AN ABSTRACT OF THE THESIS OF

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William J. Liss

The restoration of rivers and streams should be based on a strong conceptual framework. Streams are developing systems. As such, streams exhibit temporal behaviors that change with changing stream environments. Underlying the dynamic development of streams is potential capacity. Streams express this capacity as an array of habitats over time and across the landscape. Human land uses in the western United States have rapidly altered aquatic habitats as well as the processes that shape habitat. As a result, the diversity of native fishes and their habitats has been suppressed. Restoration is fundamentally about allowing stream systems to re-express their capacities. Four steps are provided to guide stream restoration activities. Key tasks include: identification of the historic patterns of habitat development; protection of the developmental diversity that remains; local application of specific knowledge about suppressive factors; classification of sensitive, critical or refugium habitats; release of anthropogenic suppression; and monitoring of biotic response to habitat change.

Applying these concepts, I describe potential habitat refugia for aquatic organisms in the Joseph Creek basin in the Blue Mountains of northeast Oregon. Five valley segment classes, differing in valley corridor landforms, are described. Of these, low-gradient wide alluvial valleys have been most altered by human land use. Riparian vegetation has been extensively removed or altered in alluvial valleys. Currently, stream habitats are structurally depauperate, and

warm to temperatures well above thermal tolerances of native salmonids. Potential refugia for native coldwater fishes in these valleys include patches of complex habitat within stream reaches. Reaches fenced to exclude domestic livestock exhibit narrower channels, more pools, and higher frequencies of stable vegetated banks than nearby unfenced reaches. During summer low flow periods, cold groundwater seeping into and accumulating in stream channels forms "cold pools". Cold pools provide potential seasonal refuge for cold-water fish at microhabitat scales. Cold pools are associated with channel complexity, and are more frequent in reaches with vigorous riparian vegetation. Seven classes of cold pools are described. Cold pool classes differ in minimum temperature, maximum depth and volume. Distributions of cold pool classes between valley segment classes suggest that valley geomorphology in addition to local channel form may influence development of certain cold pool types.

Although refugia at the microhabitat to reach scales are important, the context within which remnant or refugium habitats and associated relict populations are maintained may ultimately determine the persistence of those species and habitats. In managed landscapes, protection and restoration of habitats at many scales may be necessary if we are to best insure the persistence of native species.

Stream Habitat Classification and Restoration in the Blue Mountains of Northeast Oregon

by
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CONTRIBUTION OF AUTHORS

This thesis represents the efforts of several coauthors who assisted and guided the principle author. The coauthors were particularly instrumental in shaping the conceptual perspective of the research and establishing a strong background for this work. The principle author did most of the data analysis and writing of the thesis, and should be held solely responsible for any exaggerations or inaccuracies. The contributions of each coauthor are summarized below.

W.J. Liss -- Principle Investigator of project, involved in establishing goals and objectives; developed and refined conceptual framework; reviewed and edited manuscripts.

C.A. Frissell -- Involved in developing objectives and study design; assisted in interpretation of field observations; provided guidance in methods of stream habitat classification; reviewed and edited manuscripts.

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Stream Habitat Classification and Restoration in the Blue Mountains of Northeast Oregon

Chapter 1: Overview

Loss of diversity, both of aquatic and terrestrial habitats within the range of Pacific salmonids, and within salmon species, is becoming increasingly evident. The need for restoration of anadromous salmonids is now widely perceived. But what is restoration? Frequently, the ideal of restoration suggests a return to some former, desirable state. One often detects that steady states are most desirable. Perceptions of prior states and conditions are frequently generalized over entire regions, as if current heterogeneity is some relict of recent human activities. These perceptions and ideals yield certain types of goals. Goals for the restoration of salmon have emphasized numerical abundance of harvestable fish. For the restoration of salmon habitat, goals have tended toward uniform standards of channel condition and habitat state. Such goals may be inappropriate for salmonid persistence. Yet these goals are consistent with conceptual frameworks that presume reversibility of system development, that promote analysis of systems apart from their encompassing environments, and that assume linear cause-effect relationships between system components. Perhaps the elaboration of a restoration strategy appropriate for the persistence of salmon will require a different conceptual foundation.

The goal of this research is to provide an alternative conceptual framework for restoration. I attempt to base this framework upon the general living systems concepts of Warren et al. (1979) and Warren and Liss (1980). One requirement of this systems view is that the encompassing environment of the subject of study be kept explicit. Another is that the behaviors or performance of systems be recognized as emerging from the underlying interaction of the system and its environment. These concepts were chosen as a basis for a restoration framework because I feel they best address the interdependence of salmon, streams and human actions. This view is also appealing in that it provides a means to articulate possible values of the marginalized, peripheral or unacknowledged aspects of habitat and biotic diversity often neglected by science and management.

The stream habitat classification of Frissell et al. (1986) provides a framework for viewing stream habitats as integral components of hierarchical watershed systems. Habitats are classified according to factors that fundamentally determine the constraints on their development. In applying some aspects of this classification framework to the Joseph Creek basin, I identify patches of habitat that might be critical for persistence. My aim is to find the places where native biota might persist within a basin disturbed by a variety of land uses, as well as to enlarge my vision of the kind of stream habitat that is possible in a place. Refining this vision is the first task of restoration. This refinement will require first-hand exposure to wild places. It will take a lengthy exploration of the landscape to locate the remaining "great works..that show us what to hope for" (Berry 1991, p.73).

Chapter 2: Restoration of Aquatic Habitats in Managed Landscapes in the Western USA: Restoration as Re-expression of Habitat Capacity

INTRODUCTION

Restoration of fish stocks has become one of the primary tasks of fisheries management. Widespread deterioration of native fish populations (Nehlsen and others 1991, Frissell 1993b) has prompted heavily-funded programs to attempt to reverse declines (e.g. NPPC 1992). These efforts often involve restoration of the degraded freshwater habitats frequently implicated in population declines (Miller et al. 1989, Nehlsen et al. 1991, Frissell 1993b). For example, what is perhaps the largest and most costly habitat restoration attempt ever is underway in watersheds in the Pacific Northwest that historically sustained large and diverse runs of anadromous salmonids. Habitat enhancement efforts have emphasized riparian fencing, planting and in-channel habitat structures (Jensen and Platts 1990, Crispin et al. 1993), but recent strategies have expanded to include entire watersheds with road removal and hillslope stabilization (Weaver et al. 1987, Frissell 1993a). However, these efforts are often expensive and the probabilities of success are unknown. Even when restoration goals are widely accepted, specific actions may be controversial even among resource managers and scientists. The history of aquatic habitat management suggests that caution may be warranted; not only has evidence of aquatic community recovery associated with rehabilitation of degraded habitats been sparse to date (Everest et al. 1989, Lawson 1993), but certain tactics have actually contributed to habitat degradation (Frissell and Nawa 1992, Beschta et al. 1991) or have displaced native "non-target" biota (Fuller and Lind 1992).

Despite the uncertainties and complexities associated with stream habitat recovery, restoration is likely to become increasingly important in freshwater fishery management. A conceptual framework to guide restoration, provide evaluative criteria, and set priorities would seem prudent given the need for the rapid application of restoration management to large and complex issues such as the collapse of Columbia River basin salmonid stocks. Our objective in this paper is to propose a general framework for stream habitat restoration that incorporates concepts relating the persistence of aquatic biota to changes in their environments.

CONCEPTUAL FRAMEWORK

Our restoration framework rests upon concepts of system development and organization as presented by Warren et al. (1979). In this view, developing systems change in state and organization through time, expressing new behaviors in new environments. The direction and nature of this responsive change comprises the course of development of a system (Figure II.1). Systems develop in concordance with environmental change and within constraints imposed by an initial **potential capacity**. Potential capacity entails all possible developmental trajectories and behaviors a system could express. As systems develop, not all developmental trajectories inherent in the initial potential capacity will be expressed. Rather, prevailing environmental conditions will determine the way in which development proceeds. With development, system **realized capacity** changes. At each developmental state, realized capacity in conjunction with the prevailing environment determines observable behaviors or performances. The systems concept central to our restoration framework is that observed patterns of system development and performances are expressions of system potential capacity in interaction with system environment (Warren et al. 1979, Frissell et al. 1986).

Frissell and others (1986) incorporate these general systems theory concepts into a model of stream habitat development and organization. In this view, the stream system, encompassing all surface waters in a watershed, is stratified into successively smaller and less-enduring habitat subsystems including segments, reaches, pool/riffle units and microhabitats (Table II.1). The habitat of stream organisms at any level within this hierarchy can be conceptualized as a developing system that changes in state and organization through time in concordance with change in its environment. Habitats at higher levels of the hierarchy provide this environment. Development occurs within constraints imposed by the potential capacity of the habitat. At a given spatio-temporal scale, potential capacity is approximated by factors constraining habitat development (Table II.2). For example, the potential capacity of a stream valley segment is approximated by channel floor lithology, slope, adjacent geomorphic surfaces, and so forth. The development and performances of valley segments are determined by these factors and by the encompassing watershed environment. These factors also provide the basis for classification of stream habitats sharing similar potential capacities (Warren and Liss 1983, Frissell et al. 1986).

In a physiographic region with a certain geology and climate, streams may share potential capacity for habitat development. However, local stream environments differ somewhat across a region, as do the histories of individual watersheds. Thus, potential capacity is expressed as an array of habitat developmental patterns and performances across the landscape (Figure II.2). Over time, pressures imposed by the environment may suppress or enable the expression of specific performances. We propose that anthropogenic changes can constrain or suppress expression of the potential capacity of habitats. This is accomplished by eliminating certain habitat types, and focussing others onto degraded trajectories less suitable for native fishes. Habitat developmental diversity, expressed as the array of developmental patterns and states, is reduced. Examples include the elimination of habitat heterogeneity via landscape homogenization (Reiman et al. 1993); the introduction of invasive, habitat-altering non-native organisms (e.g. Graf 1978, Armour et al. 1991, Ludyaniskiy et al. 1993); the removal of elements that provide habitat structure and complexity (Triska and Cromack 1980); and the alteration of environmental fluctuations such as fire and flood regimes that direct habitat development and to which native biota are adapted (Poff and Ward 1990).

System development and its patterns of capacity expression and suppression, differs from system evolution, which entails fundamental change in system potential capacity such that prior performances and states are no longer possible (Table II.1)(Frissell et al. 1986). System evolution imposed by human activities we term capacity alteration, and implies irreversibility of system change (e.g. Bravard et al. 1986 and Westoby et al. 1989). Examples include desertification and topsoil loss (Milton et al. 1994), invasion and persistence of non-native and exotic species (Moyle and Sato 1991), and certain fluvial engineering projects (Bravard et al. 1986).

Restoration, the field of environmental management concerned with recovery and rehabilitation of systems impaired by human activity, specifically is concerned with the nature of reexpression of capacities and performances previously extinguished or suppressed (Figure II.2). In our view restoration involves allowing and enabling the potential capacity of stream habitat to reexpress itself by reducing or removing anthropogenic constraints. This amounts to restoring habitat developmental diversity and enabling the reexpression of native biotic diversity. We believe that the restoration of stream habitats will best be guided by an ordered conceptualization of the manner in which habitat capacities and environments provide the context for stream habitat development and the persistence of biota-habitat systems. From the elaboration of these concepts we will derive some general guidelines for stream habitat restoration.

Stream Habitat Development

Stream habitats include channels, floodplains and associated surface and interstitial waters. Habitats are also defined by the flow of energy through stream environments, measured as temperature, streamflow and nutrients cycling with hourly, daily and seasonal fluxes. The "connectedness" of streams such as is typified by the often strong linkages between terrestrial, aquatic and hyporheic processes (Stanford and Ward 1992) means that stream habitat boundaries are frequently unclear (Minshall 1988, Ward 1989). Defining the boundaries between what is habitat and what is better defined as the contributing environmental context (riparian vegetation, hillslopes, watersheds) is difficult without a classification that makes explicit the spatial and temporal domains of habitats. The habitat classification framework of Frissell et al. (1986) provides a means to delineate stream habitats and encompassing environments by defining a hierarchy of factors that approximate capacity for each hierarchical habitat level (Table II.1). Within the landscape, processes and associated elements of successively higher levels of habitat organization comprise the environments of lower level habitats. Each level is itself a habitat encompassed by a larger, more enduring environment. In this view, the definition of habitat and environment is scale-dependent, and scale must be kept explicit for effective communication. By keeping scale explicit, this framework allows the definition of factors that approximate system capacities (Table II.2). For example, at the watershed level, geology and climate provide controls on substrate and landscape weathering rates and thus can serve as proxies for potential capacity at spatial scales of 10^3m over time periods of tens of thousands of years, while at the microhabitat level streambed morphology and water velocity, which determine potential for the capture and storage of upwelling groundwater within surface waters (Keller and Hofstra 1983, Ozaki 1988), are proxies for capacity at spatial scales of 10^{-1}m over the time scale of seasons within a year. It is important to note the influence of higher-level systems that provide the environments of local phenomena. For example, the potential for the capture of upwelling groundwater in surface streamwaters is dependent not only on local microhabitat-level channel morphology but also on watershed-level geology and faulting patterns, as well as other factors that are intermediate in scale (Freeze and Cherry 1979).

Development at each level in the system hierarchy yields an array of habitat performances (Figure II.2). For instance, development of a watershed and its stream network yields an array of geomorphic valley types or segment classes (e.g. bedrock canyons, broad alluvial valleys), developing over millenia in response to geologic and tectonic factors that allow non-uniform erosion and deposition (Frissell and Liss 1986, Frissell et al. 1986). Within each of these valley segment types, an array of riparian vegetation communities and associated habitats (reach classes) develop in association with variation in local environments (e.g. soils, floodplain hydrology) and shorter-term events (e.g. beaver damming, fire) (Figure II.3) (Gebhardt et al. 1987, Swanson et al. 1988, Kovalchik and Chitwood 1990, Leonard et al. 1992). Not all possible habitats will be expressed at any one time; rather, the existing habitat array at a single point in time reflects the landscape's developmental history and environment, defined as the sequence of events that propel and direct habitat expression within the constraints of habitat potential capacity.

This conceptualization of dynamic stream habitat development suggests several implications for the way in which stream habitats change. The first is that the physical system has an innate capacity for certain kinds of performances and cannot be exceeded. The second is that the spatial mosaic of habitats expresses a diversity of developmental processes and pathways. This diversity reflects the history of the system as well as the potential of its component habitats for future change.

Biotic Adaptation to Habitat Development

The historical patterns of disturbance and recovery of habitats and biota through time and across the landscape provide dynamic patterns to which organisms, species and communities must either adapt or perish (the "habitat template" *sensu* Southwood 1977). Over evolutionary time frames biota adapt to patterns of habitat development, at least until drastic environmental change occurs. The willow and cottonwood riparian communities of interior western North America have evolved mechanisms of propagule dispersal, rooting and sprouting that not only tolerate but are largely dependent upon the historical fluxes of the hydrologic regime. Changes in riverine hydrology associated with regulation by dams has altered the environment to novel regimes that endanger these communities in many rivers (Rood and Mahoney 1990). The seasonal migrations of anadromous salmonids are similarly adapted to hydrographic patterns. Changes in timing and quantity of peak flows due to regulation of rivers in the Columbia River basin have had tremendous effects on riverine communities, mainstem habitat and salmonid survival (Li et al. 1987, Raymond 1988). Other examples of adaptation to temporally-heterogeneous environments include aquatic invertebrate life histories cued to temperature and streamflow patterns (Vannote and Sweeney 1980). Over time, various physical and biological processes operating throughout the landscape yield a dynamic mosaic of progressional states (Figure II.2) to which the native biota are adapted (Warren and Liss 1980).

Persistence of Habitat-Biota Systems

The ability of biota to persist, coevolve and maintain adaptive relationships within the habitat system is termed resiliency (Holling 1973). Resiliency is a valued characteristic of natural systems as resilient systems will persist over time. Resiliency does not guarantee stability, however. Some resilient systems are in fact highly unstable (Holling 1973).

Persistence implies the continued ability of the biota to adapt to the developing habitat and absorb stochastic events. The rate, spatial scale and intensity of environmental variation are several characteristics of habitat development that determine biotic persistence. Habitat change that is too rapid may exceed adaptive capabilities of the dependent biota, inducing extinction or emigration (Hobbs and Huenneke 1992). However, the spatial scale or pattern of development is also a factor; the occurrence of habitat patches of sufficient quality and connectivity may allow populations to successfully reproduce and persist within an otherwise hostile matrix

(Sedell et al. 1990). Also important is the intensity of change; some habitats may undergo extreme shifts in performance that are simply beyond the adaptive capacity of organisms (Connell and Sousa 1983). These factors (rate, spatial scale, and intensity of environmental variation) may interact, influencing populations in ways that are not independent. Absence of refugia or poor connectivity between habitats may increase sensitivity of a population to even mild environmental change (Taylor et al. 1993). For example, stream fishes in fragmented or marginal habitats are expected to suffer greater losses to climate change or displacement by non-native species (Baltz and Moyle 1993). Loss of certain life history types due to harvest or habitat alteration may also limit the ability of a population to absorb additional adverse changes to stream habitat (Frissell 1992, Frissell et al. in prep.). Thus the persistence of the habitat-biota system is dependent upon characteristics of the environment as well as the biological communities living within it (Detenbeck et al. 1992).

Given the apparently strong human tendency to view streams, landscapes and all natural resources as relatively static entities (Holling 1973), it is important to accommodate the dynamic nature of stream habitats in a conceptual framework for restoration. Stream habitats and their biota continue to evolve. Management, whether fish harvesting or land uses that affect stream habitats, introduces directive pressures to evolving stream habitat systems and thus plays a significant role in the persistence and expression of future stream habitat states. The result is evolutionary pressures on fish populations, other aquatic biota, and the ecosystem as a whole. The imperilment over wide ranges of native salmonids suggests that anthropogenic pressure is too severe, or too irregular or too rapid to allow adaptation to occur; refugia that remain in the landscape are inadequate to allow populations to persist; disturbance is pervasive and persistent across the landscape and over generations of salmon, or the genetic and life-history diversity attributes that allow persistence have been lost or suppressed (Meffe 1992, Reiman et al. 1993). Dominant patterns of land use and fish harvest management which seek to impose stability may in fact endanger resiliency by limiting the opportunities for future biotic and habitat diversity across the landscape.

RESTORATION MANAGEMENT

Within the conceptual framework outlined above, stream habitat restoration should be defined and evaluated as a release of habitat capacity expression; i.e. the reversal of human influences that have suppressed the evolution of desired habitat mosaics. Restoration involves at least four steps: expanding and clarifying the vision of the full expression habitat capacity; identifying anthropogenic pressures that constrain this expression; relieving these constraints; and monitoring resource response to an expanded and enriched habitat expression.

Expression of Stream Habitat Capacity in Intact Landscapes

A first step of restoration is recognizing the importance of the historic developmental diversity of the intact landscape (Sedell and Luchessa 1981). By this we mean the ecosystem processes and structures and their temporal patterns of change that have provided the template to which native fauna are adapted (Poff and Ward 1990). While fully characterizing the historical habitat template is impossible, reconstructing suites of habitats and historic regimes of environmental fluctuations can help orient restoration of ecosystems toward some dynamic state that will be less likely to exceed the persistence thresholds of native biota. The more complex the system of interest and the less complete our understanding of the historical template, the more general will be the guidelines for restoration. More explicit guidelines will emerge with specific investigations of habitat developmental diversity.

We emphasize the historical habitat template as the best empirical reference because it suggests the range of habitats and temporal dynamics which have been expressed and that may be required for the sustenance of biota. An examination of the historical template highlights the processes, structures and biota that have been eliminated or suppressed and which, if not restored, cannot to contribute to the regeneration and persistence of desirable ecosystem attributes. One example might be the keystone importance of salmon carcasses in enrichment of headwater stream and riparian communities (Cederholm et al. 1989); once salmon runs are depleted or extinct, a critical nutrient source is lost and ecosystem recovery may be arrested.

A wide variety of techniques have been used to reconstruct historic landscape and community structures. Historic data of interest may include the distribution of plant and animal species, physical characteristics of soils, hydrology and nutrient distributions as well as temporal patterns of change such as variation in population sizes, stability of substrates, fire frequencies and hydrographs. Sources of historical data include journals, survey records, commercial catch data, trapping records, and oral histories as well as data requiring more sophisticated interpretation such as photographs, sediments, pollen, dormant seed banks and soil carbon (see Sedell and Luchessa 1981 for a review).

Identification of Anthropogenic Constraints

The second step of the restoration strategy entails identification of the anthropogenic pressures that limit habitat expression. The objective of this section is to describe how a general conceptual framework will be useful in determining system constraints. Conceptual frameworks guide the acquisition of specific knowledge of system functions by providing the contexts from which hypotheses emerge. Conceptual frameworks also order and synthesize knowledge acquired through specific investigation and analysis.

For streams, investigations of habitat constraints is best guided by an understanding of system capacity. Knowing the potential developmental pathways and processes of a habitat system can direct specific questions regarding factors constraining desirable habitat expression. For example, the capacity of alluvial rivers to express active floodplains and strong linkages with riparian vegetation and alluvial aquifers has long been perceived; this understanding has provided a context for investigations of specific mechanisms linking or isolating floodplain-riverine functions (e.g. Sedell and Frogatt 1984, Stanford and Ward 1988) and a growing knowledge of the importance of these linkages to riverine productivity and biotic integrity (Junk et al. 1989, Stanford and Ward 1992). As a result, channelization, diking and floodplain deforestation are now seen as constraints to desireable stream and riverine habitat expression. "Re-linking" floodplains to river channels and restoring floodplain function has in consequence emerged as a prominent strategy for river restoration (Spark et al. 1990).

Contextual understanding also provides a heuristic function by encouraging the extension of general concepts (e.g. landscape linkages, hierarchies, patch-dynamics) to specific investigations. Research of stream and riparian ecosystems increasingly suggests that suppressing factors tend to decouple ecosystem processes and remove elements that formerly linked ecosystem components in ways to which native biota have long adapted. For example, the removal of floodplain forests eliminates sources of channel structure, alters floodplain hydrology and microclimate influencing channel morphology, streamflow and temperature characteristics (Hewlett and Fortson 1982), decoupling the physical and chemical links between floodplain vegetation and stream habitat (Gregory et al. 1991). Similarly, the removal of salmon biomass from headwater streams eliminates a nutrient return to headwater streams, severing a trophic link between the ocean and headwater environments (Mathisen et al 1988).

The general concepts of system capacity and development and derived contextual applications such as hierarchical habitat classifications provide overarching frameworks for investigations of stream and riparian habitat dynamics (Swanson et al. 1988). For example, habitats of a given class may share similar perturbation patterns, and hence be subject to similar constraints of habitat expression. Habitat or landscape classes can also be expected to differ in land use sensitivity and response (Frissell et al. 1986, Nelson et al. 1992). Habitats classified as possessing similar potential but differing in developmental trajectories due to differing environmental conditions or land uses can provide valuable case histories of how habitats develop under various constraints (Leonard et al. 1992, Naiman et al. 1992). Remnant and recovering patches of stream habitat may provide examples of habitat persistence and recovery; inferences derived from analysis of altered and remnant habitat development can guide the generation of hypotheses and investigations of constraint processes.

In summary, the identification of system constraints should start from an understanding of the capacity of the stream habitat system. A capacity-oriented classification can provide a template for habitat description, allowing the discrimination of habitat classes subject to various constraints and perturbations. From this framework, specific investigations of habitat trajectories and developmental pathways (Gebhardt et al. 1987) can be developed, allowing the cataloging (sensu Westoby et al. 1989) of stream habitat transitions and constraints.

Relief of Anthropogenic Constraints

Following the identification of factors suppressing habitat capacity expression, we can begin to identify the steps necessary to relieve them. It will be important to do so in a manner that allows biotic adaptation and persistence. The limitations of knowledge and management ability may constrain the degree to which relief can be applied or stressors removed. In this case, identifying and prioritizing critical processes and locations to be restored as well as the specific tasks necessary to best initiate restoration will require the knowledge and experience of personnel familiar with the capacity of the system in question. This knowledge and familiarity will be enhanced by the previously described investigation of habitat capacity and suppressing factors. Generally, the guidelines for coarse-scale restoration management would include at least two primary tasks:

Protect the Remaining Intact Systems

Intact riparian ecosystems and watersheds provide the examples of processes operating largely unaffected by human activity and thus provide the reference for detecting anthropogenic effects on streams. These are the *de facto* controls for the landscape "experiments" humans via land uses are conducting on natural processes and biotic communities (Hughes et al. 1990). By providing examples of unimpeded expressions of habitat capacity, intact systems enable fuller definitions of the potential performances of impacted watersheds, and could aid in detecting interactions of suppressive perturbations such as land use with capacity-altering processes such as climate change. Throughout the landscape, it will also be necessary to protect and preserve the components of resilience; i.e. those elements and processes that enable system recovery and persistence. For streams, examples include floodplain forests which can contribute channel structure and regulate valley microclimate, and events like flood and wildfire that propel recovery by mobilizing structures and nutrients and eliminating non-native biota (Meffe 1984, Stromberg et al. 1993). However, it will be critical to consider how the potential roles of formerly integral landscape processes have changed with land use and an altered habitat structure. Processes and events benign or even beneficial to native organisms in intact landscapes may endanger native biota persistence in degraded or altered landscapes (e.g. Collins et al. 1981).

Acknowledge Low-Resilience and Critical Habitats

Recovery of habitats by removal of system constraints relies upon the existence of the necessary recovery elements and processes or the ability to rapidly regain them. Examples from riparian-stream ecosystems altered by domestic livestock grazing include the vegetative species pool and sediment regimes that provided the successional and soil-building conditions for the riparian system prior to grazing. If, however, events that have occurred since the initial shift to the stable degraded state have eliminated critical elements (like the invasion by exotics or extinction of native species) or shifted critical processes (climate change that shifts the precipitation regime) or crossed a geomorphic threshold (Schumm 1979), the system may be viewed to have shifted domains, i.e., alteration of potential capacity. In this case, due to the environmental changes that have occurred, system capacity is sufficiently altered that a return to the domain of historic desirable habitat expression may be extremely difficult. While livestock grazing or some other anthropogenic event may be identified as a primary pressure, climatic or other environmental changes may provide secondary mechanisms that induce change to system capacity, and may inhibit return to a pre-disturbance regime. Restoration assumes some inherent resiliency in the system; that is, the system must be able to reexpress its potential capacity.

Stream habitats lacking resilience should be protected, as restoration may be most difficult there. Watersheds exhibiting long recovery trajectories, such as low-gradient river channels in an unstable, sediment-rich high-gradient granitic landscape like the South Fork Salmon River, Idaho (Platts et al. 1989) are much more easily provided protection than restored. One of management's shortcoming so far has been a failure to recognize and protect such systems adequately, perhaps due to mistaken assumptions of equal natural recovery and resilience capacities across the landscape.

Remnant critical habitats, spawning and rearing areas, and those habitats and associated landscapes required for the long-term viability of the biota ("centers of organization" Steedman and Regier 1987, or "refugia" Sedell et al. 1990), should be priorities for restoration. If, for example, alluvial valleys in the Pacific northwest provide critical habitat for salmon and steelhead (Reeves and others 1987, Frissell 1992), then landscape strategies that seek to "anchor" anadromous salmonid habitat within federal land reserves (FEMAT 1994) while necessary as stop-gap measures may be inadequate by themselves (Reeves and Sedell 1992), since the majority of low-gradient historically productive alluvial valley segments occur on private lands (Karr and Chu 1994). The need for effective distribution of restoration efforts between portions of the landscape that are interdependent but differ in ecological function and resilience highlights the importance of a classification that addresses the capacities of landscape elements as well as the connections between them.

Restoration Monitoring

A successful strategy should include a monitoring program that is sensitive enough to capture responses to management activities and changes of system environmental and biotic diversity at many scales (Noss 1990). Defining parameters to measure and standards to uphold while resisting premature conclusions are a few of the demanding aspects of a monitoring scheme (Lawson 1993). Just as the goals of capacity management are not measured simply by numeric yield, so the performances measured in monitoring will often be qualitative, seeking to capture responses in species persistence and an expanded, resilient and adaptable habitat and resource capacity. Responses of species persistence may for instance be defined by an increased range in occupied habitat types that indicates that a species' life history diversity is increasing in response to an increasing habitat diversity. An expanded habitat capacity expression could be described as an increased range of progressional pathways; in western U.S. watersheds, this might look like an expanded diversity of riparian shrub communities, the recovery of floodplain forests, and the re-establishment of beaver pond complexes.

SUMMARY

We propose that stream habitat restoration be based upon a solid conceptual framework; we present one framework that builds upon concepts of system capacity and development. Our conclusion is that certain expressions of stream habitat capacity are currently suppressed by human land use pressures that interfere with desirable habitat development processes and ecosystem linkages. The task for restoration management includes identifying the differing capacities for habitat development throughout the managed riverscape, identifying the stressors that limit desirable habitat expression, relieving those stressors and monitoring the response of both stream communities and habitats. Recognizing system capacities that have been fundamentally altered is also critical to avoid unrealistic expectations for restoration as well as to identify systems that require protection.

We believe the assumption that a re-expression of the dynamic conditions with which the native fauna evolved will most likely allow that fauna to persist over time is a sound basis for a restoration framework.

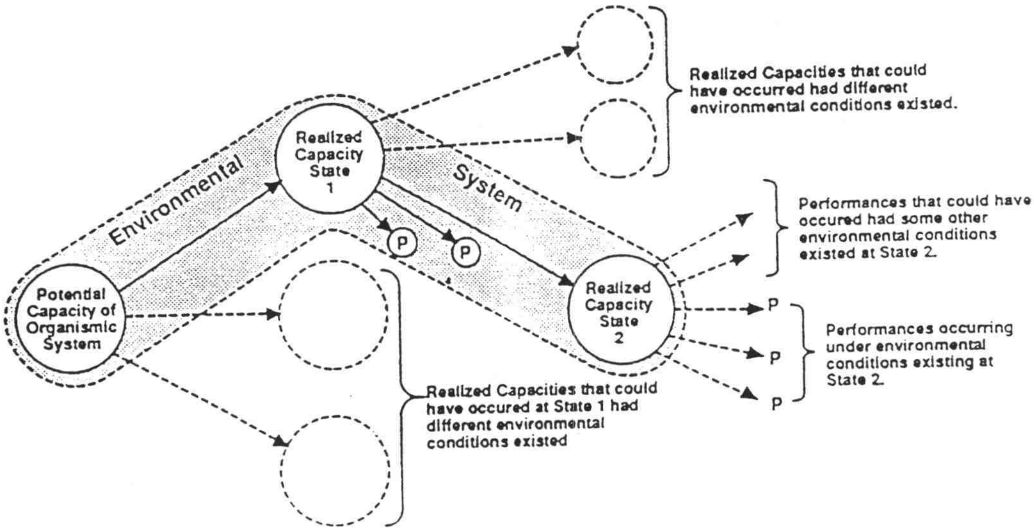


Figure II.1. A system develops in response to environmental change and within the constraints of its potential capacity. After Warren et al. (1979).

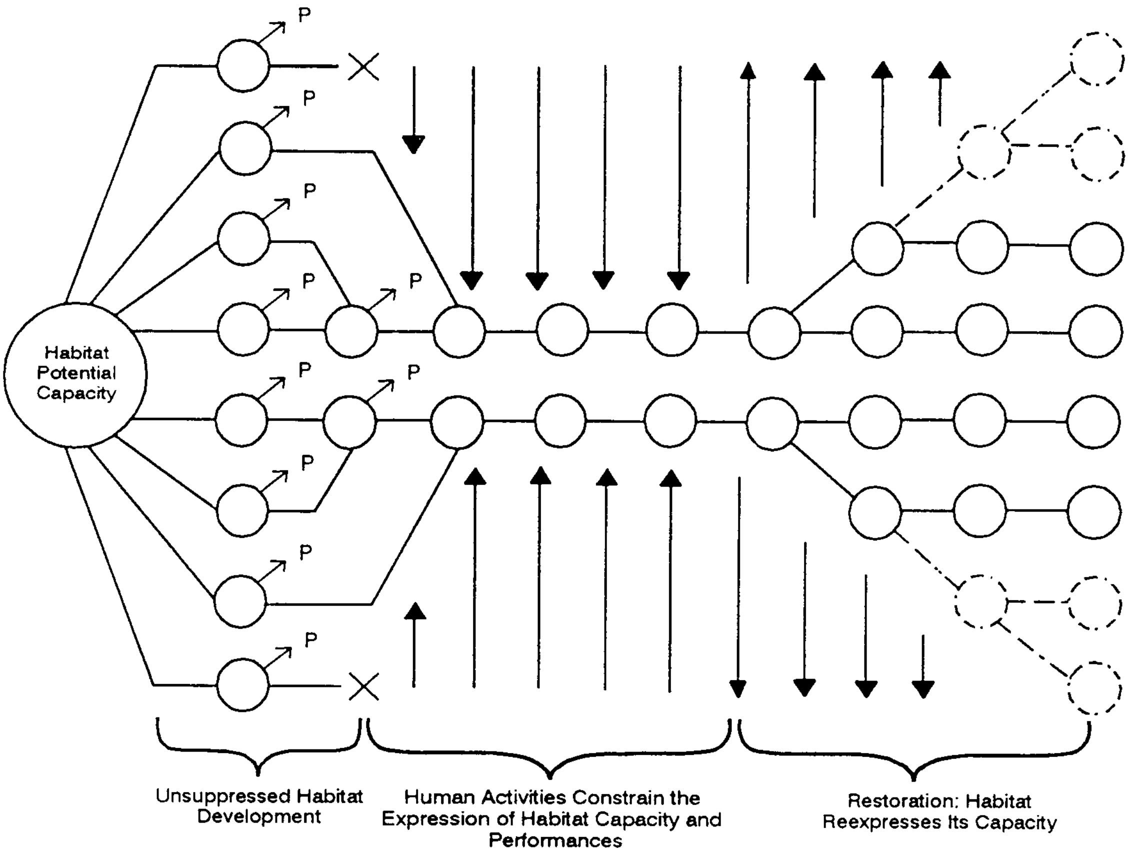


Figure II.2. The expression of the potential capacity of a habitat system yields an array of developmental pathways and habitat performances (P). Human activities can constrain habitat capacity expression by suppressing habitat diversification or eliminating specific performances (inward arrows). Restoration occurs when habitat capacity is reexpressed following the release of anthropogenic suppression (outward arrows).

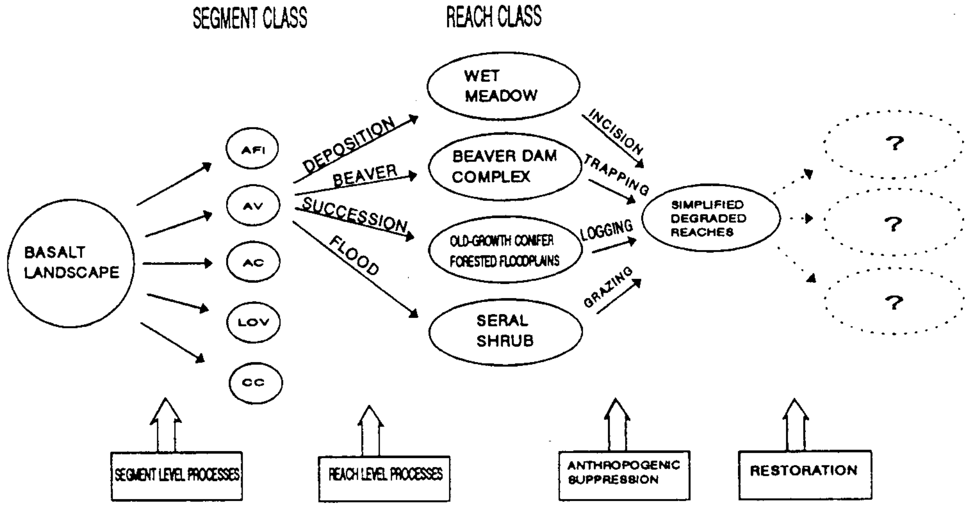


Figure II.3. An example of stream habitat development in a basalt landscape, showing pathways of reach development, suppression and restoration.

Table II.1. Some events and processes controlling stream habitat on different spatiotemporal scales (After Frissell et al. 1986).

System level	Linear Spatial Scale[a] (m)	Evolutionary events[b]	Developmental processes[c]	Time scale of continuous potential persistence[a] (years)
Stream system	10^3	Tectonic uplift, subsidence; major volcanism; glaciation; climatic shifts	Planation; denudation; drainage network development	10^6-10^5
Segment system	10^2	Minor volcanism; earthquakes; very large landslides; alluvial or colluvial valley infilling	Migration of tributary junctions and bedrock nickpoints; channel floor downwearing	10^4-10^3
Reach system	10^1	Debris torrents; landslides; log input or washout; channel shifts, cutoffs; beaver damming; channelization, diversion, or damming by man	Aggradation/degradation associated with large sediment-storing structure; bank erosion; riparian vegetation succession	10^2-10^1
Pool/riffle system	10^0	Input, washout of wood, boulders; flood scour, deposition; thalweg shifts; numerous human and livestock activities	Small-scale lateral or elevational changes in bedforms; minor bedload resorting	10^1-10^0
Microhabitat system	10^{-1}	Annual sediment, organic matter transport; scour of stationary substrates; seasonal macrophyte growth and cropping	Seasonal depth, velocity, temperature changes; accumulation of fines; periphyton growth	10^0-10^{-1}

[a] Space and time scales indicated are appropriate for a second- or third-order stream.
[b] Evolutionary events change potential capacity, that is, extrinsic forces that create and destroy systems at that scale.
[c] Developmental forces are intrinsic, progressive changes following a system's genesis in an evolutionary event.

Table II.2. General variables for classifying stream habitats by potential capacity[a] (After Frissell et al. 1986).

Watershed	Stream system	Segment	Reach	Pool/riffle	Microhabitat
Biogeoclimatic region	Watershed class	Stream class	Segment class	Reach class	Pool/riffle class
Geology	Long profile slope, shape	Channel floor lithology	Bedrock relief, slope	Bed topography	Underlying substrate
Topography	Network structure	Channel floor slope	Morphogenic structure or process	Water surface slope	Overlying substrate
Soils		Position in drainage network	Channel pattern	Morphogenic structure or process	Water depth, velocity, temperature
Climate		Valley sideslopes	Local sideslopes, floodplain	Substrates immovable in <10-year flood	Overhanging cover
Biota		Potential vegetation	Bank composition	Bank configuration	
Culture		Soil associations	Riparian vegetation state		

[a] Not all variables are necessary to distinguish classes in all circumstances; best specific indices may vary regionally or with study objectives.

Chapter 3: Lotic Habitat Classification and Thermal Refugia in a Basin of the Blue Mountains of Northeast Oregon

INTRODUCTION

Populations of anadromous salmonids native to the Columbia and Snake River basins have declined precipitously over the past century (Nehlsen et al. 1991). Losses of habitat quantity as well as quality in tributary streams have been documented (Sedell and Everest 1990, McIntosh 1992). The degraded conditions of headwater rearing and spawning habitats are strongly implicated in salmonid stock declines (Nehlsen et al. 1991, Frissell 1993). Specific stream habitat concerns include high summertime water temperatures, excessive sedimentation of spawning gravels, insufficient high-quality holding habitat for adults and lack of complex rearing habitat for juveniles (NPPC 1987, USDA Forest Service 1991). These degraded stream conditions are widespread throughout Columbia and Snake river basin tributary streams. Large scale rehabilitation efforts including riparian fencing, planting, channel structure placements are underway in response to these concerns (Jensen and Platts 1990).

Despite a long history of pervasive habitat degradation, portions of stream networks that provide sufficiently cold, unpolluted water, clean spawning gravels or complex holding and rearing habitats remain in the basin. Additionally, stream habitats subject to rehabilitation efforts such as riparian fencing, planting or channel structure placement may potentially contribute to favorable salmonid habitats if physical and biotic recovery is facilitated. Sedell et al. (1990) describe the potentially critical importance of favorable aquatic habitats within otherwise hostile or degraded environments. The role of such habitats, termed refugia, may be important for the continued persistence and restoration of Columbia and Snake River basin salmonids (e.g., Berman and Quinn 1991).

Lotic habitat refugia exist across multiple spatial and temporal scales (Sedell et al. 1990). At watershed scales (*sensu* Frissell et al. 1986), refugium habitats include watersheds entirely or partially within roadless and federally-designated wilderness areas (Karr and Chu 1994). At smaller stream segment or reach scales within managed landscapes, habitats providing critical functions may be associated with tributary or groundwater inputs (Kaya et al. 1977, Meisner 1990), intact riparian vegetation (Barton et al. 1985) or beaver dam complexes (Gard 1961). At microhabitat scales, lotic refugia include channel structures providing shelter for stream organisms during spates (Hartman 1963); hyporheic or interstitial waters providing chemical, thermal or hydraulic refuge (Stanford and Gaufin 1974, Williams and Hynes 1974); and cold water pockets providing thermal refuge within seasonally warm streams (Latta 1964, Gibson 1966, Nielsen 1993).

Several authors have called for the identification of the spatial distribution and characteristics of lotic habitats potentially serving as refugia (Hynes 1983, Sedell et al. 1990, Bisson et al. 1992). Identifying these habitats can guide land use management and habitat protection efforts (Shephard et al. 1986). The purpose of this paper is to describe potential refugium habitats for anadromous salmonids in a Snake River basin tributary stream disturbed by logging, road-building and grazing. Specifically, we asked the following questions. Do reaches with relatively dense and robust riparian vegetation provide distinct instream habitats, potentially serving as refugia? Do cold-water microhabitats exist in warm reaches of the stream network? If so, where do they occur and what are their characteristics? Additionally, what valley segment classes (*sensu* Frissell et al. 1986, Cupp 1989, Frissell 1992) provide the geomorphic context and proximate controls on lower level habitat (and refugia) development?

METHODS

Study Area

The study area is the 1500 km^2 Joseph Creek basin. The basin is located in northeast Oregon and southwest Washington within the Blue Mountain physiographic province, a region underlain by the Grande Ronde basalts, a member of the Columbia River basalt group. Terrain is characterized by gently folded basalt layers overlain by extensive loess and ash deposits (Camp and Hooper 1981). Stream courses generally follow alluviated troughs; in areas of sufficient uplift channels sharply dissect the basalt terrain into a mosaic of finger ridges and steep canyons. Adjacent to the Wallowa Mountains, valley landforms show evidence of glacial scour, outwash and overflow (Orr et al. 1992).

The climate is transitional, sharing characteristics of the moist mediterranean climate to the west and the dry interior mountain climate to the east. Most precipitation falls as snow, with peak stream discharge generally occurring March to May. Summer cloudbursts contribute locally heavy rainfall, initiating flash flooding and debris flows in steeper terrain. Summer maximum air temperatures often exceed 30° C, and winter minimum air temperatures often fall below -5° C.

Natural vegetation varies with elevation and aspect (Johnson 1982). Ponderosa pine/mixed conifer forest (*Pinus ponderosa, Abies grandis, Abies lasiocarpa, Pseudotsuga menziesii, Picea englemannii Pinus contorta, Larix occidentalis*) interspersed with shrub/grassland steppe (*Physocarpus spp., Symphoricarpus spp., Agropyron spp., Festuca spp.*) dominates the uplands. Valley bottom vegetation includes hardwood shrubs and trees (*Salix spp., Alnus spp., Populus spp., Creataegus columbiana* and *Cornus nutallii*).

Approximately 40% of the Joseph Creek watershed, predominantly higher elevation forest lands, is in U.S. Forest Service ownership. Road densities on federal forest lands in the basin approach 4 km/km^2, and few unroaded and unlogged stands remain (Wallowa Whitman National

Forest, unpub. data). The remaining private land is predominantly managed for livestock grazing, agriculture and timber. Riparian restoration and stream habitat rehabilitation projects including corridor fencing, riparian planting, log weir, boulder berm and rip-rap placement have been initiated on private lands by the Bonneville Power Administration and Soil Conservation Service and on federal lands by the U.S. Forest Service (Lacey et al. 1992). These activities are in response to concerns of fish habitat and water quality degradation associated with logging, grazing and roading in the basin. Fish species of concern include summer steelhead (*Oncorhynchus mykiss*) and a threatened population of chinook salmon (*Oncorhynchus tschawyscha*) present in nearby drainages but presumed extinct in the Joseph Creek system (Thompson and Haas 1960). These land use patterns, fish habitat, and water quality concerns make Joseph Creek basin typical of many mixed-ownership watersheds in the western United States where the cumulative impacts of a wide range of land uses have induced extinctions of aquatic fauna through habitat loss and pollution (Miller et al. 1989).

Valley Geomorphology

The first task was to identify variability in valley geomorphology by applying a valley segment classification to the Joseph Creek basin. To enable the conceptualization of stream habitat variability imposed by processes operating over multiple spatial and temporal scales we applied a hierarchical watershed habitat classification (Frissell et al. 1986). Drainage networks and their associated habitats can be conceptually organized as a spatio-temporal hierarchy extending from the regional and basin levels with processes operating over millennia to microhabitat levels with annual or seasonal processes (Table II.1)(Swanson 1980, Frissell et al. 1986). Valley segments are sections of the stream and its corridor where formative processes occur over 10^3-10^4 years and features are defined at scales of 10^2-10^3 meters. At these scales, segment characteristics are relatively unalterable by the predominant human land use activities and relatively frequent ($10-10^2$yr) natural events. Valley segment classes are defined by attributes such as valley and stream adjacent landforms, valley fill material and valley slope (Table II.2)(Frissell et al. 1986).

We used air photos, topographic maps and field reconnaissance to stratify valley segments by valley geomorphology, following methodologies of Frissell (1992). Thirty-one segments were classified into five valley classes. During the summer of 1991 and 1992 we collected floodplain and channel morphology data by establishing four to fifteen cross-valley transects within each valley segment. Sampled valley segments were selected roughly in proportion to their areal extent in the basin. At each transect we measured widths of valley fill surfaces, slopes of adjacent valley walls, channel widths, depths, and gradient.

Riparian Vegetation and Reach Level Habitat

The second task was to examine stream habitat characteristics of reaches expressing relatively well-developed riparian vegetation. Air photos (approximate scale 1:20000) from several USDA flights taken between 1938 and 1987 were examined to identify reaches that had maintained or recovered relatively dense riparian vegetation over this time interval. Our goal was to pair well-vegetated reaches with nearby reaches that were unfenced or from which riparian trees and shrubs had been removed. Reach pairs were selected for similar hydrologic and geomorphic characteristics (within the same valley segment class). Potential riparian vegetation was presumed to be similar between pairs. We found sites with substantial remnant riparian shrub vegetation, particularly in alluvial valleys, to be uncommon. Reaches with vigorously regenerating riparian shrubs are increasingly common due to recent extensive fencing and livestock management efforts. However, due to a lack of suitable control or unfenced sites, few could be suitably paired with nearby devegetated but geomorphically-similar reaches that to the best of our knowledge differed only in management history. Eventually, four fenced sites

(A-D Table III.3) (hereafter termed "fenced" reaches) with regenerating riparian vegetation were paired with similar sites nearby that were not fenced to exclude livestock grazing (hereafter called "open" reaches). Additionally, two sites with remnant vegetation ("remnant" reaches) were suitably paired with nearby similar ("open") reaches that had been devegetated by logging or other anthropogenic factors (Table III.3).

Twenty evenly-spaced transects were sampled perpendicular to the stream channel within each 200-400 meter long reach. At each transect, active channel width, depth and water depth were measured with meter stick and measuring tape. Riparian canopy density was estimated using a spherical densiometer (Platts et al. 1987). Occurrence of stable, vertical/overhanging vegetated banks (bank angle $\leq 90°$; Platts et al. 1987) or eroding banks was noted at each transect. Additionally, a 200 meter continuous survey of channel unit composition (as defined by Bisson et al. 1982) and dimensions along with a continuous tally of woody debris was conducted over the reach length. Reach data were summarized by reach and examined for differences between pairs using the Wilcoxon signed ranks test.

Thermal Heterogeneity

We also examined the frequency of occurrence and characteristics of microhabitat-scale groundwater-fed thermal patches, termed "cold pools" after Keller and Hofstra (1983). These were identified by wading and probing sections of stream channel with a digital thermocouple thermometer with a sounding probe taped to a 3.5m telescoping fiberglass pole. Temperatures were measured between mid-June and early September 1992 during periods of low flow when ambient stream water temperatures exceeded 16° C, allowing the detection of inflowing groundwater at least 3° C colder than ambient streamflow (Ozaki 1988). Surface area of each cold pool was estimated from measured width and length. Maximum depth of each cold pool was measured. Mean depth was measured for a subset of cold pools to establish a relationship between mean depth and maximum depth. This relationship was used to extrapolate mean depth to all pools measured for maximum depth. Volume was then estimated for all cold pools by multiplying measured surface area by estimated mean depth. Estimated volumes were transformed ($\log_{10} x$) to induce normality for subsequent analysis. We sketched cold pool location in relation to the stream channel, floodplain and adjacent structures and classified cold pool types on the basis of geomorphic context and apparent origin (Bilby 1984). Two continuously recording thermographs were placed at selected cold pool sites. One was placed in a cold pool and another in the adjacent main streamflow. Both were in place for several days at each site to monitor simultaneous diel fluctuation in cold pool and main streamflow temperatures.

RESULTS

Valley Segment Classification

Five major valley segment types that differ with respect to valley landform associations were identified (Figure III.1, Table III.1). Valleys, which contain floodplains many times the active channel width, are differentiated from canyons, which express little or no floodplain development (Frissell and Liss 1986, Cupp 1989, Frissell 1992). Three classes of valleys and two classes of canyons were recognized, based on differences in valley landform and geomorphic origin; Alluvial Valleys (AV's), Alluvial-Fan-Influenced Valleys (AFV's), Leveed-Outwash Valleys (LOV's), Alluviated Canyons (AC's) and Colluvial Canyons (CC's). These classes are similar to those described by Frissell and Liss (1986), Cupp (1989) and Frissell (1992). Alluvial valleys are characterized by low-gradient, wide floodplains of alluvially-deposited sediments (Table III.1). Contact of the channel with the hillslope is infrequent. Alluvial deposition and channel switching strongly shape floodplain and channel morphology. Alluvial fans occur frequently at the valley margins, but only locally impinge upon the channel; floodplains are the dominant stream-adjacent surface.

Leveed-outwash valleys are much steeper in valley and sideslope gradient than alluvial valleys. Leveed-outwash valleys are filled with bouldery debris flow deposits and valley floors exhibit a bermed and channeled surface, suggesting a history of dramatic channel shifting and high energy flood and debris-flow events. Channel-adjacent surfaces are most frequently coarse bermed and channeled floodplains with occasional contact with competent bedrock or colluvial-complex toe slopes, colluvial fans or aprons. Channel pattern can best be described as erratic, shifting across the valley surface from swale to swale, with side channels common.

Alluvial-fan-influenced valleys are characterized by the frequent occurrence of alluvial fans and aprons originating from tributaries adjacent to the stream channel. Short inclusions of alluvial fill frequently occur immediately upstream from large fans that laterally constrain the valley. Channels are often highly sinuous and generally course around massive fan toes that strongly determine the lateral location of the channel within the low-gradient valley. Coalescing fans and aprons provide a complex valley surface across which secondary channels or wetlands develop.

Of the two canyons described in the study area, alluviated canyons possess the greater degree of floodplain development. Alluviated canyons are commonly found upstream of alluvial valleys. Valley widths average seven times the active channel width and floodplains of cobble/gravel alluvium are characteristically crescent shaped. Channel-adjacent surfaces are alternately floodplains or hillslopes. Secondary channels may occur between the floodplain and the hillslope toe. Channel pattern is slightly sinuous, alternating from hillslope to hillslope across the narrow, moderate-gradient valley floor.

Colluvial canyons develop almost no floodplain surfaces, as channels are constrained by encroaching colluvial complex slopes. Valley widths are approximately one to two times the active channel widths. Toe slopes are the nearly exclusive stream-adjacent landform, contributing large boulders, trees and finer sediments directly to the stream channel. Channel pattern is relatively straight. Colluvial canyons are rare in the basin in third-order and larger stream valleys but predominate in many steep headwater valleys.

Additional valley segment classes observed within the study area include bedrock canyons and moderate slope bound valleys (described in Frissell and Liss 1986 and Cupp 1989). These are not described here due to rarity and lack of data.

Habitat Differences Between Paired Reaches

Several reach habitat attributes differed significantly between paired reaches (Wilcoxon signed ranks test, $p<0.05$)(Table III.2). Reach canopy density, a measure of percentage of sky obscured by overhanging vegetation or topography, was significantly higher for fenced and remnant reaches compared to paired open reaches. Frequency of thalweg pools was also significantly higher for fenced and remnant reaches compared to paired open reaches. Fenced reaches had significantly narrower active channels and contained more pool/riffle habitat types per channel distance than paired open reaches. Fenced reaches also had a significantly higher proportion of bank transects in the overhanging vegetated category and less in the actively eroding category than adjacent open reaches. Mean active channel depths, width-depth ratio, and woody debris frequencies did not differ significantly between fenced, remnant and open classes (Table III.2).

Five of the six reach pairs were probed for discrete cold water microhabitats. More cold pools per channel distance were located in three of the four fenced and one remnant reaches surveyed than in adjacent open reaches (Wilcoxon signed ranks test, $p<0.05$). Interestingly, one recovering reach (reach A on Peavine Creek, fenced for over twenty years) had eight cold pools within the 200 meter length surveyed. This is the highest frequency of cold water microhabitats of any surveyed reach in the basin. This reach also had a proportionatey much higher percentage of overhanging vegetated banks and a narrower active channel than all other paired reaches (Table III.3).

Cold Pool Classification

Eighty-eight discreet cold water pockets were located, measured and sketched during summer thermal probing. An additional ninety-five cold water pockets were identified and temperatures recorded but were not measured for area or depth. Mean surface area of these additional sites was estimated to be less than 0.5 m^2. From field sketches and descriptions, we classified each cold pool into one of seven categories, based upon morphology and orientation in relation to the thalweg channel and floodplain (Figure III.2). Six of the classes are off-channel habitats, and one of these is isolated, at least during summer base flows, from the main thalweg channel. **Floodplain tail seeps** occur near the downstream "tail" of the floodplain where the active stream channel intercepts floodplain groundwater flow networks. Cold groundwater emerging from the floodplain may collect in backwater alcoves or seep directly into the main channel flow. **Floodplain seeps** are defined by spring-like flow emerging on the floodplain surface, flowing across the floodplain surface to join the main channel. Many appear to have stable flows and abundant aquatic macrophytes. **Floodplain ponds** are defined by a lack of surface inflow or outflow during base flow periods and are primarily deep remnant pools of former channels that have become isolated by channel shifting. **Side channel seeps** are similar in general appearance and orientation to floodplain seeps but emerge from active side channels, the beds of which are subject to annual scour. Their discharge appears to be tightly linked to the ambient flow. Several side channel seeps became series of isolated pools as main streamflow discharge dropped. **Lateral seeps** occur where the active channel directly intercepts groundwater flow through a terrace, alluvial fan or hillslope. These cold water sources, while very frequent, are generally very small in volume occurring in shallow stream margins where inflowing cold groundwater is rapidly mixed with the main flow. **Debris-jam backwater pools** occur below channel obstructions that create sediment dams and a sharp break in channel bed longitudinal profile. Cold interstitial water emerges below the obstruction and sediment wedge to collect in channel depressions. **Stratified pools** occur in low gradient channels where pool depths are great enough and inflow weak enough to allow stratification, or the establishment of a cold water pocket in the pool bottom.

Several characteristics of cold pools differed significantly between one or more of the cold pool classes. Mean minimum temperatures for cold pools ranged from 13.7 to 15.9 °C, during periods when the main streamflow temperature ranged from 17.0 to greater than 24.5 °C (Table III.3). Mean minimum cold pool temperatures differed between cold pool types. Floodplain seeps, side channel seeps and floodplain tail seeps are significantly colder by several degrees Celsius than stratified pools and lateral seeps (ANOVA, $p<0.05$). Floodplain ponds and backwater pools are intermediate in mean minimum temperature. Cold pool temperatures were not significantly associated with elevation or cold pool maximum depth as determined by simple linear regression. Two stratified pools monitored continuously for several days show that fluctuations in cold pool temperature may follow diurnal patterns similar to, but more moderate than, the temperature fluctuations of the main streamflow (Figure III.4).

Mean maximum depths differed between cold pool types, but only significantly (ANOVA, $p<0.05$) for stratified pools, which were much deeper (one-half meter deeper on average) than all other cold pool classes (Table III.3). This difference is also reflected in cold pool volumes, which were significantly greater for stratified pools than all other cold pool classes (ANOVA, $p<0.05$).

Within the study area, patterns of cold pool occurrence and associations with floodplain and channel form are evident. Colluvial canyons are excluded from this analysis due to an inadequate length of channel surveyed. Cold pool classes are not distributed equally among the remaining four segment classes (Table III.4). Floodplain tail seeps are most frequent in alluvial valleys and floodplain seeps are most frequent in leveed-outwash valleys. Floodplain ponds occur almost exclusively in alluvial valleys and some wider alluviated canyons. Side channel seeps are most frequent in alluviated canyons. Lateral seeps, backwater cold pools and stratified pools are all most frequent in alluvial valleys. Overall, alluvial valleys have highest frequencies of cold pools of all types, followed by alluviated canyons, leveed-outwash valleys and alluvial-fan-influenced valleys (Table III.4).

We found high variability in cold pool frequency between surveyed reaches, even within a segment class. Often, one or two reaches within a segment class had very high frequencies of cold pools, while others had none. Several reach characteristics are associated with this variability. Regressions of reach cold pool frequency against a set of characteristics that contribute to channel complexity yielded several positive, but highly variable, relationships. Cold pool frequency is positively related to reach thalweg pool frequency (R^2=0.34, p=0.003), large woody debris frequency (R^2=0.18, p=0.026) and backwater pool frequency (R^2=0.21, p=0.042) (Figure III.3). Canopy density, covariance of canopy density, and covariance of active channel depth are not significantly related to cold pool frequency.

DISCUSSION

Cold Pools as Potential Habitat Refugia

The unequal distribution of cold pools among valley segment classes may reflect differences in channel and floodplain features between segment classes. Specific relationships between groundwater flownet patterns and local geomorphology could be explored with seepage meters, mini-piezometers and floodplain wells (Lee and Cherry 1978, Ozaki 1988). Floodplain seeps, defined by steady, spring-like flow emerging from floodplain depressions, occur in alluvial valleys and alluviated canyons, but are most frequent in leveed-outwash valleys, where steep valley gradients, abundant abandoned channels and coarse (and presumably highly transmissive) (Whitehead 1992) valley fill materials create conditions likely favorable for flow of water between channels, banks and floodplains. Floodplain ponds, formed by channel migration or switching, are nearly unique to alluvial valleys, where floodplains are wide enough to allow channel migration and pool isolation. However, no floodplain ponds were identified within leveed-outwash valleys where valley floors are similarly wide and channel switching is frequent. Side channel seeps are most frequent in alluviated canyons, where secondary channels frequently follow hillslope toes. This position within the narrow floodplain may allow these side channels to intercept relatively high proportions of hillslope groundwater thus maintaining cooler temperatures relative to the main channel flow. Stratified pools are primarily limited to low-gradient channels, and are most abundant in alluvial valleys where pools are sufficiently large and deep to resist mixing by inflowing currents, allowing stratification. Stratified pools also occurred in other valley segment types when low summer flows dropped to the point that pool mixing was greatly reduced. Nielsen (1993) found stratified pools to be most numerous in wider valley settings in coastal California streams. Overall, wide alluvial valleys appear to provide the greatest diversity and greatest frequency of opportunities for the channel and floodplain conditions favorable for cold pool formation.

Variation in cold-pool frequency within and among segments has several potential sources. Sampling bias imposed by site selection, sampling methods or time of sampling is a possibility. For example, detection of cold pools was dependent upon stream conditions; main streamflow water temperatures had to be sufficiently warm to allow the detection of colder pockets. This limited the available sampling period to summer afternoons. The sampling extended over an eight-week period, during which stream temperature patterns, streamflows and groundwater flow rates likely varied, with unknown effects on cold pool detection. While cold water habitats that maintain high volumes of relatively constant, cold temperatures presumably due to a predominate groundwater influence in contrast to the surrounding matrix (Figure III.4a) are likely to be detected during daytime thermal probing, sites where cold water plumes are moderated by diurnal temperature fluxes of the main streamflow have a higher likelihood of being overlooked when they warm to near-matrix temperatures (Figure III.4b).

Variation in detected cold pool frequencies between reaches could also reflect differences in basin or reach characteristics. Whitehead (1992) suggests that groundwater movements while predictable based upon basin geology may be locally heterogeneous due to faulting and variable alluvial transmissivity. Land uses may also influence groundwater-streamwater interchange rates and temperatures. Logging or other vegetation removal can lead to increases in groundwater temperature (Pluhowski and Kantrowitz 1963, Holtby 1988, Hewlett and Fortson 1983). Changes in timing and magnitude of peak flows associated with logging or river regulation may alter floodplain recharge and subsequent release into stream channels (Shephard et al. 1986) and coarse sediments from roads, grazing or logging may induce channel aggradation, widening and simplification (Lyons and Beschta 1983), increasing stream channel exposure to solar radiation. Fine sediments may reduce rates of intergravel flow leading to increased temperatures and reduced dissolved oxygen (Ringler and Hall 1975) potentially eliminating habitat for refugia-dependent organisms (Courtney 1993).

Channel configuration and structural complexity influence the degree to which cold water inflow is intercepted and stored. Keller and Hofstra (1983) and Bilby (1984) suggest that the volume of a cold water plume entering a channel from a tributary might be maximized by large wood or other structure that allowed cold water to accumulate in a backwater rather than immediately mixing with the main channel flow. Ozaki (1988), in an extensive study of cold pool formation in a heavily alluviated channel in coastal California, found large wood to provide relatively little opportunity for cold water accumulation when compared to the voluminous cold habitats provided by large backwater pools associated with bedrock outcrops and partially isolated by gravel bars. Numerous authors have suggested that floodplain isolation and channel simplification associated with channelization, logging and other land uses disconnect desirable stream-land interactions including groundwater-streamwater interchange (Sedell and Froggatt 1984, Regier et al. 1989, Stanford and Ward 1992).

We believe that colder, interstitial flow moving through relict channels and other groundwater networks seeps through the channel bed and accumulates in channel bed depressions like backwater pools and pools associated with woody debris. Where the channel is uniform, seepage into the channel is more likely to be immediately mixed and thermally overwhelmed by the main channel flow, providing little or no thermal habitat detectable by our methods. These findings concur with the conclusions of Keller and Hofstra (1983) and Bilby (1984) that cold pool formation requires adequate isolation of inflowing cold water and sufficient channel bed relief for cold water accumulation.

Multi-Scale Refugia and Restoration

We consider the individual cold pools we identified to provide potential thermal refuge at pool/riffle and microhabitat scales; that is, at areas of 1-10 m^2 and persisting over periods of weeks or months (Frissell et al. 1986). However, this is only one type of particularly small-scale refugia. While these cold water habitats may be critical for cold-water fishes during periods of thermal stress, other characteristics of stream habitats at larger spatial scales and important over longer time periods may also be important for the persistence of native fish species (Sedell et al. 1990). Stream reaches with intact riparian vegetation or with strong groundwater upwelling are larger scale (10^2-10^3 m) habitat patches providing distinct habitats (Needham and Jones 1959, Barton et al. 1985). The unique habitats and complexity associated with fenced and remnant reaches in this study may provide critical habitats in "mosaic" at scales larger and more persistent than individual pools or debris jams (Sedell et al. 1990). These habitat complexes include multiple high-quality pool\riffle sequences, beaver dam and pond networks or side-channel and backwater habitats. Habitats such as these that were historically widespread are now restricted to a fraction of the landscape. Within the study area, alluvial valleys are nearly universally severed from natural floodplain and riparian processes through channelization, floodplain deforestation, settlement, and road construction. Within this altered landscape matrix, remnant and recovering reaches that possess critical habitat structures and functions may allow the survival of sensitive biota, and serve as reach-scale refugia. For the persistence of certain aquatic organisms like salmonids that may express metapopulation dynamics, entire intact watersheds provide critical suites of aquatic habitat from first-order headwater streams to third, fourth and fifth-order valley environments. Roadless areas that retain historic process regimes and intact valley bottom environments may be the best examples of such watershed refugia. Few remain in the study region.

Stream habitat refugia have two types of restoration applications: they provide glimpses of stream habitat capacity, enlarging managers' views of restoration potential (Naiman et al. 1992, Minshall 1993) and provide "anchor points" for the extension of diverse, resilient habitats into the habitat matrix (Frissell 1993). Habitat recovery pathways and rates can be expected to vary with scale, condition of habitat environment, and degree and type of perturbation (Regier et al. 1989, Yount and Niemi 1990). Within relatively intact watersheds, thermal refugia and other microhabitat or pool/riffle scale habitats may be expected to recover relatively rapidly (10-100yr) with floodplain revegetation and recovery of floodplain hydrologic function. Recovery of suites of habitats at the reach and watershed levels will likely require centuries or more.

SUMMARY

Patches of cold water within warm streams potentially provide refuge to cold-water fishes during periods of thermal stress. Cold pool formation and spatial distribution is influenced both by valley geomorphology as well as by local riparian vegetation and stream channel expression within the valley setting. Patterns of valley fill and groundwater flow determine the capacity for cold pool development within a valley. Stream channel and floodplain configuration determine to what extent this capacity is expressed. Habitat classification at multiple scales assisted in delineating portions of the stream network possessing similar potential and sharing land use impacts.

Stream channel complexity is necessary for the expression of effective thermal refugia. Stream channel habitat complexity also provides hydraulic refuge to aquatic organisms during periods of stress. Given the extent to which aquatic habitats have been simplified by human activities, particularly within alluvial valleys, portions of stream networks that have maintained structural complexity and effective refugia may now provide disproportionate roles in sustaining populations of indigenous aquatic organisms in the face of stress, both "natural" and that imposed by habitat alteration, pollution, invasion of non-native species and exploitation. The importance and utilization of refugia, whether at the scale of cold pools, structurally complex remnant and recovering reaches, or at larger basin scales as is provided by unlogged and unroaded watersheds should be thoroughly investigated, particularly for aquatic species that are sensitive to predominate land uses and declining in resilience. The importance of refugia scale and connectivity within the landscape also needs to be understood; small refugia may be unable to sustain stressed populations if segment and basin level connectivity is severed (Taylor et al. 1993). Refugia effectiveness may also be limited by high contrast with the surrounding environment, if the ability of organisms to effectively utilize refugia space is limited (Magnuson et al. 1979). Known refugia at all scales should be protected along with the processes and structures which insure their persistence and continued development across the landscape.

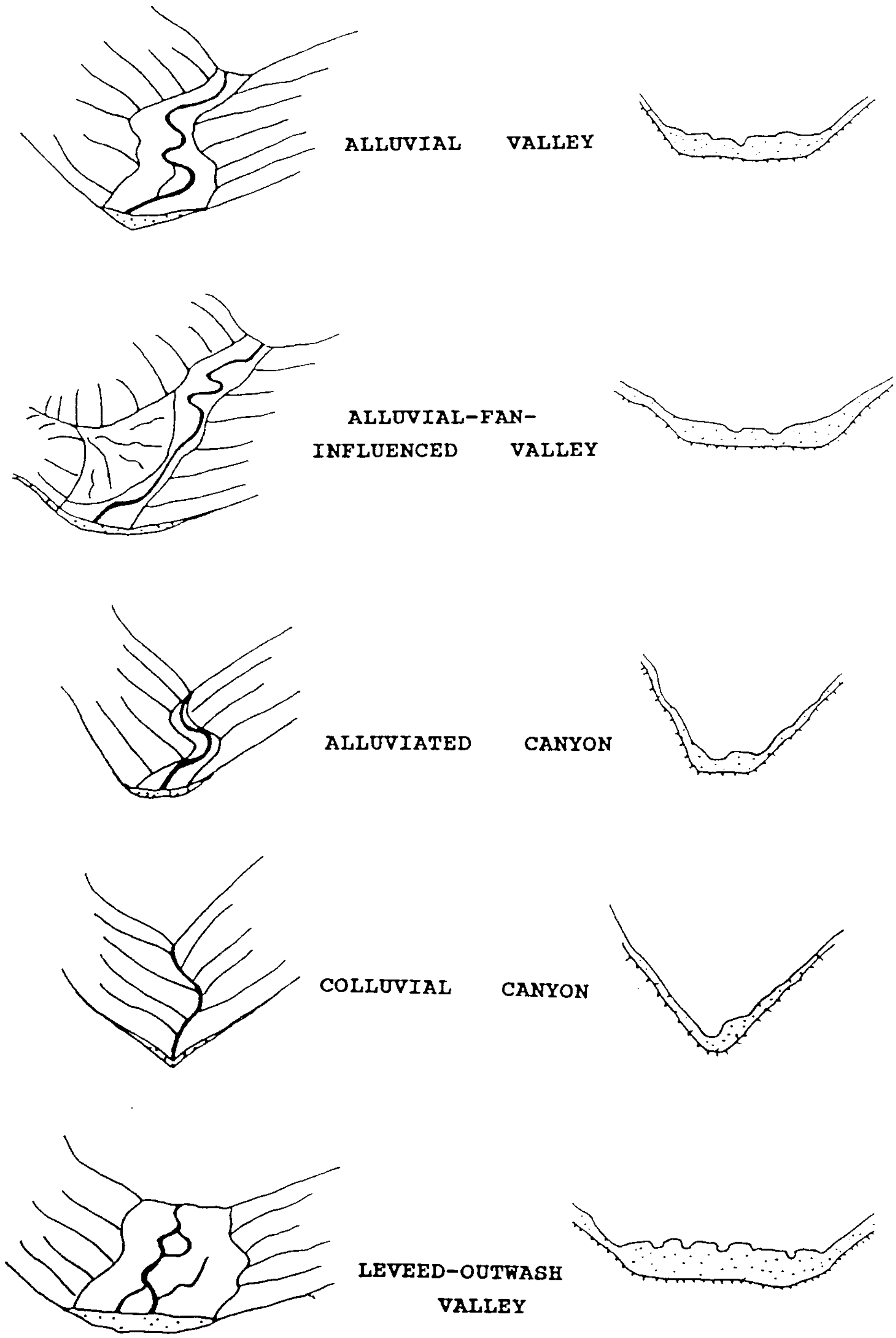
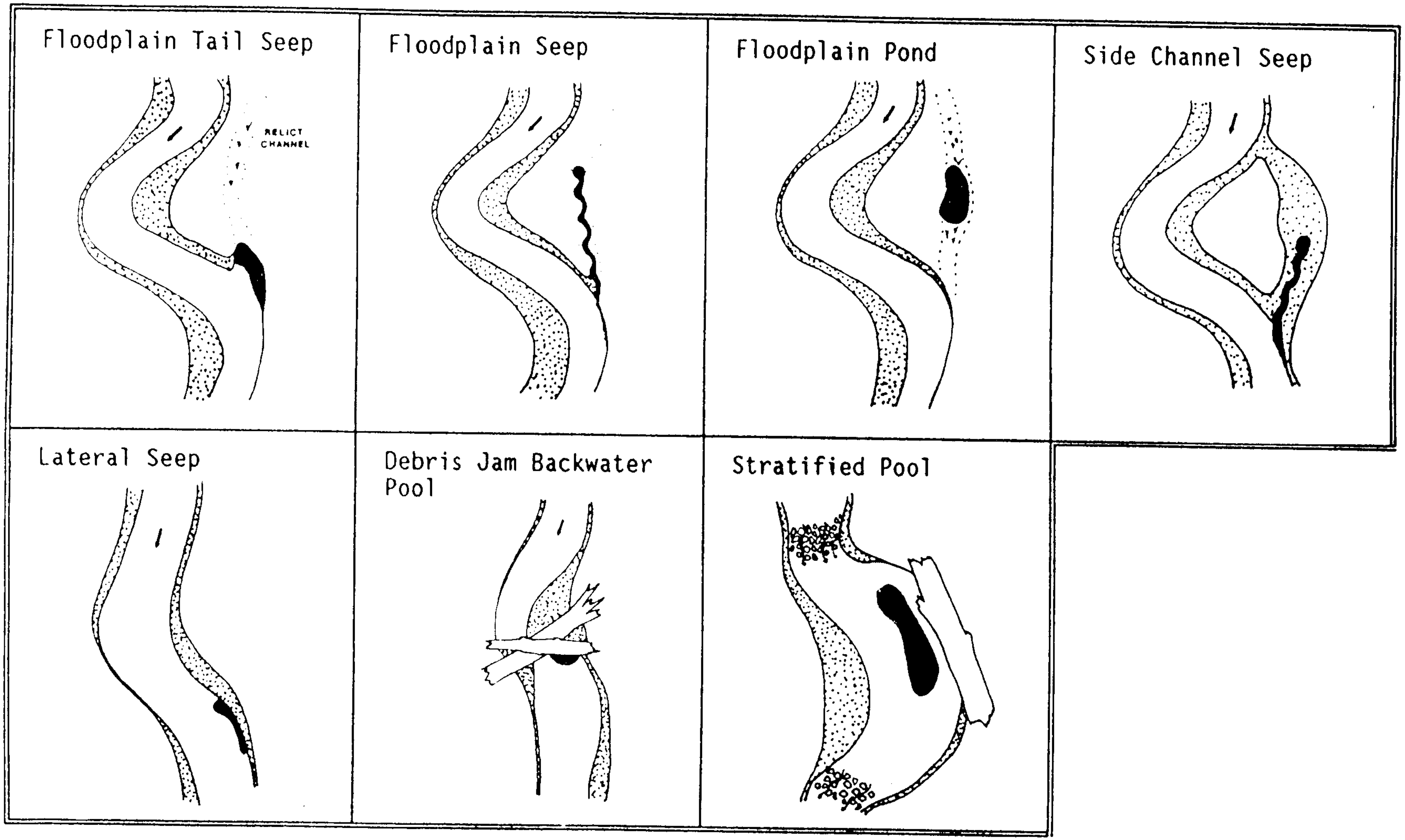


Figure III.1. Valley segment classes in Joseph Creek basin.

Figure III.2. Sketches showing features of Joseph Creek cold pool classes.



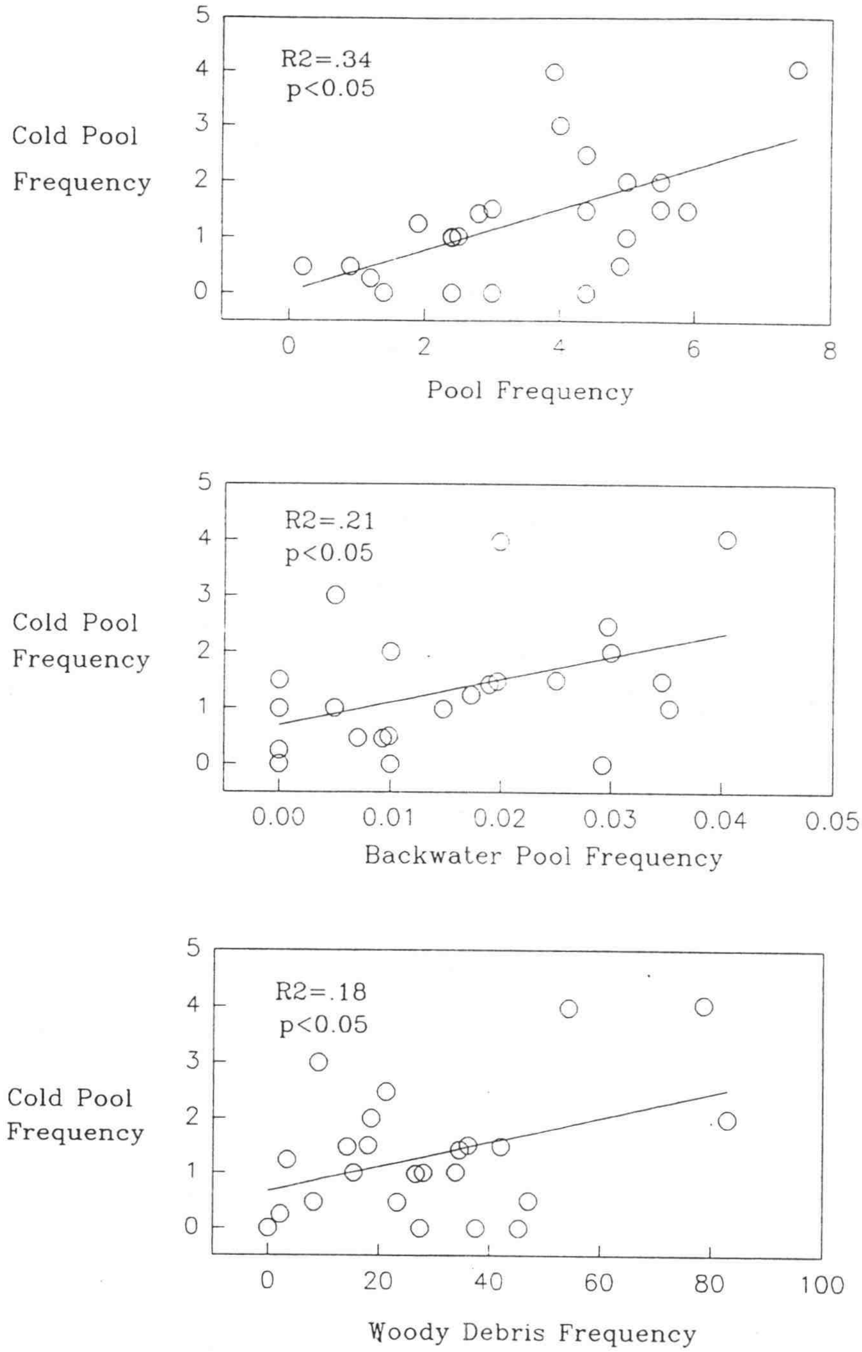
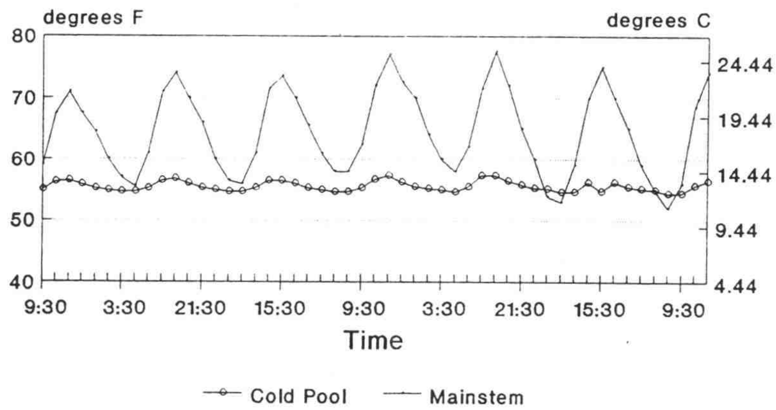


Figure III.3. Associations between three measures of reach complexity and cold pool frequency.

A



B

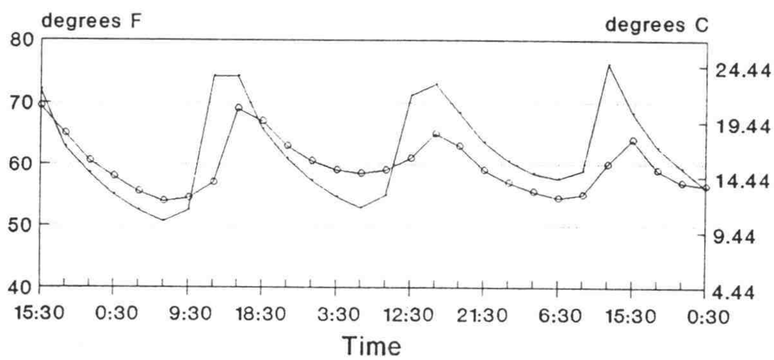


Figure III.4. Thermographs for two cold pools, showing influence of strong groundwater upwelling maintaining constant cold temperatures in pool A. Pool B temperatures are moderated by mixing with ambient streamflow.

Table III.1. Characteristics of valley segment classes described for the study area. Values shown are means and standard deviations of segment attributes.

Segment class	Segments surveyed	Number of transects	Channel slope (%)	Valley wall slope (%)	Valley width (m)	Valley index[a]	Flood plain width (m)	Flood plain index[b]	Active Channel W:D
Alluvial-fan-influenced valley	5	30	1.5 (0.12)	45 (1.2)	72 (8.7)	47.0 (7.6)	22.0 (3.8)	14.2 (2.2)	7.4 (1.1)
Alluvial valley	10	59	1.8 (0.10)	35 (2.6)	47 (3.2)	12.6 (1.1)	25.3 (2.3)	9.0 (1.0)	14.7 (1.2)
Colluvial canyon	3	10	2.4 (0.19)	47 (2.0)	15 (4.6)	2.0 (0.46)	8.3 (3.8)	2.0 (1.0)	10.2 (1.9)
Alluviated Canyon	7	50	2.7 (0.17)	48 (1.0)	20 (1.6)	7.0 (0.68)	12.8 (1.2)	5.7 (0.5)	14.3 (1.8)
Leveed-outwash valley	6	30	4.2 (0.28)	65 (1.7)	27 (2.2)	6.5 (1.2)	20.0 (2.2)	6.2 (1.2)	10.4 (1.1)

[a] Valley index = active channel width/valley width
[b] Floodplain index = active channel width/valley width

Table III.2. Characteristics of paired reaches. Vertical line denotes significant difference between group pairs (P<0.05), Wilcoxon signed ranks test.

Reach Code	Stream and location code	Riparian vegetation state	Mean active channel width (m) [a]	Mean active channel depth (m)	Mean width depth ratio	Reach canopy density (%) [b]	Woody Debris per 100m	Thalweg pools per 100m [b]	Total pool/riffle units [c]	%Over-hanging vegetated banks [c]	%Actively eroding banks [a]	Cold pools per 100m [b]	Elevation (m)
A	PEAVINE 1	FENCED 1970	2.7	0.35	8.6	46.3	78	7.5	44	42.5	0	4.04	1060
	PEAVINE 2	OPEN	4.7	0.35	18.2	34.2	83	5	30	2.5	20	2	1070
B	CHESNIMNUS 3	FENCED 1987	11.2	0.52	24.1	12.6	7	1.9	30	7.5	12.5	1.24	1000
	CHESNIMNUS 2	OPEN	15.9	0.74	25.2	3.45	8.75	0.2	15	5	15	0.47	1020
C	PEAVINE 4	FENCED 1985	4.2	0.21	21.4	29.4	21.5	4.4	41	20	0	2.5	1340
	PEAVINE 3	OPEN	4.5	0.2	26.7	26.7	25	0.9	37	0	7.5	0.47	1340
D	SWAMP 2	FENCED 1986	3.2	0.28	12.7	63.2	37.5	3	28	35	2.5	0	1110
	SWAMP 1	OPEN	4.2	0.41	12.4	40	28.5	1.4	16	10	12.5	0	1110
E	CROW 2	REMNANT ALDER	4.3	0.38	15.3	46.5	15.5	2.4	22	5	22.5	1	1130
	CROW 1	OPEN	2.3	0.28	10.2	5.5	2.25	1.2	41	7.5	17.5	0.25	1090
F	CHESNIMNUS 12	REMNANT OLD-GROWTH CONIFER	3.9	0.23	20.2	64	121.5	7.9	39	0	27.5	-	1410
	CHESNIMNUS 11	OPEN (LOGGED)	2	0.26	10	25.3	50	7	30	10	2.5	-	1410

a: Values for fenced reaches significantly lower than for open reaches.

b: Values for fenced and remnant reaches significantly higher than for open reaches.

c: Values for fenced reaches significantly higher than for open reaches.

Table III.3. Characteristics of cold pool classes. Values shown are median, range and sample size.

	COLD POOL CLASS						
	FLOOD-PLAIN SEEP	FLOODPLAIN TAIL SEEP	SIDE CHANNEL SEEP	DEBRIS JAM BACKWATER POOL	FLOODPLAIN POND	LATERAL SEEP	STRATIFIED POOL
MIN TEMP (^{o}C)	13.7	13.8	14.4	14.9	14.3	15.4	15.9
	7.4 - 17.7	9.2 - 19.7	10.8 - 17.2	10.5 - 18.9	9.8 - 18.9	11.4 - 21.0	9.4 - 20.0
	N=8	N=41	N=30	N=39	N=7	N=32	N=26
MAX DEPTH (m)	0.14	0.13	0.17	0.17	0.34	0.15	0.71
	0.06 - 0.25	0.05 - 0.5	0.03 - 0.53	0.05 - 1.00	0.07 - 0.51	0.10 - 0.20	0.09 - 1.45
	N=4	N=21	N=20	N=21	N=3	N=2	N=17
VOLUME* (m^3)	0.52	0.33	0.33	0.48	1.01	0.14	14.37
	0.06 - 0.76	0.002 - 8.55	0.003 - 5.18	0.01 - 2.5	0.04 - 7.88	0.14 - 0.15	0.01 - 302.4
	N=4	N=21	N=20	N=21	N=3	N=2	N=13

* Volume = estimated mean depth multiplied by measured cold pool area. Mean depth estimated for all pools by regressing maximum depth against measured mean depth for a subset of 46 cold pools. Regression equation: Mean depth = 0.7 (max depth) - 0.01.

Table III.4. Cold pool frequencies (#/100m) by segment class and cold pool class.

		VALLEY SEGMENT CLASS			
Cold Pool Class	N	AV	AC	LOV	AFI
Floodplain Tail Seep	42	0.46	0.34	0.1	0.16
Floodplain Seep	9	0.02	0.04	0.3	0.02
Floodplain Pond	8	0.14	0.04	0	0
Side Channel Seep	30	0.2	0.6	0.15	0
Lateral Seep	33	0.32	0.22	0.05	0.18
Debris-Jam Backwater	40	0.42	0.34	0.25	0.02
Stratified Pool	26	0.36	0.07	0	0.11
ALL COLD POOLS	188	1.9	1.6	0.86	0.5

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