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LITERATURE REVIEW

& MONITORING RECOMMENDATIONS

FOR

SALMONID SPAWNING HABITAT AVAILABILITY

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INTRODUCTION

Problem Statement

Salmonid spawning and incubation occurs in submerged gravel beds in streams or lakes where the eggs and young develop until ready to emerge. Although spawning gravel is abundant in many Washington streams, spawning habitat is scarce in some stream channels and can limit salmonid production under some circumstances. The relative abundance of spawning habitat is used as an indicator of resource condition in the Watershed Analysis fish habitat assessment. In stream segments where spawning habitat is scarce, information on hydrology, sediment supply, channel conditions and human activities is examined to determine why. To support the Watershed Analysis effort, there is a need to improve methods used to assess and interpret spawning habitat availability and to develop a standard method to measure changes in spawning habitat availability over time.

Purpose of the Report

The purpose of this report is to: 1) summarize information from the literature that describes the characteristics of salmonid spawning habitat and factors affecting its abundance and distribution, 2) identify key issues that must be resolved in developing a methodology for monitoring spawning habitat quantity in the context of Watershed Analysis; 3) describe how spawning habitat has been identified and measured in other studies, and 4) recommend a Watershed Analysis monitoring method to measure changes in spawning habitat quantity.

BACKGROUND INFORMATION ON SALMONID SPAWNING HABITAT

Introduction

Females of the genera Oncorhychus (Pacific salmon), Salmo (trout) and Salvelinus (char), referred to as salmonids in this discussion, typically reproduce by depositing eggs in a series of clusters (egg pockets) within one or more nests (redds) excavated in the gravel substrate of rivers, streams or lake-shores (Burner, 1951; Chambers et al., 1955). The process of site selection, nest construction, fertilization, deposition and burial of the eggs is referred to as "spawning". Burial of the eggs within the stream bed provides protection from freezing, drying, disturbance and predation (McNeil, 1966). Fine sediment washes away during construction of the redd (Chambers et al., 1955; Peterson and Quinn, 1994), increasing permeability of the gravel. Sub-surface flows are also improved due to the surface topography of the redd (Bjornn and Reiser, 1991) and the arrangement of particles around and over the eggs (Peterson and Quinn, 1994).

Characteristics of Spawning Habitat

In order to understand patterns of spawning habitat utilization by salmonids, it is useful to think about spawning habitat selection on the level of the species, stock and individual, and to consider spawning habitat utilization on three spatial scales, broad geographical distribution patterns, utilization of particular stream reaches within a drainage, and specific spawning sites within a stream reach.

Broad geographical distribution

Spawning areas on the west coast of North America, including Washington State, are utilized by native populations of seven Pacific salmon species, including pink (Oncorhynchus gorbuscha), chum (O. keta), chinook (O. tshawytscha), coho (O. kisutch), sockeye/kokanee (O. nerka), steelhead/rainbow (O. mykiss), and cutthroat (O. clarki) and two char, Dolly Varden (Salvelinus malma) and bull trout (S. confluentus). Introduced populations of brown trout (Salmo trutta), golden trout (Salmo aguabonita), brook trout (Salvelinus fontinalis) and lake trout (Salvelinus namaycush) are also present (Hunter, 1973; Wydoski and Whitney, 1979; Everest et al., 1985). This discussion will focus on spawning habitat of the native species, with lesser emphasis on the introduced species.

Distribution of spawning habitat within watersheds and stream reaches

Salmonids have a highly developed homing instinct that enables fish to return and spawn in the same stream from which they originated, often after long migrations (Groot and Margolis, 1991). This has resulted in the development of distinct, geographically isolated, and self-sustaining spawning populations or stocks (Rich, 1939). The reproductive isolation of distinct populations appears to have promoted the evolution of physical and behavioral adaptations to conditions within specific stream reaches and watersheds, including channel morphology, hydrology, habitat availability, resource availability and competition with other species and populations (Miller and Brannon, 1982). The partitioning of species and stocks into ecological niches has resulted in development of unique and complex life history patterns and widespread variation in physical traits and behavior (Miller and Brannon, 1982). Consequently, there is extensive variation in the timing of spawning, the type and locations of stream reaches where spawning occurs, and the characteristics of spawning sites, both between species and among stocks of the same species (Miller and Brannon, 1982). Because of the variation among stocks of the same species, spawning habitat utilization patterns can only be discussed in general terms.

The spawning reaches used by many stocks appear to be selected to promote survival of the fry. Spawning reaches are often located in close proximity to habitat utilized by emerging fry (Beschta and Platts, 1986), reducing mortality by providing quick access to needed resources (Miller and Brannon, 1982; Burgner, 1991) or areas where competition with other species is minimized (Miller and Brannon, 1982).

For example, sockeye and kokanee stocks often spawn in the inlet or outlet streams of lakes, and occasionally on gravel beaches along lake shores, allowing vulnerable fry to quickly reach the lake habitat used as rearing areas after emergence from the gravel (Burner, 1951; Miller and Brannon, 1982; Burgner, 1991). Sockeye occasionally spawn along lake shores where substrate particles are too large for them to move (Burgner, 1991). This appears to be an example of a reach-scale attribute (close proximity to lake habitat required by fry) overriding physical site criteria (substrate size) in selection of spawning sites.

Pink and chum utilize a wide range of spawning locations, including rivers, streams and inter-tidal areas, often spawning in small streams or the lower reaches of rivers relatively close to salt water (Burner, 1951; Neave, 1953). This reduces the length of the migration to salt water undertaken by vulnerable young fry soon after emergence (Miller and Brannon, 1982). The distribution of some pink and many chum stocks is constrained by their inability to migrate past obstructions surmounted by other species.

In some larger river systems chinook and steelhead stocks with divergent spawning run timings utilize different habitats, apparently minimizing competition for spawning and rearing habitat. Spring- and summer-run chinook and summer run steelhead typically occur in large river systems with stable summer flow regimes. They migrate slowly upstream during the spring and summer, eventually spawning far upstream. Fall chinook and winter steelhead occur in both large rivers and smaller coastal streams, typically spawning further downstream than spring chinook and in areas of greater flow than coho (Briggs, 1953). Chinook fry exhibit flexible life history strategies that reflect a variety of spawning and emergence times, downstream migrations of various lengths, and competition for resources (Miller and Brannon, 1982).

Several species employ life history strategies that involve extended periods of juvenile rearing in freshwater streams. Species such as coho and cutthroat typically spawn in the upper reaches of drainage systems, allowing fry to occupy rearing habitat as they migrate downstream. Coho commonly spawn in small to medium sized coastal streams, but also migrate far up into some large river systems (Miller and Brannon, 1982). They often prefer to spawn in small, gravel bottom tributary streams. Many individuals migrate as far upstream as physically possible, stopping only when confronted by an impassible obstruction (Briggs, 1953). Coho produced in headwater tributaries seed downstream habitat as they are carried downstream or displaced during intra-species competition for feeding territories (Miller and Brannon, 1982). Coastal cutthroat typically spawn in small headwater streams and tributaries of coastal rivers (Wydoski and Whitney, 1979). Resident cutthroat and rainbow trout are smaller than anadromous forms and often select areas with small gravel and lower velocity for spawning (Everest et al., 1985) in headwater streams above migratory barriers.

Characteristics used to select spawning sites

After arriving at the spawning grounds, female salmonids select spawning sites when their eggs are ready for deposition (Briggs, 1953). The process undertaken by females to select a spawning site is not well understood (Tautz and Groot, 1975), however studies of spawning sites indicate that a combination of factors are used to select locations (Chambers et al., 1955) and there is a relatively wide range of acceptable conditions for most species (Hunter, 1973). Characteristics that have been identified as factors in site selection for various salmonid species include substrate size (Chambers et al., 1955; Hunter, 1973; Kondolf and Wolman, 1993); water velocity (Chambers et al., 1955; Hunter, 1973); water depth (Burner, 1951; Chambers et al., 1955; Hoopes, 1972; Hunter, 1973; Kondolf and Wolman, 1993); permeability of the gravel (Burner, 1951); surface and sub-surface flow conditions such as areas of accelerating flow (Heard, 1991), down-welling surface currents (Vaux, 1962) or up-welling groundwater (Hunter, 1973; Bjornn and Reiser, 1991; Burgner, 1991; Leman, 1993); dissolved oxygen levels (Chambers et al., 1955); water temperature (Chambers et al., 1955); and cover (Briggs, 1953; Chambers et al., 1955; Hoopes, 1972; Everest et al., 1985).

Some of the factors influencing spawning site selection by female salmonids are related to the physical ability of the female to successfully construct a nest. A site will typically be rejected if the substrate particles are too large and heavy for the female to move (Chambers et al., 1955) or too compacted to dislodge (Burner, 1951). The site will also be unusable if the female is unable to hold position against the current due to the water velocity (Chambers et al., 1955) or is unable to maneuver because the water depth is too shallow (Hunter, 1973; Crisp and Carling, 1989).

Physical limitations such as these exclude certain areas of the stream bed as potential spawning habitat for individual fish, depending on factors such as body size and stamina. For example, large fish can successfully spawn in faster water and excavate larger substrate than smaller fish, which often select sites with smaller gravel and lower velocity for spawning (Chambers et al., 1955; Hunter, 1973; Everest et al., 1985; Kondolf and Wolman, 1993). Although larger, more powerful chinook salmon successfully spawned over a greater range of substrate size and velocity conditions than smaller-bodied sockeye salmon, the sockeye successfully spawned in areas where the water was too shallow for chinook spawning (Chambers et al., 1955). If there is extensive variation in the size of individual members of a stock or species, the differences in velocity, minimum depth, and substrate preferences may be as great (or greater) between members of the population as between similarly-sized members of different species or populations (Hunter, 1973).

Within the realm of sites where spawning is physically possible, female salmonids appear to apply a second set of criteria to select sites where flow conditions within the gravel are favorable for successful incubation of eggs and alevin. Spawning sites often occur where channel and stream bed morphology create surface or sub-surface flow patterns that enhance intergravel flow and oxygen delivery (Leman, 1993). The oxygen supplied to the eggs by water flowing through the gravel comes from interchange with water flowing above the stream bed or the influx of deep groundwater into the stream bed (Vaux, 1962; Chambers et al., 1955). Factors such as the velocity of surface water, the rate of intra-gravel flow through gravel deposits, or the presence of up-welling groundwater appear to be important criteria used by many stocks to select spawning sites favorable to the survival of eggs and alevin (Crisp and Carling, 1989; Leman, 1993). Areas where permeability is reduced because the substrate is compacted (Burner, 1951; Stuart, 1953) or contains high concentrations of fine sediments (Hunter, 1973) are often avoided.

Favorable sub-surface flow conditions occur where the interchange of surface water into gravel beds is enhanced by a combination surface water velocity, convex bed profile (pool tailouts and riffle crests) and high gravel permeability (Vaux, 1962). The strength of down-welling currents through gravel deposits in pool tailouts is more dependent on the gradient to the next pool downstream than on the velocity of the water flowing above the gravel bed. Typically, down-welling currents are strongest near the top of the mound at the riffle crest (Stuart, 1953). The tailouts of pools and the heads of riffles are preferred by many salmonid species for redd construction (Briggs, 1953; Hoopes, 1972; Hunter, 1973). For example, in the Prairie Creek watershed in California, the majority of coho, fall chinook and winter steelhead redds were constructed in pool tailouts. Riffles were the next most common location (Briggs, 1953). Sockeye spawning in small streams preferred pool tailouts and select locations in riffles along the bank on the deepest side of the stream (Hoopes, 1972). Pink salmon often select sites with accelerating surface flow, generally on riffles with clean gravel or along the borders between pools and riffles in shallow water with moderate to fast currents and avoid spawning in areas with slow currents (Heard, 1991).

The composition of the substrate also affects sub-surface flow through the gravel. Burner (1951) observed that bed compaction, due to its effect on permeability and sub-surface flow, had a greater effect on the selection of spawning sites than was generally recognized. Spring and summer chinook, coho, and sockeye preferred moderately bound substrate and most spawning occurred in areas with sub-surface permeability. Although gravel beds that were firmly cemented with silt and clay appeared suitable for spawning based on depth, velocity and substrate criteria, they were abandoned by salmon after limited test digging, presumably due to the lack of sub-surface flow (Burner, 1951).

Several salmonid species demonstrate a preference for sites where up-welling of deep groundwater occurs. Leman (1993) observed that 60-70 percent of the chum salmon in the Kamchatka River basin spawn where groundwater influence is present. Other species that use sites with up-welling groundwater include brook trout (Webster and Eiriksdottir, 1976; Curry et al., 1994), sockeye (Burgner, 1991), and rainbow trout (Sowden and Power, 1985). Observations of brook trout spawning sites in the Adirondack Mountains indicate that the presence of up-welling groundwater was more important than substrate composition in site selection. Sites with sand and silt bottoms that had up-welling currents were selected first, although gravel substrate without up-welling currents was available (Webster and Eiriksdottir, 1976). The presence of up-welling groundwater appeared to be unrelated to the channel morphology, but was influenced by the topography of the adjacent valley walls (Leman, 1993) and site specific hydro-geology (Curry et al., 1994). Consequently, up-welling groundwater creates spawning opportunities in areas that do not appear to have flow characteristics suitable for successful incubation. For example, some stocks of sockeye spawn in gravel along lake shores and spring ponds where up-welling groundwater causes water circulation through the nest. Spawning was concentrated where up-welling was strongest while areas without up-welling groundwater were avoided (Burgner, 1991).

Chambers et al. (1955) documented that up-welling groundwater provided a significant source of dissolved oxygen in several spawning areas. However, the oxygen content and flow rate of up-welling groundwater varied greatly among groundwater-influenced spawning sites in one reach of a small stream (Sowden and Power, 1985). Variation in oxygen content appeared to be related to oxygen depletion in the aquifer before the groundwater reached the stream bed, and flow rate appeared to be related to hydraulic gradient. Consequently, fine sediment content of the gravel bed had only a secondary affect on oxygen content and flow rate in sites influenced by up-welling deep groundwater, unlike sites where the water flowing through spawning gravels is predominately influenced by interchange with surface water (Sowden and Power, 1985). In the Kamchatka River, groundwater-influenced sites had a more constant temperature regime that favored steady development of embryos and prevented freezing despite the extreme winter climate. Redds in locations with groundwater influence almost never dried up despite fluctuations in stream discharge (Leman, 1993).

A third type of criteria influencing site selection is related to the safety and survival of the female during spawning, such as the proximity of cover that provides protection from predators (Hoopes, 1972; Everest et al., 1985; Bjornn and Reiser, 1991). Salmon can spawn in areas without cover, however they tend to select sites with cover when other factors are suitable (Chambers et al., 1955; Hoopes, 1972). A variety of objects and situations can provide cover including deep water such as pools (Chambers et al., 1955; Everest et al., 1985), submerged objects (Everest et al., 1985), overhanging vegetation (Chambers et al., 1955; Everest et al., 1985), woody debris (Sedell, 1984) or undercut banks (Everest et al., 1985). Hoopes (1972) observed that sockeye frequently selected spawning sites next to deeply undercut banks, banks with overhanging plants and grass, deep pools, and holes scoured under tree roots and large woody debris. Sockeye took cover in these areas when frightened by predatory brown bear on the spawning grounds, however the bears knew how to systematically search these areas for salmon (Hoopes, 1972). Briggs (1953) observed that winter steelhead hid under overhanging banks or in deep water in the vicinity of their redds in the middle of the day, emerging to spawn in the mornings and evenings.

The presence of suitable holding habitat in the vicinity of spawning areas appears to be an important criteria in spawning site selection for some stocks such as spring chinook (George Pess, Tulalip Tribes; personal communication). Spring chinook return to fresh water during the spring and summer and pass time holding in quiet locations with cool water temperatures while waiting for their eggs to ripen. In the Yakima River system, ambient stream temperatures are above optimal, so spring chinook hold in cooler “thermal refuge areas” associated with deep pools, islands and rock outcroppings. Absence of this type of holding habitat would increase exposure to above optimal stream temperatures, increasing pre-spawning mortality and lowering reproductive success (Berman and Quinn, 1990).

Biological Response to Spawning Habitat Availability

The amount of spawning habitat available at the time of spawning can limit the number of eggs successfully deposited in the gravel, setting an upper limit on the size of the next generation and potentially acting as a density-dependent regulator of population size when the density of the spawning population is very high (McNeil, 1964; Allen, 1969; McFadden, 1969; Schroder, 1973; Reeves, et al., 1989; Semenchenko, 1989). Several characteristics of salmonid populations make it possible for spawning habitat availability to act as a significant population regulation mechanism under certain circumstances, including the homing instinct that directs most members of populations to return to their natal streams to spawn, and territorial behavior by females on the spawning ground involving the establishment and defense of spawning sites (Schroder, 1973; Semenchenko, 1989). Availability of spawning habitat is more likely to affect anadromous salmonid populations, particularly species such as pink, chum and sockeye that are typically not limited by food and space in fresh water and often return to spawn in very large numbers (McFadden, 1969). Where multiple species utilize the same spawning reaches, inter-specific competition for habitat may occur (Rounsefell, 1957 cited in McNeil, 1964; McFadden, 1969).

Behavioral responses to increasing spawner density have been observed in studies of chum salmon (Schroder, 1973) and sockeye salmon (Semenchenko, 1989) at various densities under controlled conditions in spawning channels. At low densities there is sufficient space for all females to spawn, so aggression is minimal and redd construction and egg deposition occur rapidly and efficiently resulting in successful deposition of nearly all eggs. Aggression increases as the density of females on the spawning ground increases. As suitable sites are occupied, established females defend their territories from adjacent or late-arriving females (Schroder, 1973; Semenchenko, 1989). Established females are rarely evicted by another female but their spawning activities are disrupted, the size of territories and redds decreases, and the quality of redd construction decreases (Schroder, 1973). The physiological condition of most females deteriorates due to stress, decreasing their life-span and increasing the rate of egg retention (Semenchenko, 1989).

Females that arrive after all suitable sites are occupied are often pushed into unsuitable spawning sites (Briggs, 1953; McFadden, 1969) or must wait for a previously used spawning site to become available (Schroder, 1973; Semenchenko, 1989). Many of these fish die before spawning or spawn on a site previously used by another female, destroying the eggs deposited earlier (Schroder, 1973; Semenchenko, 1989). Disturbance of redds by subsequent spawners after the site is no longer defended (superimposition) is more likely in reaches where suitable spawning habitat is limited and available patches are heavily utilized (McNeil, 1964; Overton, 1984; Beard and Carline, 1991).

Observations of female density and territorial behavior on spawning grounds have been used to estimate the number of spawning females that a given amount of spawning habitat can support (Burner, 1951; McNeil, 1964). Available spawning habitat is typically divided by the average size of a redd (Bartholow et al., 1993) or the size of the territory a female defends (Burner, 1951) to determine a theoretically "optimal" number of females, where all females should have a spawning site and no females should die before spawning or disturb eggs deposited by another female.

Estimates of optimal population densities may oversimplify the interaction between salmonid populations and the stream environment in some circumstances. “Excess” females that are unable to establish territories represent a pool of potential spawners available to respond to changing circumstances (Schroder, 1973), increasing the resiliency of the stock in the face of variable environmental conditions during the course of the spawning and incubation season. When large populations spawn over an extended period, superimposition can occur when late-arriving females spawn on earlier redds (McNeil, 1964). However, a large population that spawns over an extended period can respond opportunistically to fluctuations in habitat availability due to changes in discharge (Schuett-Hames et al., 1994), and eggs deposited by females forced to use marginally suitable sites may survive better than eggs in optimal sites during infrequent catastrophic events such as floods. Late-season spawners can ensure that successful egg deposition occurs despite unfavorable conditions earlier in the season such as scour due to floods, low flows due to drought, high or low water temperatures and heavy predation. These factors may allow large spawning populations with "excess" females to weather extreme or fluctuating environmental conditions more successfully than smaller populations.

Geomorphic Influences on Spawning Habitat Availability

The type and amount of habitat available for spawning varies among stream reaches due to differences in physical characteristics and geomorphic processes among watersheds and stream channels. The primary factor determining spawning habitat availability is the quantity and distribution of deposits of suitably-sized gravels. Hydrology, particularly the flow regime at the time of spawning, affects access to spawning areas, the amount of wetted area, water depth and velocity, and sub-surface flow conditions.

Factors affecting spawning gravel abundance and distribution

The production, transport, and deposition of sediment are key elements in understanding gravel supply in a stream system (Anderson, 1971; Collins and Dunne, 1990). The quantity, particle size composition and distribution of gravel deposits throughout a stream system are determined by factors affecting sediment supply to the channel, such as the amount, type, timing and location of sediment inputs (Collins and Dunne, 1990), and factors affecting sediment transport and deposition within the channel, such as discharge, gradient, depth of flow, obstructions and channel morphology (Collins and Dunne, 1990).

Gravel supply

The interaction between the physical characteristics of underlying bedrock (lithology), climate, and watershed morphology (relief and land forms) control the nature and magnitude of weathering (breakdown of underlying rock) and erosional processes (Tarbuck and Lutgens, 1984). In turn, these factors determine the amount and size of sediment supplied to the channel (Collins and Dunne, 1990). Gravel is produced by several erosional processes that influence the location, manner and timing of sediment contribution to the stream channels (Beschta, 1987; Collins and Dunne, 1990). Mass wasting and stream bank erosion are typically the most important processes supplying spawning gravel to stream channels in the Pacific Northwest (Collins and Dunne, 1990). Mass wasting is the dominant process in many Pacific Northwest watersheds due to a combination of factors that contribute to slope instability, including steep relief, erodible soils, and climatic conditions that produce saturated soils and peak discharge events. Inputs of sediment from mass wasting are variable and sporadic, responding to precipitation and watershed disturbance (Anderson, 1971). Large storms often produce large inputs of mixed sediment from mass wasting that can influence stream channels for many years (Lisle, 1981, 1982; Platts and Megahan, 1975; Platts et al., 1989). Bank erosion is common in alluvial channels in the Pacific Northwest and can produce large amounts of sediment (Anderson, 1971), particularly in stream systems undergoing post-glacial incision and floodplain development (Collins, 1994; Benda et al., 1992) or channel adjustment due to changes in sediment supply, hydrology or bank resistance (Schumm, 1969; 1974).

The geology of the watershed has a dominant influence on the abundance and particle size distribution of downstream gravel deposits (Dunne et al. 1981; Fraley and Graham, 1981; Duncan and Ward, 1985; Collins and Dunne, 1990). The physical and chemical properties of the rock and soils are particularly important, determining (in conjunction with climate) the rate at which underlying rock weathers (breaks down) into particles that can be mobilized by erosion, the sizes of particles produced (Anderson, 1971), and the durability of the particles as they are transported down the stream channel (Dunne et al., 1981; Collins and Dunne, 1990).

For example, Anderson (1971) observed that sediment production was predictable from watershed geology. The percentage of gravel present in soils produced from seven geologies in western Oregon ranged from 10-77 %, affecting the relative amount of coarse and suspended sediment produced by erosion (Anderson, 1971). Swanson et al. (1976) observed that streams draining the Klamath Mountains carried heavy sediment loads, while streams draining the sandstones of the coast range generally had little gravel. Gravel in northeast England was usually coarser and more poorly sorted than in southwest Wales, and the finest gravel was found in Dorset, reflecting geological influence on sediment size (Crisp and Carling, 1989). Duncan and Ward (1985) found a correlation between the percentage of basin in sedimentary rock and the amount of fine sand, silt and clay particles in spawning gravel. In streams draining watersheds with mixed geologies, more resistant basaltic rocks dominated spawning riffles because soft sedimentary sandstone broke down quickly, forming few gravel-sized particles (Duncan and Ward, 1985). Collins and Dunne (1990) also observed that different types of rock abrade and break down at different rates as they are transported downstream. For example, easily weathered and mechanically weak Olympic Mountain basalt breaks down much more rapidly than mineralogically and structurally resistant granitic rocks from western Cascade Mountain streams (Collins and Dunne, 1990). In western Washington, granite, diorites, gabbros, quartzites, andesites and some basalts produce the most durable gravel particles, while easily cleaved schists and phyllites, mudstones, intensely weathered basalts and slightly indurated sediments from volcanic rocks break down easily (Dunne et al. 1981).

Transport, routing and deposition of spawning gravel

Once gravel enters the stream system, it becomes subject to transport and deposition by flowing water. The transport, routing and deposition of coarse sediment by fluvial processes has a large influence on the availability of gravel deposits suitable for salmonid spawning. These processes are influenced by a wide variety of factors, including peak flow hydrology, channel gradient, channel morphology, and the abundance of obstructions and storage sites.

The ability of a stream to transport sediment depends on the energy available to move particles downstream (Richards, 1982). Since the force required to initiate and maintain sediment transport increases with sediment size, smaller particles are more easily entrained and transported than larger particles, and tend to travel greater distances (Beschta, 1987). Channel gradient and flow (water depth) have a major influence on the size of gravel found in a stream reach (Collins, 1992; Buffington, 1995). Stream power, an index of the energy available to transport sediment, increases with stream gradient (slope) and discharge (Benda et al., 1992). In the steep, headwater portions of the drainage basin stream power is usually high, resulting in a selective sorting process as silt, sand and gravel are rapidly transported downstream and coarse cobbles and boulders are left behind (Beschta, 1987). In mountainous drainages, stream gradient typically decreases in a downstream direction, resulting in lower stream power and a general decrease in particle size (Dunne et al., 1981). As the ability of the stream to move gravel-sized particles decreases, deposits of gravel (gravel bars) typically become more abundant (Collins and Dunne, 1990). Since the energy necessary to move gravel only occurs during infrequent peak flows, the gravel particles tend to remain in storage most of the time, occasionally leapfrogging downstream short distances from riffle to riffle during storm events (Beschta, 1987). The size of the particles typically decreases in a downstream direction, due to abrasion during downstream transport (accelerated by weathering that occurs during storage) and additional decrease in gradient (and transport competence) in a downstream direction. Eventually, the bed may become dominated by sand or silt as gravel is left behind.

Benda et. al. (1992) observed the effect of stream power and watershed morphology on spawning gravel abundance in the Stillaguamish River basin, where low gradient channels (< 2 %) on recent terraces had 46 % more channel area in spawning gravel than reaches with steeper gradients and higher stream power further upstream. The distribution of spawning gravel among tributary systems was also influenced by drainage basin area, which influences stream power through discharge. Streams with higher stream power (larger drainage basins and steeper gradients) had less spawning gravel while streams with lower stream power (small basin areas and low gradients) were dominated by gravel (Benda et al. 1992). Kondolf et al. (1991) observed that little spawning gravel occurred in seven steep gradient (> 7 %) stream reaches in eastern California.

Channel morphology, and the presence of obstructions such as bedrock outcrops, boulders and large woody debris, provide locations where spawning gravels are deposited. Low gradient channels with pool/riffle morphology often have abundant deposits of gravel in pool tailouts, riffles and point bars. Bedrock outcrops, large woody debris and root-armored banks act as obstructions to flow, causing local scour that influences channel morphology, creating a relatively stable pattern of pools and bars in predictable locations (Lisle, 1986). Velocity differences between pools and riffles during peak flows result in sorting of sediments and deposition of coarse gravel in bars and riffles (Keller, 1971), creating potential spawning sites for salmonids. In steeper channels, spawning habitat is often limited to small patches of coarse gravel associated with obstructions such as boulders, large woody debris (LWD) and logjams (Keller and Swanson, 1979; Kondolf et al., 1991). The role of obstructions such as LWD in sediment storage and energy dissipation is greatest in smaller and steeper channels (Keller and Tally, 1979), however, localized flow and deposition patterns associated with LWD also provide favorable spawning sites in large river systems (Sedell et al., 1982).

Favorable spawning sites often form in conjunction with LWD and debris jams, such as stable coarse sediment deposits trapped in long-term storage behind LWD obstructions (Mosley, 1981) or deposits of well-sorted spawning gravels in the tailouts of LWD-associated pools (Sedell, 1984). Removal of large debris jams (McDonald and Keller, 1987) or stable pieces of LWD (Smith et al., 1993) from small stream channels eliminates many sediment storage sites such as low-energy hydraulic areas and bars buttressed by LWD. Following removal of LWD, local increases in water surface slope, increased water velocity and entrainment of sediment deposits were observed (McDonald and Keller, 1987; Smith et al., 1993). The increase in water surface slope and decrease in channel roughness resulted in greater boundary shear stress that caused the bed material to coarsen and become armored, making it potentially unsuitable for salmonid spawning (Smith et al., 1993).

Effect of discharge on spawning gravel availability

The streamflow regime at the time of spawning is an important factor that determines the ability of migratory salmonids to reach spawning areas (Titus and Mosegaard, 1992), the amount of submerged gravel (Hobbs, 1937; Newcombe, 1981) and the water depth and velocity over the gravel beds (Newcombe, 1981; Bjornn and Reiser, 1991). Discharge can vary substantially over weeks to months, providing opportunities to spawn in different locations over time (Schuett-Hames et al., 1994). As flows increase, gravel beds along the margins of the channel that were previously dry may become submerged and provide suitable spawning habitat, while areas near the center of the channel that were utilized at a lower discharge may become too deep or swift (Bjornn and Reiser, 1991). Consequently, more habitat is available to be utilized when spawning occurs over a wide range of flows than when spawning is constrained to a short period of time with a limited range of flows. However, large flow fluctuations during the spawning period can disrupt spawning and adversely affect reproduction (Nelson, 1986).

During peak flows, gravel patches can be scoured and transported out of steep channels (Kondolf et al., 1991). Spawning gravel can also be scoured from the thalweg of large channels and deposited along the channel margins where it is not covered by water at the time of spawning (Gangmark and Bakkala, 1960).

Land-Use Effects on Spawning Habitat Availability

Human land-use activities and catastrophic natural events can have a significant effect on spawning habitat. Many activities or catastrophic events affect spawning gravel by altering the amount or type of sediment available for transport, or by altering the ability of the channel to transport or store particles (Klingeman, 1981). Other activities or disturbances affect spawning habitat by altering channel hydrology or by blocking access of migratory salmonids to spawning grounds. For example, dam construction in the Pacific Northwest has inundated many former spawning areas behind the dams and has blocked and impeded access for anadromous salmonids to spawning areas further upstream (Chambers et al., 1955; Fulton, 1970).

Many rivers undergo changes in sediment production due to land-use or channel modification (Collins and Dunne, 1990). A wide range of land-use activities and natural events increase the supply of sediment to stream channels by accelerating mass wasting, surface erosion and bank erosion. Examples of activities that can increase erosion include urbanization, agriculture, road construction, timber harvest, livestock grazing and placer mining (Smith, 1939; Klingeman, 1981; Collins and Dunne, 1990). Natural events such as wildfire (Swanston, 1971) and volcanic eruptions (Rees, 1981) can dramatically increase sediment production. Large peak runoff events often result in large increases in sediment delivery, particularly in watersheds where the susceptibility to erosion has been increased due to land-use activities (Platts and Megahan, 1975; Lisle, 1982; Lyons and Beschta, 1983). The effect of increased sediment supply on stream channels depends on the amount and particle size distribution of the input (Lyons and Beschta, 1983). Increases in coarse sediment recruitment to stream channels can increase spawning habitat in systems where gravel supply is naturally limited, but can also cause channel widening, braiding and aggradation in sediment rich systems, potentially de-stabilizing spawning habitat (Collins and Dunne, 1990). Typically, bed material becomes finer where channels aggrade following large sediment inputs (Lisle, 1982). Sediment generated from erosion associated with land-use activities is often predominately fine material (Klingeman, 1981) and spawning beds may be buried by fine sediment resulting in loss of spawning habitat (Platts and Megahan, 1975).

Other land-use activities can reduce the supply of sediment, potentially reducing the availability of spawning gravel further downstream. Bank stabilization and armoring reduces stream bank erosion, restricting local inputs of sediment to the channel (Klingeman, 1981). In the Sacramento River, where bank erosion is an important source of gravel recruitment, bank stabilization has contributed to the loss of spawning habitat (Buer et al., 1984).

Large dams disrupt sediment supply by intercepting gravel moving down the river and altering discharge and transport patterns further downstream (Klingeman, 1981). Sediment is trapped in the reservoirs behind dams, often greatly reducing the gravel supply to downstream spawning reaches, resulting in loss of downstream spawning habitat (Buer et al., 1984). Following dam construction, substrate in the channel below the dam often coarsens due to the reduction in gravel supply and the increased transport capability of "clear water" released from the dam, however the increased transport capability may be offset by a reduction in the size of peak discharges if the reservoir is used for flood control (Collins and Dunne, 1990; Kondolf and Swanson, 1993).

Extraction of gravel from the channel by gravel mining operations conducted on a large scale disturbs the channel at the site and can alter downstream sediment supply and transport processes (Collins and Dunne, 1990; Kondolf and Swanson, 1993), resulting in loss of spawning habitat (Buer et al., 1984). Bars downstream from large gravel mining operations often decrease in size or are eliminated due to a reduction in sediment supply (Collins and Dunne, 1990), and channel incision and coarsening of the substrate typically occur due to increased transport capability associated with the reduction in sediment supply (Kondolf and Swanson, 1993).

In channels where LWD and debris jams play an important role in retaining spawning gravel, reduction in the size or abundance of LWD obstructions due to removal of wood from the channel or cutting of riparian vegetation could result in a reduction in gravel patches (Swanson et al., 1976; Keller and Swanson, 1979; Bisson et al., 1987) and coarsening of the substrate (Smith et al., 1993; Buffington, 1995).

Splash dam operations (Wendler and Deschamps, 1955) and catastrophic events such as debris torrents (Keller and Swanson, 1979) often scour away woody debris and spawning gravels. The lack of spawning habitat is likely to persist because the relatively straight, armored channels left following these events have few obstructions or low velocity zones for spawning gravel to be deposited. Dredging (Klingeman, 1981) and channelization (Cederholm and Koski, 1977) can also reduce or eliminate both obstructions and spawning gravel. Channels are typically straightened and narrowed during channelization, increasing channel slope, depth and transport capability (Collins and Dunne, 1990).

Biological Effects on Spawning Habitat Availability

Salmonids have a limited ability to modify the stream bed to increase the quantity and quality of spawning habitat. A number of studies have measured changes in gravel composition due to redd construction. Nearly all studies demonstrate that small particles are selectively transported by the current when the substrate is lifted into the water column during redd construction. Following spawning, substrate is typically coarser (Kondolf et al., 1993; Peterson and Quinn, 1994; Montgomery et al., in prep.), better sorted (Kondolf et al., 1993), more permeable (McNeil and Ahnell, 1964; Crisp and Carling, 1989), less compacted (Crisp and Carling, 1989; Peterson and Quinn, 1994; Montgomery et al., in prep.) and lower in fine sediments (McNeil and Ahnell, 1964; Everest et al. 1987; Crisp and Carling, 1989; Kondolf et al., 1993; Peterson and Quinn, 1994). Southeast Alaska streams with large pink salmon spawning populations typically had lower levels of fine sediment than streams with smaller spawning populations, due in part to the estimated 18 kg of fine sediment < 0.1 mm removed from each pink redd during spawning

(Everest et al. 1987). Approximately 75 % of the fine sediment (< 1 mm) present in the stream bed of a low gradient, alluvial stream was removed during spawning, however subsequent infiltration and sediment transport can cause fine sediments to return to pre-spawning levels during the incubation period (Peterson and Quinn, 1994).

In addition to changing the substrate composition, salmon can alter channel morphology during spawning to increase suitable spawning habitat (Montgomery et al., in prep.). Dense concentrations of female salmon altered the morphology of a low gradient western Washington stream by moving large amounts of substrate during spawning, partially filling pools, lowering riffle crests and excavating bar margins. The resulting changes resulted in a channel that was broader, shallower and had more area suitable for chum spawning (Schuett-Hames, in prep).

KEY ISSUES TO CONSIDER IN DEVELOPING A MONITORING APPROACH

We have identified a number of important issues that need to be considered in developing a method for monitoring spawning habitat availability for Watershed Analysis. These issues have been expressed in the form of a list of questions related to the purpose of monitoring, the data needed, how the data will be interpreted, how monitoring studies should be designed and what sampling methods will be used.

What is the purpose of a Watershed Analysis methodology to monitor spawning habitat availability?

What data are needed to assess and monitor spawning habitat availability for Watershed Analysis?

1. What parameters are most useful to assess and monitor spawning habitat availability?
2. What additional information is needed to help interpret spawning habitat availability data?

What is a valid study design for sampling spawning habitat availability?

1. How should a sampling program be designed to characterize spawning habitat availability on a stream reach scale appropriate for Watershed Analysis?
2. How should variation in streamflow be addressed?

What sampling methodologies should be used to collect spawning habitat availability data?

1. How accurate and repeatable are spawning habitat availability measurement techniques?
2. How does the feasibility (logistics, time and cost of sampling) of methods compare?
3. What methods are suitable for assessment and monitoring?
4. How should data on discharge and physical channel characteristics be collected?

How will the data be interpreted?

1. How will spawning habitat availability be interpreted in the context of discharge?
2. How will spawning habitat availability be interpreted in the context of species-specific preferences?
3. How will spawning habitat availability data be interpreted in the context of physical channel characteristics?

These questions have been used to focus our efforts in developing a spawning habitat availability monitoring method.

HOW THE KEY ISSUES HAVE BEEN ADDRESSED IN OTHER STUDIES

In this section of the report, existing studies are examined to determine how the key issues listed above have been addressed.

Purpose of Studies Assessing and Monitoring Spawning Habitat Availability

Studies of spawning habitat availability have been conducted for several purposes, including:

1) to inventory the amount of spawning habitat available for a particular species of concern, and evaluate whether spawning habitat is limiting fisheries production (Schuett-Hames et al., 1988; Reeves et al., 1989; Ebasco Environmental, 1993);

2) to determine the potential effects of water withdrawals or flow regulation on the amount of spawning habitat available in a stream reach, and develop instream flow recommendations to maintain fisheries production (Stober and Graybill, 1973; USGS, 1977; Wampler, 1980; Caldwell and Hirschey, 1990);

3) to evaluate the effectiveness of spawning habitat restoration and enhancement projects (Moreau, 1984; House and Boehne, 1985); and

4) to monitor changes in spawning habitat availability over time in response to human activities or natural events (Platts and Megahan, 1975; Platts, et al., 1989).

Parameters Used to Assess and Monitor Spawning Habitat Availability

The results of many spawning gravel studies are expressed in terms of the area of spawning habitat suitable for use by a particular species of salmonid in a stream reach or entire stream system at the point in time and flow level when the survey is done. In some cases the amount of habitat available is divided by the size of a spawning site or spawning territory to estimate the number of spawning females the available habitat could support (Burner, 1951). In other cases, the amount of available habitat is expressed as a percentage of the total wetted channel area.

It is necessary to define and determine what constitutes spawning habitat for species of interest in order to successfully quantify the amount of available spawning habitat. One approach to this problem is to define spawning habitat as only those areas where spawning actually is observed, allowing the fish to define habitat suitability. This approach may provide the most true measure of habitat suitability because spawning salmonids appear to evaluate a complex suite of factors in a process that is difficult for human observers to replicate. It also avoids the problem of incorrectly including areas that salmonids would not actually use. However, estimates of habitat availability limited to areas where fish were observed spawning would be flawed in years when adult returns were low because many potentially suitable sites would not be used. This would result in a low estimate of spawning habitat availability. Year-to-year variation in the number of spawning females would create further difficulties in data interpretation.

Most observers have used an alternate approach, defining spawning habitat as portions of the stream with physical characteristics similar to those observed where spawning has occurred. All areas of the stream meeting the physical criteria are counted as suitable habitat, regardless of whether they are actually used in any given year. This approach requires the observer to define a set of characteristics that can be used to delineate portions of the stream that appear suitable for salmon spawning. The quality of any spawning habitat analysis conducted using this approach is ultimately dependent on the adequacy of the criteria used to identify suitable spawning habitat (Stalnaker and Arnette, 1976).

The characteristics and criteria used to define suitable spawning habitat have been derived from studies that examined patterns of spawning habitat utilization by specific stocks or species. Habitat preferences were determined by locating active spawning sites and collecting data on characteristics such as substrate size, water depth and velocity (Burner, 1951; Chambers et al., 1955; Heiser, 1971; Hoopes, 1972; Hunter, 1973; Smith, 1973; Vogel, 1982; Kondolf and Wolman, 1993). Other characteristics of spawning sites such as gravel permeability, the presence of up-welling currents, and proximity to cover have been occasionally recorded. The results of these studies indicate that members of salmonid stocks spawn over a fairly wide range of conditions, and variability in the range of suitable spawning conditions is even greater among stocks and different species (Smith, 1973; Bjornn and Reiser, 1991; Kondolf and Wolman, 1993). Some of the variability observed is due to differences in the size of fish, which affects their ability to move particles and hold position in fast water (Kondolf and Wolman, 1993), variability in local conditions that determine and often limit the characteristics of sites available (Burner, 1951; Hunter, 1973), the effect changing spawner density on habitat selection (Briggs, 1953), and possible adaptations of various stocks to watershed-specific conditions.

Information generated from studies of spawning habitat utilization have been used to determine stock- and species-specific preferences for attributes such as depth, velocity and substrate size (Smith, 1973; Vogel, 1982) that can be used to identify potential spawning habitat. Since the range of values for all sites used by members of the population is often very broad, a narrower range of values for each attribute, typically referred to as the range of optimal or preferred habitat, is developed by eliminating outlying observations on the tail(s) of the frequency distribution curve (Hunter, 1973; Smith, 1973; Reiser and Bjornn, 1979).

Species-specific preferences for spawning habitat have been widely used to quantify available spawning habitat. Preference information has been used to develop spawning and incubation habitat suitability index (HSI) models for many salmonids species which can be used to identify limiting factors and evaluate project impacts and restoration efforts (Raleigh and Nelson, 1985). Preference information has also been incorporated into the Instream Flow Incremental Methodology (IFIM) to evaluate the effect of changes in streamflow on spawning habitat availability. Suitability Index (SI) curves for habitat variables related to stream hydraulics are used in the IFIM Physical Habitat Simulation System (PHABSIM) to model the effects of changing discharge on availability of spawning habitat (Stalnaker and Arnette, 1976).

Estimates of spawning habitat based on suitability criteria for a small set of physical characteristics are problematic for several reasons. The amount of suitable spawning habitat is likely to be overestimated when only depth, velocity and substrate criteria are used. These criteria identify habitat where females are capable of building redds but don't identify or eliminate areas that would be rejected due to factors such as inadequate sub-surface flow, lack of up-welling currents, or lack of cover. For example, many areas that appeared suitable for spawning on the basis of velocity, depth and substrate criteria are avoided by spawning females due to bed compaction (Chambers et al., 1955).

Several other problems have been identified with this approach. Studies of spawning sites have employed various or inconsistent measurement techniques (Hunter, 1973). Consequently, some of the differences in results among studies may be due to methodological differences that obscure actual preferences and create problems when the results of studies are combined. Furthermore, suitability criteria based on data sets from streams lacking a wide range of habitat conditions may be fairly narrow, because the range of possible choices was too limited to allow the full preference range to be expressed (Hunter, 1973; Stalnaker and Arnette, 1976). For example, the range of depths and velocities recorded for chinook spawning sites in tributaries of the Columbia River were much lower than those for spawning sites in the main-stem Columbia. This reflected differences in the range of conditions available, rather than true differences in the preferences of the fish (Chambers et al., 1955). Eliminating observations on the tail of the frequency distribution curve would exacerbate this problem. Application of criteria based on a small number of observations from a stream with homogenous habitat conditions would lead to underestimation of suitable habitat when applied to a stream with a wider range of conditions (Hunter, 1973).

Additional information is occasionally collected to help interpret spawning habitat availability. Estimates of the total wetted area can be used to calculate the percentage of the total habitat in the reach suitable for spawning. Information on the amount of fine sediment between larger substrate particles (particle embeddedness) is sometimes collected as an indicator of spawning habitat quality. The type of channel or habitat unit where spawning habitat occurs is also occasionally recorded.

Study Design and Sampling Methods

Two approaches have been used to sample spawning habitat availability, an inventory approach that requires measurement of all suitable spawning habitat in the entire survey reach, and a transect approach that involves collection of data along a series of transects established in a sub-sample of suitable spawning locations.

The inventory approach

A commonly employed approach to sampling available spawning habitat is to simply measure the total amount of available spawning habitat throughout an entire reach or stream (Schuett-Hames et al., 1988; Reeves et al., 1989; Ebasco Environmental, 1993). Criteria for one or more characteristics such as water depth, velocity, substrate size and minimum spawning site size are used to identify suitable habitat for the stock or species of interest. The specific characteristics and range of values used as criteria to delineate spawning habitat are typically based on the results of habitat preference studies. Observers walk the stream and assess the selected habitat characteristics. Gravel patches that meet all of the criteria are considered to be suitable habitat. The length and width of each patch are recorded so that surface area can be calculated. Data are collected at a discharge representative of flows that typically occur during the spawning period.

Advantages of the inventory approach include: 1) the entire segment is sampled, so the issue of sub-sampling is avoided; 2) the information generated can be used to estimate the carrying capacity of spawning habitat for the discharge at the time of the survey; and 3) the method can be applied relatively rapidly so that it is feasible to survey entire stream segments. Disadvantages of the inventory approach include: 1) inventories only produce information on habitat availability at a single flow (unless entire survey is repeated at other flows); 2) to compare changes over time, future surveys need to be conducted at the same discharge; and 3) it may be difficult to conduct surveys during late fall or winter to document habitat available for stocks that spawn at that time of year, because high flows limit access and increased turbidity could impair visibility.

The transect approach

The second approach to measuring spawning habitat availability involves the collection of data along a series of transects. This technique is widely employed in instream flow studies to develop an estimate of available spawning habitat for the stream reach at various flows (Stalnaker and Arnette, 1976). Typically, a limited number of transects located in representative or critical reaches are surveyed over a range of flows (Stalnaker and Arnette, 1976; Newcombe, 1981; Washington Department of Ecology et al., 1990). Each transect is divided into a series of cells, and data on water depth, velocity and dominant substrate size are collected in each cell. Planimetric mapping techniques or computer models such as PHABSIM can use the transect data to estimate the amount of suitable spawning habitat available in the entire reach at various flows (Stalnaker and Arnette, 1976). To measure changes over time, future surveys could be conducted using the same transects. However, due to variability within stream reaches, changes detected at a small number of transects may be more representative of local change at specific locations rather than change throughout the entire reach.

Transects have also been used in applications other than instream flow studies. Periodic measurements of dominant substrate size along a relatively dense network of transects established in a few key spawning areas have been used successfully to document changes over time in the amount of spawning gravel covered with fine sediment (Platts and Megahan, 1975; Platts et al., 1989).

Advantages of a transect approach include: 1) if surveys are conducted using the IFIM procedure, spawning habitat availability can be estimated for a range of flows, and cumulative habitat available over a range of flows can be determined; 2) the smaller number of sample sites per segment makes it feasible to measure (rather than estimate) depth and; and 3) a larger network of transects employed in key spawning areas can provide rather precise documentation of change in those areas. Disadvantages of a transect approach include: 1) IFIM is intensive, can be time consuming, and requires specialized training to utilize the PHABSIM model; and 2) IFIM may not be a suitable monitoring method because it is unknown if a small number of representative transects would accurately characterize change over time on a stream segment scale, and 3) an intensive network of transects would be time consuming to employ over an entire stream segment.

Data Interpretation

Interpretation of the significance of spawning habitat availability for salmonid populations

Available spawning gravel is sometimes interpreted in the context of the carrying capacity of the reach, i.e. how many spawning females of a selected species would be required to utilize all the available habitat and how many eggs would be deposited if the reach was fully utilized (Burner, 1951; Reeves et al., 1989). If information on the carrying capacity of the stream system for subsequent life history stages is available, various models can be used to determined if availability of spawning habitat is a limiting factor (Raleigh and Nelson, 1985; Reeves et al., 1989).

Spawning habitat data collected during the Watershed Analysis fish habitat assessment is interpreted by applying suitability criteria for two size classes of salmonids, which produces an estimate of the habitat available for both large- and small-bodied salmonids (WFPB, 1995).

Interpretation of spawning habitat availability in the context of discharge

There are several ways to address discharge variability in data interpretation. Data from a single point in time can be used to estimate available habitat at the survey discharge. If measurements are made over a range of flows, as in IFIM studies, then peak spawning habitat availability at an optimal discharge can be determined. Finally, by determining the distribution of spawning habitat that becomes available at different flows as changes in depth and velocity occur, the cumulative amount of habitat available over a range of flows can be determined (Stober and Graybill 1973).

Interpretation of spawning habitat availability in the context of physical channel and watershed conditions

Little information was found regarding the interpretation of spawning habitat availability in the context of variation in physical channel conditions, watershed conditions or land-use.

RECOMMENDED MONITORING APPROACH

Purpose

We recommend that monitoring for spawning habitat availability be designed to accomplish the following purposes:

1. To assess availability of suitable spawning habitat on a reach scale.
2. To monitor changes and trends in spawning habitat availability over time.
3. To interpret spawning gravel availability in the context of channel conditions and watershed input processes.

Approach

The literature review identified two methods for defining and identifying suitable spawning habitat. Suitable spawning habitat can be narrowly defined as only those areas where members of a salmonid population are observed to have spawned, or more broadly defined as all areas with suitable characteristics meeting criteria developed from previous studies of spawning sites.

Defining suitable spawning habitat as only areas where spawning occurs would typically provide a low estimate of spawning habitat availability because spawning populations in many Washington streams are often low. The estimate of suitable habitat would also vary from year to year due to fluctuations in population size. To avoid these problems we recommend using a set of characteristics and criteria derived from existing studies of spawning habitat utilization to identify suitable spawning habitat, although no simple set of criteria that can be easily applied by human observers can evaluate the wide range of factors influencing salmonid habitat selection.

Water depth and velocity have been the most common characteristics used to identify suitable spawning habitat in many studies (Hunter, 1973; Smith, 1973). Many of these studies were designed to generate information that would be useful for managing instream flows. Consequently, the focus was on determining how spawning habitat availability would respond to changes in discharge due to water withdrawals and flow regulation. Since water depth and velocity are sensitive to incremental changes in discharge, they are critical parameters to evaluate when establishing instream flows to protect salmonid spawning habitat. The Watershed

Analysis cumulative effects model does not identify changes in discharge at typical spawning flows as a potential cumulative effect of forest practices. Consequently, a spawning habitat monitoring methodology that focuses on modeling changes in water depth and velocity associated with fluctuations in discharge would not be particularly useful in the context of Watershed Analysis.

Substrate is the primary spawning habitat characteristic directly affected by the inputs (sediment, wood and peak flows) evaluated in Watershed Analysis. Not only is the quantity and size of substrate directly influenced by the sources and amount of sediment input, but changes in peak flow and woody debris input also affect substrate composition (Buffington, 1995). Consequently, a approach that emphasizes monitoring changes in the quantity and particle size distribution of spawning gravel deposits will be most useful for Watershed Analysis. This information can be evaluated in the context of changes in sediment supply, helping to evaluate the effectiveness of mass wasting and surface erosion prescriptions. It can also provide supplemental information useful for interpreting the effect of changes in LWD loading and peak flow events on the particle size and abundance of substrate suitable for spawning.

The literature review identified inter-gravel flow conditions and cover as potentially important characteristics of spawning habitat. Unfortunately, currently available methods to measure inter-gravel flow are too labor intensive to apply broadly to inventories of spawning habitat availability (Stuart, 1953; Sowden and Power, 1985; Leman, 1993). However, bulk substrate sampling provides a means of identifying areas where fine sediment levels are likely to impede intergravel flow. This approach is recommended by USFWS Habitat Suitability Index models for salmonids (McMahon, 1983; Raleigh, et al., 1984; Raleigh and Nelson, 1985; Raleigh, et al., 1986). The TFW Ambient Monitoring Spawning Gravel Composition methodology can be used to document fine sediment levels in conjunction with surveys of spawning habitat availability in stream reaches where fine sediment accumulation or bed compaction appear to be a problem. The USFWS Habitat Suitability Index model for chinook also includes an approach for documenting the presence of suitable holding pools and cover for adult chinook (Raleigh et al., 1986). Collection of supplemental information on the availability of holding pools and cover in stream reaches utilized by spring and summer chinook is recommended.

Parameters to Assess and Monitor Spawning Habitat Availability

We recommend using the surface area of gravel deposits suitable for salmonid spawning as the primary parameter of spawning habitat availability. Available spawning habitat should be defined and identified using substrate, depth, velocity and minimum spawning site size criteria that are inclusive of the range of salmonid populations found in Washington streams (that is, inclusive of a variety of body sizes ranging from resident cutthroat and rainbow trout to chinook salmon). This will allow the data to be broadly applied in the analysis of stream segments utilized by multiple salmonid stocks, a common situation in Washington streams. However, surveyors should have the option of applying stock- or species-specific criteria during data collection or analysis to document spawning habitat availability for stocks of special concern.

To define salmonid spawning habitat to encompass the salmonid species occurring in the state, we recommend including gravel patches equal to or greater than 1 square meter in size where the dominant particle size is equal to or greater than 8 mm and less than 128 mm. Each patch should be covered with flowing water to a depth equal to or greater than 10 cm (4 inches) at the time of the survey. Surveys should be conducted at a discharge representative of conditions during the period of time spawning occurs in the stream segment.

These criteria are based on information reported in the literature, however the extensive variation in reported values both within stocks and between stocks and species made selection of criteria difficult. Consequently, the criteria recommended above are rather broad and tend to be inclusive of the range of suitable conditions reported in papers that examined large data sets for multiple stocks and species, especially Burner (1951), Smith (1973), Bjornn and Reiser (1991) and Kondolf and Wolman (1993). Surveyors interested in spawning habitat availability for particular stocks or species have the option of substituting a criteria based on preference studies for the stock or species of concern.

During the survey, we recommend documenting: 1) the length and width of each gravel patch, 2) the associated geomorphic/habitat unit (e.g. riffle, pool tailout), 3) the diameter of the dominant substrate particles, and 4) the embeddedness of the dominant substrate particles. Supplemental information on the proximity to holding habitat and cover should be collected for stream reaches utilized by spring or summer chinook.

To help interpret spawning habitat availability we recommend collecting information on the total wetted area, so that the percentage of the wetted area providing suitable spawning habitat can be calculated. We also recommend further investigation of the utility of generating data on the total area of suitable substrate within the bankfull channel to estimate cumulative habitat availability over a range of flows.

Study Design and Sampling Methods

We recommend using an inventory sampling approach as the primary means of collecting spawning habitat availability data for Watershed Analysis monitoring. Stream segments should be delineated according to the methodology in the Watershed Analysis channel assessment module (WFPB, 1995) as described in the TFW Ambient Monitoring Reference Point Survey Module. Use of an inventory approach will provide the most accurate and replicable method of documenting changes in spawning habitat availability on a stream segment scale given the likelihood of large within-segment variability in spawning habitat distribution.

We recommend conducting spawning habitat inventories immediately prior to the spawning period of the primary salmonid stock(s) of interest in the watershed at a discharge representative of conditions that typically occur during the spawning period. Spawning habitat inventories should be conducted by observers on foot. Discharge should be measured at the time of the survey so that future surveys can occur at the same discharge.

In addition to the inventory method, we recommend providing an option to use an intensive transect network similar to that described in Platts and Megahan (1975) and Platts et al. (1983) in situations where intensive monitoring of specific critical spawning sites is needed.

Data Interpretation

Recommendations for criteria to interpret spawning habitat data in the context of the species present in a stream segment are shown in Table 1. Species are divided into two groups. Small bodied salmonids are typically less than 35 cm long when mature. This group includes resident rainbow, cutthroat , kokanee, brown, brook, bull trout and Dolly Varden. Large bodied salmonids are typically greater than 35 cm when mature. This group includes anadromous pink, chum, coho, chinook, steelhead and sockeye. Sea-run cutthroat trout are intermediate in size but are grouped with the resident trout.

Table 1. Recommended criteria to interpret spawning habitat suitability for two size classes of salmonids.

	Small bodied salmonids	Large bodied salmonids
Dominant substrate particle size	8-64 mm (0.32-2.56")	16-128 mm (0.64-5.12")
Water depth	10 cm (4")	15 cm (6")
Velocity	moving	moving
Minimum gravel patch size	1.0 m^2	2.0 m^2

Spawning habitat quantity is often interpreted in the context of carrying capacity or limiting factors to production. This is done by estimating the number of spawning sites available to females, and the number of eggs that could be deposited to initiate the next generation (Reeves et al., 1989). For example, Burner (1951) provides estimates of the amount of spawning gravel occupied and defended by females of various salmon species. Estimates of the carrying capacity of the spawning habitat available in a stream segment would be useful in determining if lack of spawning habitat could potentially be affecting salmonid populations.

More research is needed to improve our understanding of how variation in the physical characteristics of stream channels and watershed conditions affects in spawning gravel size or abundance. This issue is critical for successful interpretation spawning gravel availability in the context of Watershed Analysis. Further study could improve our ability to interpret both current conditions and changes in spawning habitat availability over time.

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