That depends on the hydrology of the stream and the degree to which the valley is constrained and/or the stream is incised. Relatively small drainage areas and steep hillsides limit the duration and extent of flooding. Large streams flowing across unconfined valley floors generally have extensive complex floodplains that remain flooded for long durations. (Sedell et al.1989).

  Flooding is an essential ecological interaction between the river channel and its associated floodplain (Junk et al. 1989, Benke et al., Tockner et al.). Flooding creates, maintains, modifies and destroys physical floodplain features such as bars, levees, swales, oxbows, backwaters, and side channels. Flowing water sorts sediments creating floodplain soils that are stratified both vertically and horizontally. And floodwaters carry sediment, organic material, nutrients, and biota to and from the floodplain. The varied floodplain topography creates a gradient of depth and duration of flooding. Every plant has an optimal position along this hydraulic gradient. The hydraulic gradient, coupled with variations in soil structure, vegetation, and topography create a complex and dynamic network of habitats throughout the floodplain. (Junk et al. 1989).

  Floodplains alternate between aquatic and terrestrial environments and the change can be stressful, or even detrimental, to the affected biota. The biological response of biota to the dynamic floodplain environment varies with the regularity, frequency, and duration of inundation as well as the rate of change. Unpredictable flood pulses generally impede the adaptation of organisms and are counter productive for many of them. Conversely, a regular pulse allows organisms to develop adaptations and strategies for efficient utilization of habitats and resources within the aquatic-terrestrial transition zone, rather than depend solely on permanent water bodies or permanent terrestrial habitats… Regular pulsing coupled with habitat diversity favors high diversity of aquatic and terrestrial plants and animals, despite considerable stress that results from the change between terrestrial and aquatic phases. (Junk et al. 1989).

  Depending on the type, extent, and density of riparian vegetation, riparian areas may retain water during storm events and release it slowly over time and stabilize stream banks. They have the additional benefits of reducing the depth of in-stream flow during high- flow events, thereby lowering the sediment carrying capacity of the stream (and, in turn, bed and bank erosion) and the buoyancy of woody material.

- Stream Habitat Restoration Guidelines, WDFW, Draft *(not necessarily best available science),* 2003: Streams and floodplains have historically been subject to periodic catastrophic disturbances. Disturbance in the stream or watershed can pose an environmental risk, but it also serves as a mechanism for creating and maintaining aquatic and floodplain/riparian habitat (Benda et al. 1998). The diversity of riparian vegetation and floodplain waterbodies (e.g., periodically isolated side channels, ponds, and wetlands) is directly related to the frequency and magnitude of disturbance events that reset these communities toearlier successional stages (Ward et al. 2001, Cowx and Welcomme 1998, Vannote et al. 1980). These plant communities and waterbodies would otherwise continue on a trajectory towards terrestrialization; abandoned meander bends eventually becoming merely a wet depression on the floodplain. Disturbance can cause abrupt changes in habitat conditions, altering hydrologic and nutrient cycling processes; reconfiguring the stream channel; creating and filling pools, oxbows, side channels, and off-channel ponds; and redistributing sediment and organic matter so as to create and erode islands, bars, streambanks, and floodplains. The temporal and spatial variability of disturbance creates a mosaic of habitats representing various serial stages of succession and recovery across a watershed in any given year (Ward et al. 2001, Benda et al. 1998, Reeves et al. 1995).

- The Critical Areas Assistance Handbook. Department of Community, Trade and Economic Development, 11/03 *(not necessarily best available science*): Floodplain and stream channel migration play an important role in the formation of productive aquatic habitats. Historic losses to salmon habitat have occurred as a result of development encroaching into floodplains. In addition to minimizing adverse effects to human health, safety, and infrastructure, floodplains are ideal locations for salmon habitat restoration. While floodplains are potentially hazardous areas for development due to flooding and erosion, fish and wildlife depend on the habitat created when a river is allowed to migrate and overflow its banks. Natural floodplains, channel migration zones, and associated riparian wetlands are critical components of a properly functioning aquatic ecosystem. Frequently flooded areas are the interface between upland and the river channel. They function as riparian habitat because they influence and are influenced by the river... Biofiltration, maintenance of base flows, aquifer recharge, introduction of woody debris to rivers, and food chain support are important functions of the floodplain. These all work together to function as important habitat for fish and wildlife. An important component of habitat function in these systems particularly where they have not been degraded is preservation of connectivity and the associated fluvial dynamics and connectivity gradients in the floodplain, which is essential for diversity and species richness in these critical areas.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW, Center for Streamside Studies, July 2001, pg. 14. Many of the biological effects that occur as a result of channelization activities are in response to changes in the physical environment. Streamflow, stream velocity, channel morphology, vegetation and channel substrate are all affected by channel activities. The physical nature of stream channels reflects a continuous readjustment of the interrelated variables of discharge, slope, channel width and depth, flow velocity, channel roughness and sediment characteristics (Brookes 1988). These parameters form the habitat that plants and animals need. Typically, changes due to human activities in the channel migration zone result in a reduction in habitat diversity, which affects the numbers and kinds of animals that can be sustained (Schneberger and Funk 1971; Hahn 1982; Simpson et al. 1982). As the physical habitat changes, stresses are placed on individual plants and animals. These stresses, depending on the tolerance of the species and individual, may limit growth, abundance, reproduction and survival (Lynch et al. 1977). Biologically important parameters that change following channel activities include water temperature, turbidity, flow velocity, variable water depths, hydrologic regime, a decrease or change in vegetation, changes in storage of organic matter and sediment, and changes in the size and stability of channel substrate (Hahn 1982). These changes can decrease habitat connectivity and the exchange of energy and matter between habitats. The direction of change varies by site and circumstance. Because of the complex changes in physical, chemical and biologic properties that follow from channelization activities, it is not feasible to address the biological effects as they relate to individual physical changes. One needs to look at the whole system to understand the changes in the biology. *(pg. 14).*

- Best Available Science, Channel Migration Zones, 10/2003 Draft, King County: A migrating channel will sweep across and rework its alluvial floodplain, entraining sediment, organic material, and wood in the process. Within the corridor affected by channel migration, water and entrained materials are moved by fluxes between river and floodplain. Materials are routed from headwaters to mouth over time scales that vary from days to centuries. Because of the dynamic nature of such fluxes and routings, channel migration poses a hazard to public safety. But in the context of natural resource protection the dynamic fluxes and routings caused by channel migration benefit the habitat of many species of fish and wildlife, especially salmon. Increased channel complexity benefit salmonid spawning and rearing habitat. Bank erosion from both gradual and abrupt channel migration recruits spawning gravel from alluvial riverbanks. With bank erosion, trees often topple into the channel and become large woody debris, creating high quality, diverse habitat for rearing, spawning, migration and refuge purposes. The flux of gravel and wood to the river due to channel migration is an example of the connectivity between a river and its floodplain.

- Stream-Riparian Ecosystems, A Review of Best Available Science. May, 2000, pg 57: Floodplain connectivity is critical to a properly functioning stream-riparian ecosystem. This means that the active channel migration zone (CMZ) and floodplain must be included in the riparian management zone. This is the area where are typically the most conflicts with development and land-use. Both from an ecological and public safety perspective, development should excluded from the floodplain and CMZ.

- White, RJ. Resisted lateral scour in streams –Its special importance to salmodid habitat and management, 1991: Stream channel migration and shoreline erosion are key erosional processes that are critical for creating and sustaining healthy, diverse habitats. In large part, they are ecological processes driven by disturbance regimes, such as floods and cycles of freezing and thawing which periodically deliver large volumes of water, sediment, and large woody debris. They contribute fine sediments, spawning gravel, woody debris and nutrients that sustain and invigorate existing habitats, create new habitats, such as side channels and oxbow ponds, where none previously existed, or fill in old, less productive habitats. In less dramatic ways, these processes also result in lateral scouring along banks and shorelines creating pools and riffles in stream channels and diverse habitats along marine, estuarine and lake shorelines.

- Best Available Science, Channel Migration Zones, 10/2003 Draft, King County: Development in floodplains and riparian corridors affects aquatic areas when it removes or modifies native forest vegetation, or when it alters rates and patterns of bank and channel erosion, migration, surface, and groundwater flow. Riparian areas provide a variety of functions including shade, temperature control, water purification, woody debris recruitment, channel, bank and beach erosion, sediment delivery, and terrestrial-based food supply (Gregory et al. 1991; Naiman 1998; Spence et al.1996). These are potentially affected when riparian development occurs (Waters 1995; Stewart et al. 2001; Lee et al. 2001). Bolton and Shellberg (2001) provide an extensive discussion of the effects of riparian and floodplain development on aquatic habitats and species. Effects include: (1) reduction in amount and complexity of habitat; (2) increased scouring of channels due to channel and floodplain confinement; (3) reduction or loss of channel migration, vegetation, sediment supply; and (4) woody debris recruitment.

- Management Recommendations for Washington’s Priority Habitats-Riparian, 1997, pg 90: Because floodplains strongly influence the aquatic system and support a combination of riparian and upland vegetation used by wildlife, their entire extent is included in the RHA. Floodplains also assist in the control of flooding downstream. The entire floodplain accumulates tremendous quantities of organic matter. During floods, this organic matter along with dissolved nutrients is flushed into the river, supplying fish and aquatic invertebrates with a rich source of food that enhances fish production (Junk et al. 1989, Gregory and Ashkenas 1990).

- Best Available Science, Flood Hazard Areas, 10/2003 Draft, King County: A natural river floodplain is a highly productive, dynamic environment that provides the proper structure, processes and functions for sustaining a viable ecosystem. During flood events, large volumes of water and debris move downstream. By definition, floodwaters are those waters that, at some interval, overtop the river or stream bank and flow onto the floodplain and also along smaller-sized side-channels. Flooding therefore acts to provide connectivity between the river or stream, its riparian soils, vegetation, and the hyporheic and perirheic zones. Floodwaters transport sediments and nutrients that replenish floodplain lands. Floodwaters move and distribute large woody debris that builds structure and creates the physical characteristics of the main channel and side-channels.
- Ecological Issues in Floodplains and Riparian Corridors, Susan Bolton and Jeff Shellberg, UW Center for Streamside Studies, 2001, pg. 30: In many natural systems in the Pacific Northwest, the hyporheic zone functions as a source of nutrients for relatively nutrient poor surface waters. (The hyporheic zone is that area between the stream channel and the stream banks that is saturated by a mixture of stream channel water and groundwater. The perirheic zone is a complex mixing zone of surface water and hyporheic water.) However, in degraded fluvial systems in urban and agricultural areas of the Pacific Northwest and elsewhere where anthropogenic nutrient loading can greatly exceed background conditions, the hyporheic zone can act as a sink for nutrients entering the hyporheic zone along many different paths. In many heavily developed watersheds, intact riparian zones, floodplains, perirheic zones and hyporheic zone have the potential to significantly mitigate anthropogenic disturbances such as increased nutrient loading, altered discharge and sediment transport regimes. However, channelization often is associated with human development, masking any potential benefits of a functional riparian corridor, hyporheic corridor and channel migration zone. Therefore, the preservation of intact hyporheic corridors and floodplain connectivity is key to the promotion of functional fluvial systems. In currently degraded areas, the potential for reconnecting floodplain ecosystems and restoring hyporheic zones and corridors exists and is a growing sub-field in river restoration.

- Best Available Science, Flood Hazard Areas, King County Draft, February 2004Research is needed to increase the understanding between the channel forning floods and aquatic and riparian habitats. Today's floodplain regulations are for the single-purpose of protecting human safety and property and are based on the 100-year existing condition flood event. If floodplains were specifically delineated for protection of fish and riparian habitat, the protected land area would be considerably larger than proposed aquatic areas buffers. The result would have significant impact on personal and public property land use but ultimately would significantly reduce the risk to people and property.

- Floodplain management, Higher Regulatory Standards, FEMA Region 10, 2002: Floodplain connectivity with streams and rivers is recognized as a necessary habitat element in order for wild salmon to continue to exist. As stated in Portland Metro's Streamside CPR, "the interaction of the channel with its floodplain tends to create unique biological communities, cutoff oxbows, sandbars, backwaters, undercut banks, floodplain pools and extensive high water tables - much of the aquatic productivity occurs in the floodplain."

Natural resource agencies at every level of government have consistently emphasized the contributions of floodplains to healthy fish habitat. With the recent listing of several salmonid species as threatened or endangered under the Endangered Species Act (ESA) in large areas of the Northwest, the need to protect and restore aquatic habitat has taken on a new urgency. Unfortunately, many communities continue to rely on the minimum requirements of the National Flood Insurance Program (NFIP) to regulate activities in the floodplain. Others, however, have realized that the purely economic flood loss reduction objectives of the NFIP may not provide an adequate level of stream habitat protection.What is clear is that sound stewardship of floodplains can be an extremely important factor in protecting habitat for fish, and that an enhanced flood damage reduction ordinance which incorporates the measures to protect riparian habitat listed below can be of great value.

5. Compensatory Storage:

- Best Available Science, Flood Hazard Areas, King County Draft, February 2004: The best available science for floodplain management recognizes that any filling of the floodplain that takes away flood storage must be compensated by removing an equal amount of fill. Compensatory storage should be provide and also be hydraulically connected to the river or stream. This ensures that fish are not stranded in pooled areas that were dug out for compensatory storage. There is little or no information specifically on the impact of compensatory storage on aquatic habitat or species. However, compensatory storage could result in habitat isolation, which may result in fish stranding (Bolton and Shellberg 2001). The NFIP does not require compensatory storage.

6. Impervious surfaces/forest cover.

- Forest Cover, Impervious-Surface Area, And The Mitigation Of Urbanization Impacts In King County, Washington, Derek B. Booth, Ph.D., P.E. 2000: Reports on the hydrological impact of urbanization and deforestation on urban stream systems. Findings, which are listed on page 16, include, in part:

  -Land development removes forest cover and disturbs soil, which in turn significantly alters the hydrology of stream basins, leading to stream channel instability.
  -Stormwater detention ponds do not effectively mitigate the hydrological impact of land development. Other measures, such as riparian buffer retention, do not fully mitigate the hydrologic impact of intense urban development.
  -Loss of forest cover in rural areas adversely impacts watershed hydrology as much as associated increases in impervious area.
  -The threshold at 10% effective impervious area and 65% forest cover “marked an observed transition to severely degraded stream conditions.”
  -“Not every watershed responds equally to a given level of human disturbance, but some degree of measurable resource degradation can be seen at virtually any level of urban development.”

  Land development that eliminates hydrologically mature forest cover and undisturbed soil can result in significant changes to urban stream hydrology and, in turn, to the physical stability of stream channels. Land development modifies streamflow patterns ; even with stormwater detention ponds, it can produce seasonal and stormflow patterns that are substantially different from those to which native biota have adapted. Although factors other than hydrologic change can undoubtedly affect the magnitude of urban impacts, the breadth of the existing data suggest that improvements in these other factors (e.g., riparian buffers) cannot fully mitigate the hydrologic consequences of overly intense urban development. Under typical rural land uses, the magnitude of observed forest-cover losses affects watershed hydrology as much as or more than associated increases in impervious area.

Twenty years of empirical data display a good correlation between readily observed damage to channels and modeled changes in hydrology that correspond to loss of about one-third of the forest cover in a “typical” western Washington watershed. A similar degree of observed damage also correlates to a level of watershed effective imperviousness of about ten percent. Field observations and hydrologic modeling showed that the watershed plans of the early- to mid-1990’s could only hope to meet plan-stipulated goals for resource protection by imposing clearing and impervious-area restrictions. The most commonly chosen thresholds, 10 % effective impervious area and 65 % forest cover, marked an observed transition to severely degraded stream conditions.

Of the hydrologic elements relevant to urbanization, the most important is storm runoff, that part of the rainfall that reaches a stream channel quickly. ..if the precipitation falls on the soil surface more rapidly than the soil can absorb it, causing the excess precipitation to run over the surface of the land. Water moves very slowly off the hillslopes, and only those parts of the basin near the stream itself will contribute to the storm runoff. As a storm continues, changes occur in the flow patterns, runoff quantities, and subsequent stream flow… These changes are due to a rapid reduction in soil infiltration capacity as the ground first gets wet. The change typically occurs within the first hour after the onset of a storm, with the infiltration capacity then remaining constant (e.g., Strahler, 1975). Under the subsurface flow regime, this change is unimportant, as the soil always retains adequate infiltration ability to absorb water as rapidly as the rain can fall. Instead, a different process causes a change in runoff quantity. Water tables in the soil will rise as water is added to the subsurface. If those water tables lie at or near the surface, their progressive rise expands the area of saturated ground in the drainage basin. In these saturated areas, new precipitation cannot infiltrate because the soil has no space to absorb more rainfall. …Therefore, the total area of saturated ground, and thus the area where overland flow will occur, expands as the water table rises. This expansion occurs over a period of days, and so the part of a drainage basin that is contributing rapid storm runoff to the channel steadily increases during the course of a single storm. Areas of saturated ground also tend to expand through an entire storm season, making any changes in stream flow more intense for similar-sized storms occurring later in the rainy periods (Hewlett and Hibbert, 1967).

Modifications of the land surface during urbanization produce changes in both the magnitude and the type of runoff processes. In the Pacific Northwest, the fundamental hydrologic effect of urban development is the loss of water storage in the soil column. This may occur because the soil is compacted or stripped during the course of development, or because impervious surfaces convert what was once subsurface runoff to Horton overland flow. In either situation, the precipitation over a small watershed reaches the stream channel with a typical delay of just a few minutes, instead of what had been a lag of hours, days, or even weeks. The result is a dramatically changed pattern of flows in the downstream channel, with the largest flood peaks doubled or more and more frequent storm discharges increased by as much as ten-fold (Figure 2).

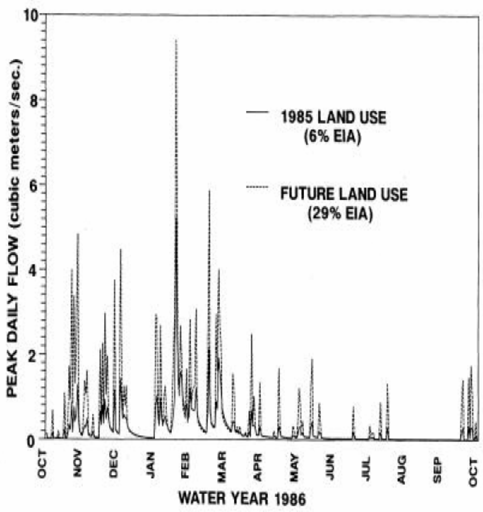

Figure 2. One year's modeled discharges for the 14-km^2 Soosette Creek watershed in south-central King County (King County, 1990a). Two land-use scenarios are modeled: the first, under existing 1985 land use, shows a typical low-development pattern of large wintertime peaks, and low and relatively constant discharge between mid-spring and early fall. The second, presuming full build-out under the 1985 zoning for the area, results in a final effective impervious-area coverage ("EIA") of 29 percent and dramatic increases in both winter and (especially) summer storm flows (from Booth, 1990).

The first recognized hydrologic consequences of urbanization were those associated with peak flow increases (i.e., "more flooding"). Careful analysis, culminating in a synthesis of many separate studies (Hollis, 1975), showed how the dual factors of percent impervious and percent of a watershed in storm sewers increased the peak discharges of floods (Figure 3; Hollis's "Figure 2"). Large, infrequent floods were increased less than smaller, more common events; in general, Hollis found peak-flow increases of two- to three-fold are common for the moderate-sized floods in moderately urbanized watersheds. These general results have been replicated in both empirical and modeling studies, on many dozens of watersheds throughout the United States and in the Pacific Northwest.

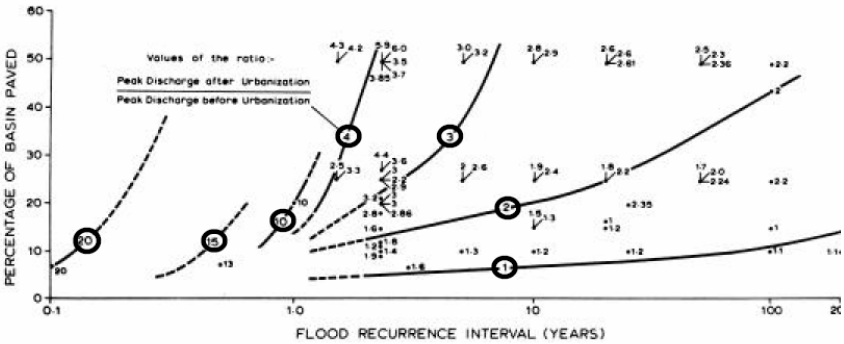

Fig. 2. Effect of urbanization on flood peaks. (Data taken from Table 1.)

Figure 3. Relationship between watershed imperviousness (vertical axis) and increases in peak flows for floods of various recurrence intervals. At the graph's extremes, the line labeled "1" marks the limit of observed flow increases; those labeled "15" and "20," marking very large increases in very frequent flows, are based on minimal data (from Hollis, 1975)

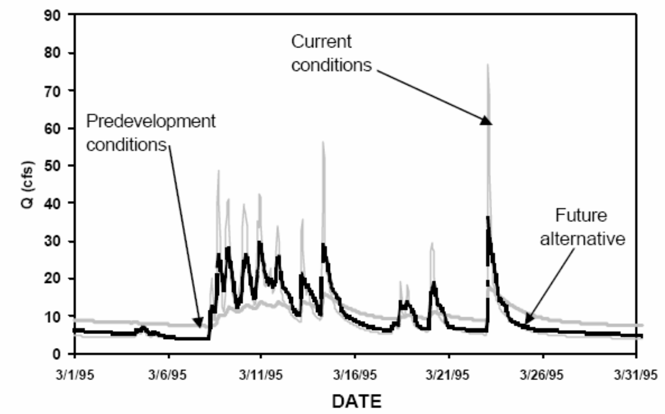

Figure 4b. One month's hydrographs for Des Moines Creek: current flows, predevelopment (i.e. forested) flows, and those under anticipated future conditions. Note that although the flow-duration curves (Figure 4a) suggest that the future alternative is mid-way between current and predevelopment conditions, the future hydrograph shows flashy discharge and low base flows much more like current conditions than those of predevelopment time.

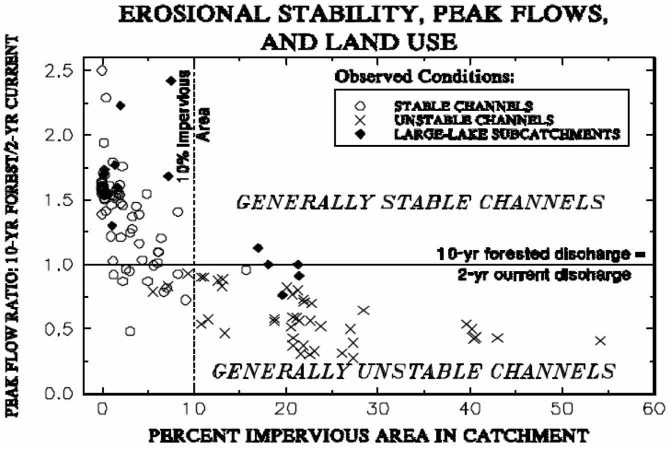

Figure 9. Observed stable ("O") and unstable ("X") channels, plotted by percent effective impervious area (EIA) in the upstream watershed (horizontal scale) and ratio of modeled 10-year forested and 2-year current (i.e. urbanized) discharges (vertical scale). "Stable channels" consistently meet the apparent thresholds of either {EIA ≤ 10 percent} or {$Q_{2\text{-cur}} \le Q_{10\text{-for}}$}, except for the few catchments containing large lakes.

Although these data compose a robust set of observations, spanning a wide variety of streams with remarkably consistent results, they also carry two limitations. First, the absence of observed instability does not guarantee an absence of any effects. The converse, however, is more likely true: if there is instability, other conditions (particularly biological) are almost certainly degraded as well. The second limitation is more vexing: these data were collected on watersheds without much, if any, effective stormwater detention. Had larger and more effective ponds been present, would the observed impacts been reduced? Such a possibility certainly exists, but there are as yet no equivalent data from a "well-detained" watershed to demonstrate that success. Insofar as detention ponds can mitigate for only some of the aspects of urban-altered hydrology (see above), complete success is quite unlikely.

The Issaquah Creek Basin Plan developed model predictions of post development runoff conditions and their likely consequences on channel erosion and bank stability. These initial assessments, presuming basin wide application of the mitigation tools that were then "accepted practice" (i.e. exemption of rural-zoned developments from detention requirements, and SCSbased hydrologic designs for the rest), produced results that were inconsistent with the goals of the basin plan—to protect aquatic habitat and to resolve existing and potential future flooding problems. The empirical criterion for channel instability (Q2-cur > Q10-for) was exceeded pervasively throughout the watershed under most if not all future development scenarios. As a consequence of these results, the Issaquah plan evaluated a variety of alternative rural development scenarios. The analyses found that with **65-percent forest retention** in a nominal 5-acre zone (i.e. 20 houses per 100 acres, clustered on 35 percent of the land area), the criterion of keeping the 2-year developed discharge below the 10-year forested discharge could be just met **on till soils** *(common in northern Thurston County)*. Greater amounts of cleared land resulted in 2-year developed discharges that exceeded 10-year forested discharges, even though the amount of effective impervious area was well under 10 percent. The analysis noted that development on **outwash soils** *(common in southern Thurston County)* failed the criterion at virtually any level of forest retention, because so little runoff occurs there naturally that almost any amount of imperviousness produces proportionally large peak-flow increases. The analysis also found that with additional forest retention (on till soils), additional density could by accommodated on the remaining developed land, and it observed that the retention of forest cover was far more significant in determining discharge increases at rural densities than typical increases in impervious area (Figure 10).

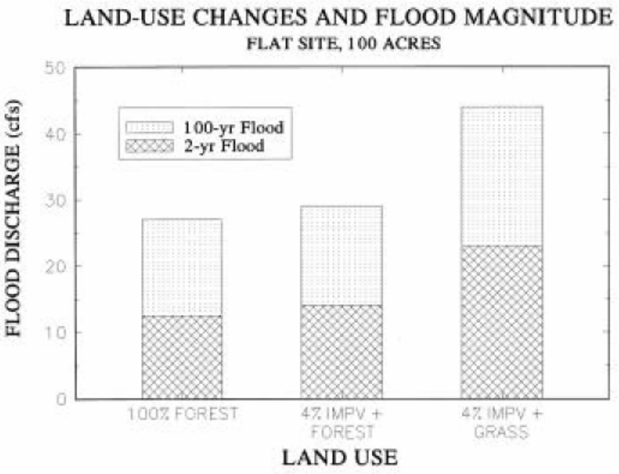

Figure 10. HSPF-modeled increases in 2-year and 100-year discharges that result from forest conversion on moderately sloping till soils. Four percent (effective) imperviousness, a typical value for 5-acre residential densities, shows particularly significant hydrologic changes only when accompanied by clearing on the remaining 96 percent of the watershed.

In the realm of physical channel conditions, the data collected from field observations have consistently shown remarkably clear trends in aquatic-system degradation. In western Washington, approximately 10 percent effective impervious area in a watershed typically yields demonstrable degradation, some aspects of which are surely irreversible. Hydrological analyses suggest that **forest cover is more important than impervious-area percentages**, at least at rural densities. Even if both are critical to protect stream conditions, current land-use practices suggest that mandating retention of forest cover is the more pressing regulatory need. Watersheds with less than 10 percent EIA and less than 65 percent forest cover are common (“cleared rural”); in contrast, none have more than 65 percent forest cover and also more than 10 percent EIA (“forested urban”) (Figure 12).

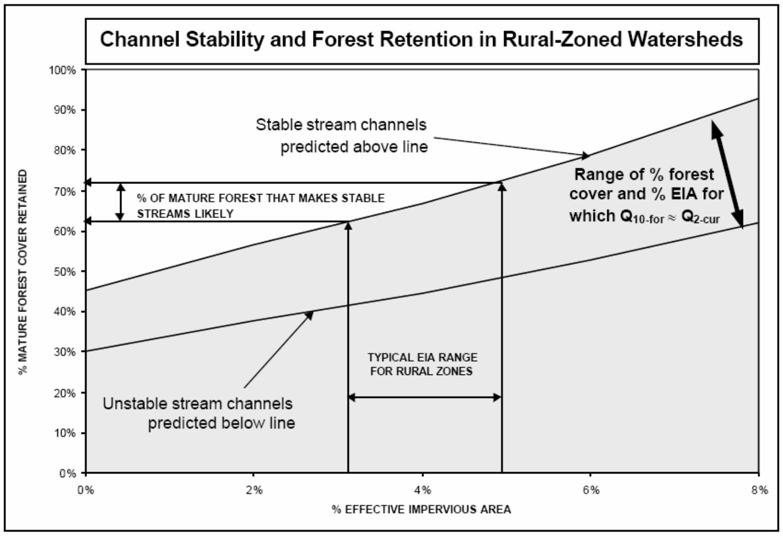

Figure 11. Conditions of forest cover and impervious area in an HSPF-modeled watershed with moderate slopes and till soils relative to the channel-stability criterion $Q_{2\text{-cur}} = Q_{10\text{-for}}$. The range of forest-retention values reflects uncertainty in the hydrologic parameters; the range of effective impervious areas reflects variation in rural land cover conditions (D. Hartley, writ. comm., 2000).

The apparent correlations between stream stability and both impervious-area and forest-cover percentages present a vexing quandary for watershed managers. On the one hand, these correlations point to a tangible, defensible criteria for achieving a specific management objective, namely “stable stream channels.” On the other hand, this objective, however worthy, still allows the possibility of serious and significant aquatic-system degradation—and as development is allowed to approach these clearing and imperviousness criteria, degradation is virtually guaranteed. The thresholds implied by these data are simply the “wrong” type on which to base genuine resource protection. They do not separate a condition of “no impact” from that of “some impact;” instead, they separate the condition of “some impact” from that of “gross and easily perceived impact.” Hydrologically and biologically, there are no truly negligible amounts of clearing or watershed imperviousness, even though our perception of, and our tolerance for, many of the associated changes in downstream channels appear to undergo a relatively abrupt transition. Almost every increment of cleared land, and of constructed pavement, is likely to result in some degree of resource degradation of loss.

- Results from Forest Hydrology Studies: Is There a Lesson for Urban Planners? S. Bolton and A. Watts: Reports on data from studies on the impact on streams of traditional timber harvest and applies them to forest cover removal in urban settings. Concludes that “changes in urban areas are analogous to those due to harvest but are more severe and more long lasting. To minimize excess storm flow generation in streams, it is crucial to maximize natural areas, provide for infiltration opportunity, and minimize the generation of overland flow.”

  “Years of hydrologic research have not resulted in an entirely consistent set of results for predicted impacts of forest harvest on streamflow. However, the majority of studies show increases in peak stream flows and volumes in basins with timber harvest. The increase in flow is most noticeable in small basins from average storm events. The period of record, climate variability and harvesting histories make it very difficult to draw strong conclusions about the effect of harvesting on low frequency, high magnitude storms, especially in large basins. Many urban developments take place in relatively small drainage basin so the analogy between forest studies and expected changes due to urbanization is appropriate.

In small basins, hillslope processes dominate storm runoff processes. Critical hill slope processes are infiltration, evapotranspiration, and soil moisture at the beginning of the storm. Timber harvest impacts three main components of the hydrologic cycle.

> (l) Removal of the trees increases snow accumulation and decreases evapotranspiration which combine to increase soil moisture levels. Higher soil moisture leads to saturated subsurface/surface flow which increases the amount of water reaching the channel quickly.
>
> (2) Removal of large woody debris from the stream channels and the lack of large, older trees for recruitment to the channel decreases pool formation (pond storage) and decreases flow resistance, which means less water can be stored in the channel and water moves through the channel faster.
>
> (3) Road building to access the timber harvest sites compacts the soil in the road pathway which decreases infiltration and increases surface runoff. The cut banks of the roads intercept subsurface flow and turn it into surface flow. The road cut also decreases the soil available for moisture storage. The ditches and culverts along the roads create new channels for overland flow. The effect of roads is to increase the drainage density and hence water delivery to the streams. Water in channels travels much faster than does water flowing through the soil.

Each of these three activities push the hydrologic cycle towards faster runoff and greater storm runoff. The forest studies were designed to evaluate changes in stream flows due to total or partial timber harvest. Most studies show that clear cutting in small basins increases storm runoff, especially early fall storm runoffs and winter storm runoff.

Recovery does occur from the three impacts mentioned above when the land is kept in forest usage and trees are replanted. Evapotranspiration recovers in about 5 years as new vegetation pushes roots into the deeper soil layers. Canopy interception may take decades to recover as the trees need go through several stages to form a complex canopy structure. Large woody debris, unless placed by humans, takes at least 60-90 years to recover because trees have to grow, become large and fall over. Roads, even in forests, tend to be relatively permanent changes in the systems. Data are inconclusive as to whether recent attempts at road abandonment and removal are effective. History has shown that the old railroad grades have been colonized by alders on the west side of the Cascades but it does take decades for this to occur.

Table I shows differences in the various processes that affect the water balance in different vegetation/climate zones. Annual increases in water yield are important and harvest has been used to increase streamflow. Most planning is done for single precipitation events so it is necessary to see where water is stored in the system, how much water can be stored in different compartments and how long it is stored.

Table 1. Average Annual Water Balance (in inches) for West Coast Forests and Potential Increase in Yield due to Harvesting.

Forest Type	Precipitation	Streamflow	Evapotranspiration	Potential Water Yield Increase
Douglas fir/ hemlock/redwood	75	45	30	15.0
Mixed conifers	44	22	22	4.5
True fir	60	36	24	6.0

The hydrologic cycle can be viewed as a system of six compartments with fluxes carrying mass and energy among the compartments.

. energy sphere (the sun)
. atmosphere (wind and precipitation)
. hydrosphere (streams, lakes and ground water)
. biosphere (vegetation)
. terra sphere (soil)
. cultural sphere (human activities)

The sun is the driving force behind the hydrologic cycle and provides the energy that melts snow, condenses water vapor, evaporates water, and drives weather systems. It also drives photosynthesis and respiration in plants that lead to water uptake from the soil by plants... Water is stored on and in vegetation as interception or tissue water, respectively... Water moves through the soil by gravity except when it is responding to tension gradients exerted by plants and soil particles. Humans have little control over the sun or the weather, but we do alter storage in the hydrosphere, soil, and vegetation.

Water can be stored temporarily in soil depressions in response to a precipitation or runoff event. This water is ultimately either infiltrated or evaporated. Soil detention storage is soil water that drains via gravity and is not held in tension by soil particles. It is seldom held more than 24 hours. Detention storage is the difference in soil water between saturation and field capacity. Soil retention storage is water held by bonds between water molecules and soil particles and can only be extracted by plant roots. Some water is held so tightly by soil particles that it cannot be extracted by plant roots. Retention storage is the difference between field capacity and wilting point. Table 2 shows storage values for two common soil types in Puget Sound. Table 3 uses data from the literature to estimate the amount of water storage in different compartments. Evapotranspiration ranges from 0 to 0.2 inches per day depending on soil moisture availability, weather conditions and photosynthesis rates.

Table 2. Potential Water Storage in Soil (inches per foot of soil depth)

Soil moisture level

Saturation (S)	6.3	5.2
Field capacity (F)	4.7	2.4
Wilting point (W)	2.7	1.4
Detention storage = S - F	1.6	2.8
Retention storage = F - W	2.0	1.0
Total potential soil storage	3.6	3.8

Table 3. How much water can a forest hold?

Douglas fir	1 inch
Rain Interception (canopy)	0.01- 0.7 inch
Snow Interception (canopy)	0.01- 1 inch
Interception (litter)	0.02- 0.44 inches
Soil detention storage	sandy loam 1.6- silty clay loam 2.8 (in/ft of soil)
Soil retention storage	sandy loam 2.0—silty clay loam 1.0 (in/ft of soil)

Many Pacific Northwest precipitation events are low intensity and low volume. Intact forests with thick canopies and deep litter layers can prevent many precipitation events from reaching the soil at all. Water that is stored as canopy interception by the litter layer either evaporates and is lost from the storm event or it drips and moves slowly to the soil and infiltrates. Very little precipitation ends up as overland flow in mature, undisturbed forests. Overland flow occurs on compacted soil areas like trails and roads, in places where leaves may bind and form a sheet for water to run over, and in areas where the soil is saturated and cannot store any more water.

Urbanization follows the same pattern as forest harvest in its effects: tree removal, channel cleaning and straightening, and road building. However, the changes tend to be permanent. Soil is compacted or graded and removed, thus reducing soil storage. Vegetation is cleared and replaced with house, lawns, and parking lots. Roads are paved and cover vast amounts of the original soil surface. In periods of low precipitation when water has time to drain, detention storage is still available providing that the water has some way of reaching the soil. If the water is guttered and piped to storm sewers or streams, then very little will reach the soil. Without trees or other deeply rooted plants to remove the soil water bound to soil particles, retention storage may remain almost full and not be available for storm storage. In a two-foot deep soil with very low ET due to lack of deep-rooted vegetation, retention storage may remain almost full. This would decrease available soil storage by 2-4 inches depending on the soil type and depth and presence of glacial till layer.

In summary, studies of forest hydrology give us an understanding of how alteration of the land affects the hydrologic cycle. Changes in urban areas are analogous to those due to harvest but are more severe and more long lasting. To minimize excess storm flow generation in streams, it is crucial to maximize natural areas, provide for infiltration opportunity, and minimize the generation of overland flow. Compared to other regions in the United States and the world, some Puget Sound streams still have some ecological functions intact. Now is the time to recognize that certain activities are impacting these streams and to limit the impacts. The longer we wait, the harder and the more expensive it will be to restore the streams, if it is possible at all.

- Regional Study Supports Natural Land Cover Protection as Leading Best Management Practice for Maintaining Stream Ecological Integrity, R.R. Horner and C.W. May, 1999: This paper focuses on the limitations of structural BMPs and the importance of forests and other non-structural BMPs for protecting salmon-producing streams from the effects on increased stormwater runoff. General forest retention throughout watersheds was also shown to offer important potential mitigation benefits, just not as extensive as riparian retention. It should be a high priority especially in managing the growth of undeveloped and lightly developed watersheds, in connection with impervious surface limitation and riparian protection efforts.

Most likely, the potential benefits shown for riparian and forest retention could be compounded by pursuing both in concert. Full coverage of otherwise unmitigated development with structural BMPs should be specified after all possible use of non-structural techniques.

The results presented here show that the relatively recently introduced initiatives in conservation design (e.g., Delaware Department of Natural Resources and Environmental Control 1997), also known as low-impact development, have considerable promise. On the other hand, the findings point out ai-en that these methods are not applicable to pursuing a11 goals, are not panaceas, and have limitations. Some limitations are simply spatial; e.g., it is obvious that success should not be expected if reaching the set goal requires 80 percent forest retention in development with 25 percent imperviousness. Further, the results suggest that the capabilities of non-structural set asides can become overwhelmed at some level of development.

With neither structural nor non-structural mitigation offering us unlimited ability to 'have our cake' (in the form of healthy resources) and 'eat it too' (in realizing the economic gains of development), we should be prepared to prohibit or very severely limit development around the streams still offering the greatest ecological good or these best places the watersheds and the streams they drain should be preserved as public resource lands and private land trusts. Extensive measures of this magnitude will be required if the Pacific Northwest is to observe the Endangered Species Act and save its salmon."

- Traditional Alternatives: Will More Detention Work? D. Beyerlein and J. Brascher: Reports on the limitations of current stormwater detention facilities in the Puget Sound region on mitigating impacts of urbanization on watersheds. ANSWER: No. Concludes that detention facilities will not fully mitigate impacts and stresses the importance of retaining forests.

  For the past 20 years local jurisdictions in the Puget Sound region have required stormwater detention facilities (ponds, tanks, and vaults) to be constructed to mitigate the impacts of development on our streams, rivers, and lakes. Standards were established to attempt to prevent runoff from development from increasing streamflows.

  As hydrologists and engineers we participated in setting the standards, selecting the methodologies, and designing and building detention facilities. This was all for the purpose of protecting our aquatic systems while allowing development in our watersheds. We have failed. With development has come increased winter flood flows, decreased summer low flows, and a general degradation of our stream systems. We have failed because we are trying to replace the complex interactions of the hydrologic cycle with a pond. It can't be done. Table 1 shows why. Table 1 shows where our average annual rainfall of 40.70 inches goes.

Table 1.	Surface Runoff (in)	Interflow (in)	Ground-water (in)	Evapotrans-piration (in)
Land Use				
Forest	0.09	8.46	13.40	18.79
Pasture	0.29	13.26	10.15	17.02
Lawn	0.61	16.72	8.89	14.48
Rural Residential (forest)	1.56	10.81	11.05	17.31
Rural Residential (pasture)	1.64	12.73	9.75	16.60
Suburban Residential	9.30	12.37	6.58	12.44
Multi -family Residential	16.66	8.69	4.62	10.72
Commercial	29.37	2.34	1.24	7.74
Impervious	34.05	0.00	0.00	6.64

In the natural forested environment almost half of our rainfall returns to the atmosphere via evapotranspiration. Evapotranspiration (ET) is the combined effect of evaporation of water from surfaces and transpiration of water from the soil by plants. In the paved environment less than 20 percent of the rainfall becomes ET. With development we have more water that becomes runoff. We have less natural storage for it because we are putting less water into the ground. It is this groundwater that supplies our streams with water during summer dry periods. Instead we are increasing surface runoff, which is the water that gets to the streams the quickest. Interflow, the water that travels just below the surface, is not far behind. Together, surface runoff and interflow produce floods.

Storm water detention is suppose to slow down the runoff from development and make it behave like natural runoff. It isn't working. And it can't work when you look at the numbers in

Table 2.

Table 2. Land Use	Surface Runoff + Interflow (in)	SR+I Change from Forest (in)	Groundwater (in)	GW Change from Forest (in)
Forest	8.55	0.00	13.40	0.00
Pasture	13.55	5.00	10.15	-3.24
Lawn	17.32	8.77	8.89	-4.51
Rural Residential (forest)	12.37	3.82	11.05	-2.35
Rural Residential (pasture)	14.37	5.82	9.75	-3.65
Suburban Residential	21.67	13.12	6.58	-6.82
Multi-family Residential	25.35	16.80	4.62	-8.78
Commercial	31.71	23.15	1.24	-12.15
Impervious	34.05	25.49	0.00	-13.40

Just the act of cutting down trees and replacing them with pasture increases the bad runoff (surface runoff plus interflow) by 5 inches per year and decreases the good runoff (groundwater) by more than 3 inches. No detention is required by government agencies. Replacing forest with lawn (residential sod) is worse. The bad runoff increases by almost 9 inches and the good runoff decreases by 4.5 inches. Again, no detention is required by public agencies because no impervious area has been added.

…Even if stormwater ponds were sized to the actual required size (based on HSPF-generated runoff), mitigation based on the 2-year and the 10-year floods does not protect our streams. Development with ponds increases the smaller flood flows and increases the length of time of flooding. This can be just as destructive to the streams and the salmon as the bigger floods. Controlling flow durations is the key to protecting them. Flow duration is the percent of time that a particular size of flow is exceeded. For example, if a flow in a stream is greater than 1 cfs (cubic foot per second) for a total of 876 hours in a year then the flow duration for 1 cfs is 10 percent of the time (365 days times 24 hours equals 8760 hours in a year; 876/8760 equals 10%).

The annual flood (l.0l-year flood) for 100 acres of forest is 1 cfs. Table 4 shows how often this flow is exceeded for each of the 100-acre developments. Converting 100 acres of forest to suburban residential development (with a 13 acre-foot pond) still results in 1 cfs (the l.0l-year forest flood) occurring for an additional 23 days a year. The excess runoff has to go somewhere.

Table 4.	Percent of Time Flows Exceed 1 cfs	Number of Hours per Year	Increase from Forest (hours)	Percent Increase
Land Use				
Forest	2.1%	181	0	0
Pasture	4.6%	401	220	122%
Lawn	6.3%	549	368	204%
Rural Residential (forest)	4.8%	419	238	132%
Rural Residential (pasture)	4.8%	422	241	134%
Suburban Residential	8.3%	730	549	304%
Multi-family Residential	10.1%	887	706	391%
Commercial	13.6%	1194	1013	561%
Impervious	15.0%	1313	1132	627%

The numbers in Table 4 are based on requiring the "Actual Required Size" ponds. In addition, it is assumed that ponds are also required for pasture, lawn, and rural residential, regardless of the amount of impervious area (or lack of). In other words, the number of flood flow hours will still increase even if we build ponds for everything. That is because we still have too much of the bad runoff (see Table 2 again).More detention won't work. What will? Keep the forests.

Where we do have development we need to change bad runoff to good runoff. In other words, take all of the bad runoff, clean it of pollutants and sediment, and put the water into the ground. In areas with till soils this will require drilling through the hardpan layer of cemented silt and clay underlying the topsoil to get the water into the ground. <u>In areas of high water table infiltration of runoff will not work and development should not be allowed</u>**.**

- The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion C.W. May, et. al. University of Washington: The paper reports on research conducted on 22 small stream watersheds in Puget Sound, including Green Cove Creek in Thurston County to “identify the linkages between landscape-level conditions and instream environmental factors.” Studied impervious area, condition of riparian corridor, chemical water quality, salmon habitat, and biological integrity (B-IBI). Findings identified “a set of necessary . . . conditions required to maintain a high level of stream quality or ecological integrity” (listed on page 18 of the paper).

“Watershed imperviousness ranged from undeveloped (%TIA < 5%) to highly urbanized (%TIA > 45%). Imperviousness (%TIA) was the primary measure of watershed development; however, other measures of urbanization were investigated. Calculating impervious surface area can be costly, especially if computerized methods like GIS are utilized. In addition, the land-use data required for calculation of %TIA may be unavailable or inaccurate. As part of this study, a low-cost alternative to imperviousness was also investigated. Analysis demonstrated that the relationships to be discussed were very similar if development is alternatively expressed as road-density (Figure 3). This is especially relevant in that the transportation component of imperviousness often exceeds the "rooftop" component in many land-use categories (Schueler 1994). A recent study in the Puget Sound region has shown that the transportation component typical accounts for over 60% of basin imperviousness in suburban areas (City of Olympia 1994).

Watershed urbanization results in significant changes in basin hydrologic regime (Leopold 1968; Hollis 1975; Booth 1991). This was confirmed for streams in the PSL study. The ratio of modeled 2-year stormflow to mean winter baseflow (Cooper 1996), was used as an indicator of development-induced hydrologic fluctuation (Figure 4). This discharge ratio is proportional to the relative stream power, and thus is representative of the hydrologic stress on instream habitats and biota exerted by stormflow relative to baseflow conditions. The modified basin hydrologic regime was found to be one of the most influential changes resulting from watershed urbanization in the PSL region.

Streambank erosion was also far more common in urbanized PSL streams than in streams draining undeveloped watersheds. Using a survey protocol similar to Booth (1996), all stream-segments were evaluated for streambank stability. Stream segments with >75% of the reach classified as stable were given a score of 4. Between 50% and 75% stable banks were scored as a 3, 25-50% as a 2, and <25% as a 1. Artificial streambank protection (rip-rap) was considered a sign of bank instability and graded accordingly (1). Only two undeveloped, reference (%TIA < 5%) stream-segments had a stability rating less than 3. In the 5-10% basin imperviousness (%TIA) range, the streambank ratings were generally 3 or 4. Between 10-30% sub-basin impervious area (%TIA), there was a fairly even mixture of streambank conditions from stable and natural to highly eroded or artificially "protected". Above a sub-basin %TIA of 30%, there were no segments with a streambank stability rating of 4 and very few with a rating of 3. These outliers were found only in segments with intact and wide riparian corridors. Artificial streambank protection (rip-rap) was a common feature of all highly-urbanized (%TIA > 45%) streams. Overall, the streambank stability rating was inversely correlated with cumulative upstream basin %TIA and even more closely correlated with development within the segment itself, perhaps reflecting the local effects of construction and other human activities. Streambank stability is also influenced by the condition of the riparian vegetation surrounding the stream. In this study, the streambank stability rating was strongly related to the width of the riparian buffer and inversely related to the number of breaks in the riparian corridor. While not completely responsible for the level of streambank erosion, basin urbanization and loss of riparian vegetation, contribute to the instability of streambanks. Besides vegetative cover, other stream corridor characteristics, such as soil-type and valley hillslope gradient, also contribute to the stability potential and current condition of the banks.

As would be expected, larger scour and/or fill events normally resulted from larger storms and the resultant higher flows. The available stream power and basal shear stress may be the most significant factors with regard to the potential for streambed instability. Stream power is proportional to discharge and slope. Since flows tend to increase with urbanization, it would generally be expected that stream power would increase as urbanization does, all else being equal. Cooper (1996) found this to be the case for the PSL study streams. Shear stress is dependent on slope, flow velocity, and bed-roughness. It is the critical basal shear stress that determines the onset of streambed particle motion and the magnitude of scour and/or aggradation. In that local slope and streambed roughness are highly variable, it is not surprising that scour and fill are also variable and that no significant relationship was noted between the 2-Year stormflow to winter-baseflow ratio and any of the scour monitor measurements. This tends to emphasize the local nature of scour and aggradation events. Nevertheless, basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD, were found to be more susceptible to scour than their undeveloped counterparts.

Results of the PSL stream study have shown that physical, chemical, and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion. Although the patterns of change differed among the attributes studied and were more strongly evident for some than for others, physical and biological measures generally changed most rapidly during the initial phase of the urbanization process as %TIA above the 5-10% range. As urbanization progressed, the rate of degradation of habitat and biologic integrity usually became more constant. There was also direct evidence that altered watershed hydrologic regime was the leading cause for the overall changes observed in instream physical habitat conditions.

Chemical water quality constituents and concentrations of metals in sediments did not follow this pattern. These variables changed little over the urbanization gradient until imperviousness (%TIA) approached 40%. Even then water column concentrations did not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment guidelines. As urbanization (%TIA) increased above the 50% level, with most pollutant concentrations rising rapidly at that point, it is likely that the role of water and sediment chemical water quality constituents becomes more important biologically.

The findings of this research indicate that there is a set of necessary, though not by themselves sufficient, conditions required to maintain a high level of stream quality or ecological integrity (physical, chemical, and biological). If maintenance of that level is the goal, then this set of enabling conditions constitutes standards that must be achieved if the goal is to be met. For the PSL streams, imperviousness must be limited (< 5-10 %TIA), unless mitigated by extensive riparian corridor protection and BMPs. Downstream changes to both the form and function of stream systems appear to be inevitable unless limits are placed on the extent of urban development. Stream ecosystems are not governed by a set of absolute parameters, but are dynamic and complex systems. We cannot "manage" streams, but instead should work more as "stewards" to maintain naturally high stream quality. Preservation and protection of high-quality resources should be a priority. Engineering solutions in urban streams have utility in some situations, but in most cases cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds. In order to support natural levels of stream quality, the following recommendations are proposed:

-Reduce watershed imperviousness, especially targeting transportation-related surfaces and compacted pervious areas.

-Preserve at least 50% of the total watershed surface area as natural forest cover.

-Maintain urbanized stream system drainage-density to within 25% of pre-development conditions (i.e. urban/natural DD ratio < 1.25).

-Retrofit existing BMPs or replace with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.

-Actively manage the riparian zone to ensure a long-range goal of at least 60% of the corridor as mature, coniferous forest.

-Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area……"

- Alberti, M., D. Booth, K. Hill, B.Coburn, C. Avolio, S. Coe, and D. Spirandelli. 2003: The study indicates that at the scale of the watersheds supporting individual tributary streams, patterns of urban development affect ecological conditions on an urban-to-rural gradient. At this scale, previous research has shown that impervious surfaces result in characteristically altered and often extreme hydrologic conditions that provide an endpoint on a disturbance gradient (Meyer et al. 1988, Booth and Jackson 1997, Konrad and Booth 2002). However, % impervious area and % forest in the contributing watershed is only a coarse predictor of biological conditions in streams, in part because hydrological change is only one of several' factors that affect stream biota. The location and spatial configuration of forest patches and paved areas explain most of the variability in B-IBI not explained by TIA. Strong statistical relationships are found between selected landscape patterns and ecological conditions in streams. While the findings clearly suggest that patterns of urban development matter to watershed function, this relationship does not indicate a specific threshold but shows that both the increase in percentage impervious surface and its aggregation have both a direct impact on stream macroinvertebrates. In particular, as the probability of paved areas being adjacent rises from 50% to 100%, typical B-IBI values decline from 50 (excellent) to 10 (very poor).

Our multiple-scale analysis aimed at discriminating across patterns that operate at different scales-from riparian local zone to basin. Since landscape metrics are scale-dependent, we systematically examined the relationship between each variable and B-IBI at each scale. Except for the local riparian zone, all variables are highly correlated with B-IBI across the various scales. Our study, however, clearly indicates that the effects of land cover composition and configuration vary with scale. At the basin scale, landscape configuration metrics (AI and PLADJ) are better predictors of B- IBI, while at the local scale the landscape composition metrics (% TIA and % Trees) are. This reinforces the finding that scale is an important factor in assessing the utility of landscape metrics that link urban patterns to ecological conditions. However, since the riparian and sub-basin variables are closely correlated ($R= 0.95$, $P < 0.001$), it is difficult to discriminate between riparian and sub-basin effects through statistical measures, even though the processes that affect aquatic ecosystems are clearly different in each.

The findings of this study indicate strong statistical relationships between urban landscape patterns and ecological conditions in streams. Although many studies have addressed the. relationship between urbanization and aspects of ecosystem function (e.g., Karr et al. 1985), few have asked directly how patterns of urban development affect aquatic ecosystems. Most studies of the impacts of urbanization on environmental systems correlate changes in environmental systems with simple aggregated measures of urbanization (e.g., human population density, % impervious surface). However these metrics are only coarse predictors of biological conditions and do not discriminate between different landscape patterns. As such, they can offer only crude predictions of conditions and a limited suite of planning or management responses. We show that complex interactions in urbanizing watersheds control ecological conditions and need to be explicitly accounted in order to understand and manage urban stream ecological function. Our analysis of land use-land cover reveals that urbanizing landscapes are characterized by a complex pattern of intermixed high- and low-density built-up areas, showing that urban land-cover patterns cannot be derived directly from land use. Rather, they can best be described using a series of urban pattern metrics that describe spatially aggregated variables of land-use intensity and land-cover types (e.g., density of human population, road density, or amount of impervious surface) and spatial distributions and configuration of the landscape. We also show that dynamic interactions between urban patterns and ecosystem function occur at multiple spatial scales, and our results show the importance of determining the scale at which to make inference.

Strong statistical relationships are found between ecological conditions in streams and selected landscape patterns-both amount and configuration of impervious area and forest patches. While other studies have investigated the relationship between impervious surface and B- IBI (Booth at al. 2001, Morley and Karr 2002, Booth at al. 2002), here we find that patterns of urban development matter to aquatic ecosystems. Since the 42 selected sub-basins represent a cross-section of varying levels and patterns of urbanization in the Puget Lowland, the results are transferable to other urbanizing sub-basins of similar size and hydrogeology. The established relationship between urban pattern and ecological conditions however does not indicate a specific threshold of effects <u>but it shows that both the increase in percentage impervious surface and its aggregation have a direct impact on stream ecological conditions</u>. Furthermore, our scale analysis findings indicate that landscape configuration at the basin scale may influence the effectiveness of riparian function at the local scale. Strategies that aim to maintain biological integrity in streams need to both target the extent and pattern of development and simultaneously address local- and basin-scale actions.

- Impervious Surface Cover Concepts and Thresholds, M. Kaplan and M. Ayers: Reviews recent research on the effect of impervious area on watersheds and reports statewide data from biomonitoring studies conducted on <u>New Jersey</u> streams. Notes that impervious area is only one indicator of the impact of urbanization on aquatic habitat and that the often-used impervious cover threshold classification (i.e. sensitive stream = 0-10%; impacted streams =11-25%; non-supporting stream = >25%) is based on “average behavior of stream indicators over a range of impervious cover.” Reports that biomonitoring in New Jersey generally support the threshold classification, but notes that results vary from one site to another. For example, there were two sites that showed impairment at well below the 25% level of impervious cover.

- Urbanization and Streams: Studies of Hydrologic Impacts, U.S. EPA, Office of Water: Examines and summarizes some of the published literature on the hydrological impact of impervious surfaces. Concludes that “case studies conclusively link urbanization and increased watershed imperviousness to hydrologic impacts on streams” and “provide strong evidence that urbanization negatively affects streams and results in water quality problems such as loss of habitat, increased temperatures, sedimentation, and loss of fish population.”

- The Importance of Imperviousness,1994: Reviews scientific literature regarding the effects of impervious area such as stormwater runoff, stream channel morphology, water quality, stream warming, and aquatic biodiversity.
    - Salmonid and anadromous fish species were most negatively impacted by increase in impervious area, citing two Pacific Northwest studies that reported poor quality fish habitat in watersheds with impervious area ranging from 8% to 15%.
    - High levels of bacteria occur even at low levels of urbanization resulting in shellfish bed closures.
    - Notes that it is “extremely difficult to maintain predevelopment stream quality when watershed development exceeds 10 to 15% impervious cover.”

- Interactive GIS-based Impervious Surface Model (S. Prisloe, et al. University of Connecticut) -Reviews recent research on impervious surface and reports on the development of an impervious surface model that may “help land-use officials ‘see’ the future and better understand how land-cover change from forest to urban may impact local water resources.” -Notes that the impervious cover threshold classification “should be viewed only as general guidelines to help determine where a watershed falls along the percent impervious surface-stream quality continuum. . . . Variables such as topographic relief, distribution of impervious surfaces within a watershed, soil and land-cover types, stream network density, and other terrain characteristics can serve to raise or lower a particular watershed's percent impervious area thresholds."

- The Impervious Cover Model: A review paper summarizing the findings from research around the country on the effect of urbanization on aquatic systems.
  -Reports significant negative impact to aquatic insects (which are the food source for fish), fish, water quality, and watershed morphology at around 10% impervious area.
  -Reports that between 11% to 25% impervious area, the most sensitive fish and aquatic insects disappear from the stream. It reported a shift at 10% to15% impervious area from coho salmon, which are sensitive to stream degradation, to the more tolerant cutthroat trout.
  -There is a steady decline in aquatic habitat as the impervious area increases. Once the impervious area exceeds 25%, streams are categorized as non-supporting and "essentially become conduits for conveying stormwater flows."
  -Urban stormwater BMPs have only "very modest" ability to mitigate the effects of impervious area.
  -Intact riparian corridor can somewhat mitigate effects of impervious area.

- The Local Impacts of Road Crossings on Puget Lowland Creeks Christina Marie Avolio, UW, 2003: The stream condition that is perhaps best known to be influenced by urbanization is the hydrologic regime. <u>Removal of vegetation, compaction of soils, and the installation of drainage networks associated with roads combine to transport water more "efficiently" to the stream during storms</u> (Konrad 2000, Booth 1991, Burges 1989, Hollis 1975). Such alterations made to stream discharge also affect the other components of the hydrologic cycle. While surface runoff experiences net increases during and immediately after storms, groundwater recharge, evapotranspiration, and throughflow typically suffer net reductions (Imhof 1991). This pattern commonly results in a flashy response (quick water level rise) to storms and decreased base flow during dry periods. Repetition of these patterns over multiple-year periods is likely to induce persistent physical and biological consequences (Booth et al. 2001, Moscrip and Montgomery 1997).

  As hydrologic change influences the frequency and magnitude of stream discharges, the physical equilibrium of the channel is offset and the geomorphic form is changed (Imhof 1991). One such physical adjustment occurs with the alteration of channel-forming flows, or the discharges where sediment transport is regulated and the channel geometry is effectively maintained (Dunne and Leopold 1978). As impervious surfaces and ditches increase the rate and magnitude of the in-stream storm response, these channel-forming flows occur more frequently (Center for Watershed Protection 1996). Depending on geological conditions, this trend can promote downstream bank erosion, channel widening, and incision. Booth and Henshaw (2001) <u>found that watershed urbanization and the annual rate of channel change were closely linked</u>; their channels draining established neighborhoods exhibited lower rates of change than channels draining newly developing neighborhoods. These results suggested an ability of the channel to reestablish some sort of physical equilibrium, although such equilibrium is not necessarily an indicator of revised overall stream function or habitat quality (Booth and Henshaw 2001).

7. Vegetative cover in channel migration hazard areas and floodplains.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW, Center for Streamside Studies, July 2001, pg 10: Channel morphology is affected by the presence of trees, shrubs, and logjams. There are few controlled studies on the before and after effects of vegetation removal from the floodplain or stream channel (Shields and Nunnally 1984), but physical effects can be identified by considering the processes affected by vegetation. Vegetation may provide bank stability through root reinforcement of the soil (Krogstad 1995). This strengthens the soil's resistance to the erosive force of the streamflow. Millar and Quick (1998) demonstrated that the effect of vegetation on bank stability could be expressed as an increase in critical bank shear stress. They estimated that critical shear stress is about three times higher when trees and shrubs are present compared to just grass covered banks. However, there is some evidence that this effect is limited by root density and depth which varies with species and soil types. Rowntree and Dollar (1999) found that willows provided increase bank stability at flows less than bank-full, but did not appreciably affect long-term shifts in channel position from major floods. Nanson and Hickin (1986) found that outer bank migration in meandering channels was largely a function of river size and grain size in the large sand- and gravel-bed rivers that they studied. Vegetation both in channel and along the floodplain provides roughness, which slows water and removes energy from the water. Shields and Nunnally (1984) describe several studies that show changes of 30% in Manning's' 'n' depending on whether the channel is clean or has lots of vegetation and snags. …Trees and shrubs along the stream slow flood waters and provide time for water to soak into the ground, which can reduce flooding in downstream areas. Streamside vegetation can also filter out pollutants before they reach the stream keeping the stream and groundwater clean. Sediments and nutrients that get filtered out in the riparian zone are quickly colonized by new vegetation, which stabilize the sediment and use the nutrients for growth.

8. **Large woody debris (LWD) in stream channels**.

- Ecological Issues in Floodplains and Riparian Corridors Susan Bolton and Jeff Shellberg, UW Center for Streamside Studies, 2001, pg 12: The hydraulics of native and engineered LWD is not fully understood. In some jurisdictions all stream improvement designs must be assessed to determine whether they will or will not cause an increase in flood elevation. Gippel et al. (1992; 1996) studied the hydraulics of woody debris in the Thompson River, Victoria, Australia and concluded that re-introduction of LWD into previously cleared streams "is unlikely to result in a large loss of conveyance, or a detectable increase in flooding frequency." Abbe and Montgomery (1996) have also combined field studies with theoretical and flume studies to explore the hydraulics of debris jams and logs with root wads. Their interest was to better understand how LWD affected stream geomorphic processes. Abbe (2000) and Drury (2000) present information on hydraulics when using wood in large streams for bank protection.

- Results from Forest Hydrology Studies: Is There a Lesson for Urban Planners? S. Bolton and A. Watts: Removal of large woody debris from the stream channels and the lack of large, older trees for recruitment to the channel decreases pool formation (pond storage) and decreases flow resistance, which means less water can be stored in the channel and water moves through the channel faster.

- The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion C.W. May, et. al. University of Washington: Nevertheless, basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD, were found to be more susceptible to scour than their undeveloped counterparts.

- Best Available Science, Channel Migration Zones, Draft, King County, 2/2004: Scientific literature documents the effect that accumulation of LWD can have on channel hydraulics, channel morphology, sediment accumulation, channel migration, and riparian forest development. LWD is identified as a primary trigger mechanism for avulsions. Much of the research on LWD in channels has been conducted in undeveloped, forested watersheds and floodplains. While the general principles reported by such research are globally applicable, some findings keyed to occurrence, density, or distribution of LWD in predominantly undeveloped and forested settings do not appear to be directly applicable to mainstem lowland channels… An example of a globally applicable principal is that sediment deposition behind an accumulation of LWD would be expected to occur and affect channel bed elevation within its local extent of influence. It follows that a systemic change in bed elevation might occur due to multiple LWD accumulations such that channel migration in turn would be affected systemically. However, given the present-day densities and distribution of LWD in most King County channels, it does not appear likely that a systemic change in channel bed elevation, and a resulting systemic alteration of channel migration characteristics, would occur in lowland mainstem channels of the Puget Sound.

Accumulation of large woody debris (LWD) as stable, in-channel structures can influence channel hydraulics, channel morphology, sediment accumulation, channel migration, and riparian forest development morphology at the sub-reach and reach scale (Abbe and Montgomery 2003, O'Connor et al. 2003, Collins and Montgomery, 2002, Bilby and Bisson 1998, Abbe and Montgomery 1996). <u>Stable L WD structures can resist channel migration, forming a revetment that halts local bank erosion,</u> often altering the orientation of flow relative to the jam. Stable L WD jams that persist long enough to be buried in a floodplain are associated with anomalous forest patches older than the surrounding floodplain forest (Abbe and Montgomery 1996), indicating long-term resistance to lateral erosion. The type of debris jam and the presence, number, size, stability, and orientation of the key pieces of LWD will determine the stability of the jam and the effect of the jam on channel stability (Abbe and Montgomery 2003, Abbe and Montgomery 1996).

<u>The effects of LWD accumulations on channel stability can vary, e.g., either increasing or decreasing bank stability depending on the specific setting</u> (Keller and Swanson 1979). Bank erosion and channel shifting that entrain floodplain sediment and LWD can promote channel movement and instability by diverting flows that in turn causes further bank erosion and entrainment of sediment and wood. Woody debris jams in low gradient meandering channels of moderate size may facilitate formation of meander cutoffs, increase channel width, produce midchannel bars, and affect channel morphology (Keller and Swanson 1979). LWD can be a primary determinant on channel form in small streams; wood has less of an effect on channel form in larger streams (Bilby and Ward 1989, Bilby and Bisson 1998).

Woody debris accumulations appear integral to formation and maintenance of an anastomosing (i.e., branching and recombining) channel pattern (Abbe and Montgomery 2003) and to causing avulsions, maintaining multiple channel morphology, and regulating flow from main channels to perennially flowing floodplain sloughs (Collins and Montgomery 2002). Wood jams are often the mechanism that triggers a channel to avulse or switch flow from one channel to another (Collins and Montgomery 2002, Collins et al. 2003). May (2002) states that channels with abundant accumulation of in-channel LWD often have more active channel migration.

Accumulation of L WD induces upstream deposition of sediment and thereby can raise the elevation of the channel bottom and water surface for channel distances on the order of 1-10 channel widths (Abbe and Montgomery 2003). Increases in channel bottom and water surface elevations in turn allow flows into previously inaccessible side channels and thereby increase the likelihood of horizontal channel movement, as described in "Types of channel movement", above.