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TFW Ambient Monitoring Program

LITERATURE REVIEW

& MONITORING RECOMMENDATIONS

FOR

SALMONID SPAWNING GRAVEL SCOUR

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INTRODUCTION

Problem Statement

Salmonid eggs and larvae undergo a critical period of early development while buried in stream bed gravel. During this time eggs and alevin are vulnerable to scour and disturbance of the stream bed. Mortality at this early stage in the life cycle can affect recruitment to later life stages. Scour to the depth of salmonid egg pockets typically occurs during peak discharges when bedload transport processes are active. The magnitude and frequency of peak flow discharge and sediment transport are influenced by watershed conditions that affect the hydrologic and sediment regimes. A variety of land-use activities alter peak flows and sediment transport dynamics. The Watershed Analysis fish habitat module recommends using information on the frequency of redd scour to identify potential changes in peak flow hydrology and channel stability, but does not contain methods to document scour. A standard procedure is needed to assess and monitor spawning gravel scour in the context of Watershed Analysis.

Purpose

The purpose of this report is to: 1) present information on scour from the literature; 2) identify the features required in a scour monitoring method for Watershed Analysis; 3) identify key issues that need to be resolved in the development of a scour method; 4) examine how existing studies have addressed these issues, and 5) make recommendations for the design of the Watershed Analysis scour module.

BACKGROUND INFORMATION ON SCOUR

Significance of Scour to Salmonid Populations

Salmonid eggs are deposited in clusters (egg pockets) and buried in nests (redds) constructed in gravel stream beds. The larvae spend several months in the gravel while they develop and hatch from the eggs, and transform into fry. During this time the eggs and alevin are relatively immobile and are vulnerable to any disturbance of the stream bed that results in mechanical shock, crushing or entrainment.

Scour and entrainment of eggs and alevin incubating in the gravel has been frequently documented (Gangmark and Bakkala, 1960; McNeil, 1966; Duncan and Ward, 1985; Tripp and Poulin, 1986; Lisle, 1989; Nawa et al., 1990; Kondolf et al., 1991; Orsborne and Ralph, 1994; Schuett-Hames et al., 1994). Loss of eggs and alevin due to gravel movement occurred frequently in southeast Alaska pink (Oncorhynchus gorbuscha) and chum salmon (O. keta) spawning streams. Mortality often exceeded 50 % and ranged as high as 90 % (McNeil, 1966). In the Queen Charlotte Islands of British Columbia, estimated mortality of chum and coho (O. kisutch) eggs from scour was as high as 80-90 %. Scour frequently had a greater effect on salmonid survival to emergence than fine sediments (Tripp and Poulin, 1986). In north Olympic peninsula streams, scour of egg baskets placed in artificial redds ranged from 0 - 80 %, exceeding mortality from other causes in some instances (McHenry et al., 1994). Disturbance of more than 75 % of the chinook redds monitored in a southwest Oregon stream due to scour or burial by bedload material lead to the conclusion that "...stability of gravels during flood events appears to be a major factor affecting survival of chinook and coho salmon in south coast [Oregon] rivers" (Nawa et al., 1990).

Widespread scour during large peak flow events can have long-term effects on the size and composition of resident trout populations. In a California stream with fall spawning brook trout and spring spawning rainbow trout, winter floods scoured brook trout eggs while spring snow-melt floods scoured rainbow trout eggs. Scour-induced mortality to one stock increased survival of fry in the other, so the species composition changed periodically in response to the timing of flood events (Seegrist and Gard, 1972).

In addition to destroying egg pockets, scour can kill juvenile and adult fish hiding in the gravel (Erman et al., 1988; Seegrist and Gard, 1972). In a Minnesota study, a series of floods scoured trout larvae and benthic invertebrates in the gravel, and filled in pool habitat used by adults. The combined effects of these events resulted in the near elimination of two year classes of brook trout (Elwood and Waters, 1969).

Role of scour in fine sediment intrusion

In addition to causing direct mortality by disturbing and entraining larvae, scour and subsequent deposition can adversely affect incubating salmonids by causing changes in the stream bed above egg pockets. The fine sediment composition of gravel beds can be altered by scour and fill processes (Lisle, 1989). Partial scour of material above the egg pocket provides an opportunity for fine sediment to infiltrate into or immediately above the egg pocket where it can impede inter-gravel flow and reduce the influx of oxygenated surface water into the gravel. In addition, the material re-deposited on top of the egg pockets on the receding limb of the peak flow can be high in fine sediments in streams transporting large quantities of sand. When a substantial amount of fine sediment is mixed with the gravel deposited, the interstitial spaces between the gravel particles can be filled (Lisle, 1989), blocking the movement of fry when they attempt to emerge from the gravel (Koski, 1975; Tripp and Poulin, 1986).

Factors Affecting the Vulnerability of Salmonid Populations to Scour

A variety of factors affect the vulnerability of salmonid larvae to scour, including biological factors related to spawning behavior and physical factors related to geomorphic processes.

Biological factors

The behavior of spawning salmonids influences the vulnerability of their progeny to scour. Some biological factors include: the depth at which eggs are deposited; choice of spawning locations; the timing of spawning and incubation; and changes in the composition of the substrate resulting from redd construction.

Depth of egg burial varies substantially within and between salmon populations (Burner, 1951; van den Berghe and Gross, 1984; Tripp and Poulin, 1986). In some cases, larger females deposit eggs at greater depth than their smaller counterparts (van den Berghe and Gross, 1984), reducing the probability of scour. Physical factors such as water velocity, the size of substrate and compaction of the stream bed also influence the depth of egg burial (Burner, 1951).

The likelihood of mortality from scour increases when stocks incubate during seasons when peak flows commonly occur (Seegrist and Gard, 1972). In coastal watersheds with rainfall dominated hydrologic regimes, salmonids that incubate during winter such as coho, chum, pink, chinook, bull trout and Dolly Varden have the greatest probability of encountering peak flow events. Spring-incubating salmonids such as steelhead, rainbow and cutthroat are likely to be most vulnerable in streams with snow melt-dominated hydrology that produces peak flows in late spring or early summer.

As female salmonids excavate and subsequently cover their egg pockets, larger particles are incorporated into the redd while smaller particles are selectively transported downstream (Peterson and Quinn, 1994). There is evidence that coarsening of the surface substrate increases resistance to entrainment, raising the threshold shear stress necessary to initiate scour (Montgomery et al., in prep.). However, loosening of the bed during spawning may lower the resistance of the bed to scour, counteracting the effect of bed coarsening (Reid et al., 1985).

Scour is not distributed uniformly throughout a stream channel so the site selected for egg deposition has a bearing on the probability of mortality from scour. Since scour is highly variable and conditions during peak flows are very different from conditions at flows when spawning site selection typically occurs, it appears unlikely that salmonids select spawning location to avoid scour.

Geomorphic factors

Entrainment and scour of stream bed gravel is a natural process associated with bedload sediment transport. Scour of gravel particles on the surface of the stream bed occurs when the shear stress produced by flowing water is sufficient to overcome the forces resisting particle motion. The depth and frequency of scour is determined to a large extent by complex interactions among factors such as the magnitude and duration of peak flow discharge, the abundance and particle size distribution of bedload sediment, and the abundance and stability of obstructions such as large woody debris. Changes in these factors, and their interactions over space and time, result in heterogeneous patterns of scour, sediment transport and deposition.

Three categories of variability have been observed in scour and bedload transport studies: 1) variability within a stream reach in response to the same peak flow event (Hassan, 1990; Schuett-Hames et al., 1994); 2) variability within a stream reach in response to different peak flow events (Duncan and Ward, 1985; Reid et al., 1985; Sidle, 1988; Schuett-Hames et al., 1994); and 3) variability among different streams or reaches in response to similar peak flow events (Tripp and Poulin, 1986; Lisle, 1989; Nawa et al., 1990).

Variation in Depth and Distribution of Scour Within Stream Reaches

Shear stress is highly variable throughout stream channels and does not increase uniformly with discharge (Bathurst, 1979). Consequently, portions of the bed move independently of one another as the threshold of motion is reached at a given location (Leopold and Emmett, 1984) and bedload movement tends to occur in irregular pulses or waves (Campbell and Sidle, 1985; Reid et al., 1985; Beschta, 1987; Sidle, 1988).

The distribution of shear stress (and associated scour) within a stream reach is determined by factors that locally influence near-bed velocity gradients. Examples include the primary pattern of flow through the channel, the presence of secondary currents, and turbulence caused by bed roughness or obstructions. Local differences in other factors that influence the resistance of the bed to scour (such as particle size and the degree to which the bed is compacted or substrate particles are interlocked) increase variability in scour patterns.

Effect of flow patterns and secondary currents on scour

The interaction between the pattern of primary flow and the patterns of secondary circulation causes much of the variation in the distribution of shear stress observed at a given discharge (Bathurst, 1979). The primary flow (main current in the thalweg of the channel) interacts with the channel pattern and bed forms (such as pools and riffles) to create regions of high and low velocity and regions of flow acceleration and deceleration (Bathurst, 1979).

Secondary circulation currents are another significant source of local variability in shear stress in stream channels, particularly at moderate flows. In straight reaches, multi-cell, stress-induced secondary circulation patterns cause shear stress to vary greatly. Areas of higher shear stress associated with down-welling currents (pools) alternate with areas of lower shear stress associated with up-welling currents (riffles). In bends, skew-induced secondary circulation patterns develop due to centrifugal forces (Bathurst, 1979). Obstructions such as bedrock outcrops (Lisle, 1986) and large woody debris (Lisle, 1986; Smith and Beschta, 1994) create secondary currents in the form of vortices that intermittently raise near-bed velocities in pools, causing local scour during peak flows (Smith and Beschta, 1994).

Scour associated with bedload transport and channel adjustment

Scour and fill of stream bed sediment occurs in response to changes in sediment load and/or discharge, acting as a mechanism for channel morphology to adjust to changing conditions. Adjustment occurs on a variety of scales ranging from changes in individual bars, pools and riffles, to changes in the overall channel morphology (pattern and dimensions) of stream reaches. Scour or fill can occur whenever there is a change in the energy available to entrain sediment or the energy required to do so (resistance to motion). Locally, where the supply of sediment in transport exceeds transport capacity, sediment will be deposited. Scour will occur when available energy exceeds the energy needed to transport the sediment load and entrain new material. The relationship between transport capacity and sediment availability often changes during peak flow events due to changes in shear stress and sediment availability as pulses of sediment move downstream, causing localized scour and fill to occur. Consequently, bedload transport (and associated scour and fill) are typically uneven in space and time.

In streams with pool-riffle morphology (Montgomery and Buffington, 1993), different patterns of scour and fill in pools and riffles have been observed (Hassan, 1990; Schuett-Hames et al., 1994). This appears to be due to differences in hydraulics associated with primary and secondary circulation patterns that result in differential competence to transport sediment at various flows (Campbell and Sidle, 1985; Schuett-Hames, in prep.). Consequently pools and riffles appear to respond differently when adjusting to sediment influxes or changing discharge.

Role of obstructions in local scour

Channel obstructions, such as bedrock outcrops, boulders and large woody debris (LWD) have an important influence on bedload movement and storage (scour and fill). Obstructions can deflect and alter the pattern of flow through a reach, locally concentrating flows and creating secondary circulation vortices, down-welling currents and turbulence (Lisle, 1986; Smith and Beschta, 1994). Obstructions often help create a stable pattern of pools and gravel bars (Lisle, 1986).

The effect of LWD pieces or debris jams on the frequency and pattern of scour and fill in a reach depends on their abundance and stability. Localized scour can occur when LWD pieces are initially recruited into the channel (Duncan and Ward, 1985), when pieces shift during a peak flow event (Lisle, 1989; Schuett-Hames et al., 1994), or when large debris jams break up (McNeil, 1966). However, stable LWD pieces and debris jams can play a important role in stabilizing gravel deposits (bars) and reducing movement of the channel bed, helping to establish a relatively stable pool-riffle sequence with zones of bedload storage and scour. Removal or displacement of large woody debris due to activities such as stream clean out or catastrophic events such as floods or debris flows can de-stabilize the stream bed, leading to severe and chronic scour (Beschta, 1979; Tripp and Poulin, 1986; Booth, 1990).

Variation in Depth and Distribution of Scour Between Peak Flow Events

There is inadequate energy to move bedload material in gravel bed streams at most flows, so sediment transport (and associated scour) is an episodic process highly dependent on peak flow discharge. Differences in magnitude and spatial distribution of scour in stream channels in response to different discharge events has been commonly reported (Duncan and Ward, 1985; Hassan, 1990; Schuett-Hames et al. 1994). The variation in response is often related to differences in the magnitude of the peak flows experienced.

A positive relationship between scour and discharge has been reported in several studies. For example, McNeil (1964) observed measurable reductions in egg and larvae abundance following storms with four inches or more of rainfall in 72 hours in southeast Alaska. Duncan and Ward (1985) found significant correlation between discharge and the depth of scour and fill in Thrash Creek in southwest Washington.

Nevertheless, not all variation between events is explained by differences in the magnitude of peak discharge events. The response of channels to peak flow discharge from storm to storm is inconsistent because many other factors influence the frequency and depth of scour, making prediction of scour depths difficult (Lisle, 1989). Many of the same factors that contribute to spacial variation in scour also contribute to variation between events, include differences in sediment supply, changes in bed compaction and movement of large woody debris. The amount and particle size distribution of sediment entering a stream reach may vary over time, causing changes in the sediment transport regime (Sidle, 1988). The shear stress required to initiate movement of a gravel stream bed changes if the bed becomes compacted and consolidated during a long interlude between storm events. For example, the shear stress required to initiate movement of a stream bed was five times higher after it consolidated for several months compared to when it had been loosened by a recent storm event (Reid et al. 1985).

Variation in Scour Between Different Stream Reaches

Depth and frequency of scour varies considerably among different stream reaches during the same or similar peak discharge events. In several northern California streams, scour to egg pocket depth occurred during small peak flows at some locations while other streams remained stable during the highest observed flows (Lisle, 1989).

In studies that have compared the response of different stream reaches to the same discharge events, greater scour occurred in stream reaches where LWD was uncommon or unstable (Tripp and Poulin, 1986), where sediment supply was elevated due to upstream mass wasting (Tripp and Poulin, 1986; Nawa et al., 1990), and in wider, more complex reaches deposition reaches where the thalweg could move laterally and interact with bars and obstructions (Nawa et al., 1990; Schuett-Hames, et al., 1994).

Changes in channel or watershed conditions

Changes in inputs of sediment, runoff, and large woody debris to the stream channel can cause changes in the depth and frequency of scour. Land-use activities or natural events that increase runoff and erosion or alter large woody debris recruitment can disrupt the channel equilibrium, initiating a period of adjustment that can result in instability and increased scour and fill (Schumm, 1974).

Scour typically increases with discharge, so land-use activities that cause an increase in the magnitude or frequency of peak flow events are likely to increase the frequency and depth of scour. For example, increased storm water runoff from impervious surfaces associated with urban development increased the occurrence of peak flow events capable of producing scour (Booth, 1990). Other land-uses that increase runoff, such as timber harvest in areas susceptible to rain-on-snow runoff events (Harr et al., 1989), are also likely to increase scour.

Greater scour has been observed in channels that received an increased supply of coarse sediment due to upstream landslides (Tripp and Poulin, 1986; Nawa et al., 1990) or were directly disturbed by debris torrents (Tripp and Poulin, 1986). Erosional processes, such as mass wasting or surface erosion, that can deliver sediment to stream channels can be accelerated by timber harvest, roads (Swanston, 1974), mining operations (Nelson et al., 1991) and urban development.

The amount and stability of large woody debris in the channel can be reduced immediately by removal of large woody debris from the channel, or reduced gradually over time due to removal of stream side trees needed to replenish the supply of large woody debris to the channel. In either case, the reduction of in-channel LWD can result in increased scour. Activities that often involve removal of LWD from stream channels include stream clean-out following timber harvest (Beschta, 1979; Bisson et al., 1987), urban development (Booth, 1990), and removal of debris jams to improve fish passage (Beschta, 1979, Bisson et al., 1987). Stream side vegetation is sometimes removed or disturbed by timber harvest (Bisson et al., 1987), urban development (Booth, 1990), and agriculture and grazing operations (Platts, 1991). Other events that have resulted in extensive scour and de-stabilization of stream channels include splash damming (Wendler and Deschamps, 1955), debris torrents (Tripp and Poulin, 1986) and stream channelization projects (Cederholm and Koski, 1977).

PURPOSE OF THE WATERSHED ANALYSIS (WA) SPAWNING GRAVEL SCOUR MONITORING METHODOLOGY

The spawning gravel scour methodology must fulfill the following purposes:

1. to accurately assess scour of salmonid spawning gravel for Watershed Analysis;
2. to detect and monitor changes in the depth and frequency of scour over time;
3. to document variability in scour on a stream segment scale appropriate for Watershed Analysis; and
4. to provide information on discharge and physical channel characteristics to help interpret scour in the context of physical input processes for Watershed Analysis.

KEY ISSUES TO ADDRESS IN DEVELOPING A SPAWNING GRAVEL SCOUR MONITORING METHODOLOGY

Key issues to address in developing a methodology to monitor scour include questions related to the data that needs to be collected, how the data will be interpreted, how the sampling scheme will be designed and what sampling methods will be used.

What data are needed to assess and monitor spawning gravel scour for Watershed Analysis?

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

How will the data be interpreted?

1. How will scour data be interpreted to determine if scour is having a significant affect on salmonid incubation?
2. How will scour data be interpreted in the context of peak discharge events?
3. How will scour data be interpreted in the context of physical channel characteristics?
4. How will scour data be interpreted in the context of watershed condition, climate and land use?

What is a statistically valid design for sampling spawning gravel scour on a stream reach scale?

1. How should a sampling program be designed to characterize scour on a stream reach scale appropriate for Watershed Analysis?
   - a. How should stream systems be sub-divided into reaches?
   - b. How should appropriate sampling locations be identified within a stream reach?
   - c. Should stream reaches be stratified and sub-sampled by habitat/channel types within the stream reach?

d. How many samples are needed?

What sampling methodologies should be used to collect data?

1. What is the accuracy of scour measurement techniques?
2. How reliable are scour measurement methods under peak flow conditions?
3. How does the feasibility (logistics, time and cost) of scour monitoring methods compare?
4. How should data on discharge and physical channel characteristics be collected?

HOW THE KEY ISSUES HAVE BEEN ADDRESSED IN PAST SCOUR STUDIES

Description of the Studies

Fourteen references were identified that discussed measurement and interpretation of scour data in a manner relevant to fish habitat or channel processes. These references are listed in Table 1 and referred to by number in the following discussion. Two studies (2, 5) focus solely on geomorphic processes. Ten studies (1, 3, 4, 6, 7, 9, 11, 12, 13, 14) were oriented towards scour of fish habitat, although many fisheries studies incorporated significant analysis of geomorphic factors. In addition, two papers describing methodologies for monitoring scour were also examined (8, 10).

Data Used to Assess and Monitor Spawning Gravel Scour

Depth of scour was the parameter most frequently used to assess and monitor scour. There were two common variations, mean scour depth or frequency of scour to a “significant” depth (usually related to the depth of salmonid egg pockets). Several additional parameters were used in scour studies to help interpret scour data and to characterize stream channels. These included bed elevation change (fill), peak discharge, substrate, gradient, velocity, channel width and depth, channel pattern, channel morphology, evidence of aggradation, LWD loading, mass wasting, geology, elevation, and hydrologic regime.

Data Interpretation

Interpretation of the significance of scour and fill for salmonid populations

Many studies compared scour depth to the depth that eggs are buried in the gravel to determine the effect of scour and fill on salmonid populations. Some studies determined the percentage of

Table 1. Existing scour studies and methodologies.

1. Crisp, D.T. 1989. Use of artificial eggs in studies of washout depth and drift distance for salmonid eggs.

2. Dinehart, R.L. 1992. Gravel-bed deposition and erosion by bedform migration observed ultrasonically during storm flow, North Fork Toutle River, Washington.

3. Duncan, S.H. and J.W. Ward. 1985. A technique for measuring scour and fill of salmon spawning riffles in headwater streams.

4. Gangmark, H.A. and R.G. Bakkala. 1960. A comparative study of unstable and stable (artificial channel) spawning streams for incubating king salmon at Mill Creek.

5. Hassan, M.A. 1990. Scour, fill, and burial depth of coarse material in gravel bed streams.

6. Kondolf, G.M., G.F. Sada, M.J. Sale and T. Felando. 1991. Distribution and stability of potential salmonid spawning gravels in steep boulder-bed streams of the eastern Sierra Nevada.

7. Lisle, T.E. 1989. Sediment transport and resulting deposition in spawning gravels, North Coastal California.

8. Lisle, T.E. and R.E. Eads. 1991. Methods to measure sedimentation of spawning gravels.

9. McNeil, W.H. 1966. Effect of the spawning bed environment on reproduction of pink and chum salmon.

10. Nawa, R.K. and C.A. Frissell. 1993. Measuring scour and fill of gravel streambeds with scour chains and sliding-bead monitors

11. Nawa, R.K., C.A. Frissell and W.J. Liss. 1990. Life history and persistence of anadromous salmonid stocks in relation to stream habitats and watershed classification.

12. Orsborne, J.F. and S.C. Ralph. 1994. An aquatic resource assessment of the Dungeness River system.

13. Schuett-Hames, D., N.P. Peterson and T.P. Quinn. 1994. Patterns of scour and fill in a low-gradient alluvial channel.

14. Tripp, D. and V.A. Poulin. 1986. The effects of logging and mass wasting on salmonid spawning habitat in streams on the Queen Charlotte Islands.

sites which scoured to the average burial depth of eggs (usually for a target species), or to a "significant" threshold depth where it was assumed impacts would, or could, occur. One study

(14) took a different approach, computing the average scour depth for the reach and comparing that with the distribution of egg burial depths for various species to calculate the mean percentage of eggs lost.

Interpretation of scour in the context of peak discharge

Nearly all studies interpreted scour data in the context of peak discharge. Peak discharge was found to have a very strong correlation with frequency and depth of scour in many studies. The simplest (and most common) form of analysis was simply to compare scour depth data with instantaneous peak discharge. Several studies also estimated the recurrence interval of events where an adequate gaging record was available. Precipitation data were used as a surrogate for discharge in one study (9) in an area with rainfall dominated runoff events.

Interpretation of scour data in the context of channel and watershed conditions

Data on substrate particle size was used to characterize the stream bed and to interpret scour data in many studies. Information on particle size was used to calculate mean grain size, D_{50}, or overall particle size distribution.

A variety of other parameters were used to characterize channel or watershed conditions. In some cases this information was used to interpret differences in scour among study sites. Examples of data collected to characterize stream channels included: bankfull width, bankfull depth, bankfull discharge, water surface slope, stream order, channel pattern (braided, meandering), channel morphology (pool-riffle, boulder-bed), mean annual flow, elevation, LWD loading, channel gradient and confinement, debris torrent damage and presence of aggradation. Examples of data collected to characterize watersheds included basin area, geology, hydrology, extent of mass wasting, and logging history. Several studies employed a systematic classification system to stratify stream segments on the basis of physical features. One study (11) used data on streams and watershed conditions in a hierarchical watershed/stream classification system to establish linkages to land use impacts.

Sampling Design

Sub-division of stream networks into reaches

Few studies attempted to systematically stratify sampling reaches within a watershed on the basis of stream segment characteristics. In one study, stream segments were selected based on the channel and watershed characteristics (11). In another study, sampling reaches were stratified according to channel morphology (13). In most cases, sampling locations were selected for other reasons, and a variety of parameters were measured to help characterize the study reach and allow comparison with other reaches.

Identification of potential sampling locations within a stream reach

Three approaches were used to identify sampling sites significant to fish: selection of current redd locations (11, 12); selection of areas where salmon were known to spawn in the past (1, 3, 4, 9, 11, 12, 13); and selection of potential spawning habitat based on physical criteria (6, 7, 11, 12, 13, 14). Particle size, and occasionally depth and velocity, were the physical characteristics used to identify potential spawning habitat, however the specific criteria were typically not well documented.

Stratifying and sub-sampling stream reaches by habitat/channel types

Few studies attempted to systematically sample different types of spawning habitat or channel geomorphic units within stream reaches. Six studies (1, 3, 4, 7, 9, 14) purposely restricted sampling to one consistent habitat or channel location (typically riffles or pool/riffle boundaries) to minimize variability. Three studies (5, 6, 13) systematically sampled different habitats. Various types of strata were sub-sampled depended on whether the study had a geomorphic or fisheries orientation, the nature of the stream channel, and the habitat present to be utilized. Examples of geomorphic/habitat strata used in various studies includes: riffles, riffle crests, pools, pool tailouts, glides, pool lateral bars, the thalweg, bars and various types of gravel deposits in high gradient streams. This information was useful in identifying specific locations where scour occurred most frequently.

Determining the number of samples needed

The number of samples collected was highly variable, ranging from over 100 to less than 10. None of the studies provided a rationale for the number of samples collected. It appears this issue has not been thoroughly examined.

Sampling Methodologies

Description of methods used to measure scour

Five basic methods of monitoring depth of scour were used. Six studies (3, 7, 11, 12, 13, 14) used some type of scour monitor device that was inserted in the gravel to measure scour and fill. Artificial redds placed in the stream bed were used in two studies (1, 4). Two other studies used tagged or marked particles that were buried in the stream bed (5, 6). In one case an ultrasonic depth sounder was used to create a continuous record of bed elevation (2) and one study relied upon periodic counts of egg density in the gravel throughout the incubation period (9).

Design of monitoring devices varied. The most widely used monitor design consisted of a series of beads or plastic perforated golf balls strung on a line and inserted vertically into the gravel. As scour occurred, the beads or balls were exposed and carried to the end of the line by the current where they could be counted to determine scour depth. Brightly colored plastic floats produced for steelhead fishing have also been used in this manner (Jim Matthews, Yakama

Indian Nation, personal communication).

Scour chains buried vertically in the gravel were used in another study. Depth of scour was measured by counting the number of links from the upper end down to the deflection point where horizontal portion of the chain (the portion exposed to the current washed in a downstream direction) meets the undisturbed, vertically oriented portion, and comparing the difference before and after scour. Another monitor device (3) consisted of a metal shaft with a sliding mechanism (rebar L attached to plastic pipe) that rested on the surface of the gravel and slid down the shaft when scour occurred.

Two types of artificial redds were used. One type of artificial redd was constructed by burying plastic mesh bags containing live eggs at a known depth (4). The second type was made by burying disk-shaped pieces of ice containing artificial eggs at three depths in the stream bed (1).

Accuracy of scour measurement methods

Scour monitor devices provide satisfactory accuracy and resolution since scour depth can be measured in increments over a large range (typically 40 to 100 cm depth). Resolution depends on the diameter of the measurement apparatus (ball, beads, chain link). Artificial redds and tagged particles provide less resolution, since the redd or tagged particle was frequently placed at only one depth. Resolution was improved in one case by placing color-coded eggs at three depths in the artificial redd (1). Tagged particles had limitations similar to artificial redds because they only document whether scour reaches the depth of the particle but provide no resolution above or below that depth.

The ultrasonic monitor had a high degree of resolution and provided a continuous record of scour depth that documented episodes of scour and fill during storm events. The egg sampling method provided no actual depth of scour data since scour depth was inferred based on the presence of absence of naturally deposited eggs in the gravel following peak flows.

Reliability of various methods under peak flow conditions

The golf ball and sliding bead monitor devices performed satisfactorily in stream channels during peak flows. One advantage of these devices is that scour depth can be documented between storm events without excavating the stream bed. Collecting data from scour chains is more difficult because they do not float and have to be examined at low flows. Excavating buried scour chains requires extreme care since disturbance of the chain can alter the deflection point, changing the measurement.

The metal shaft monitor device is subject to problems when woody debris floats down the stream during storm events. Small debris can snag on the shaft, jamming the sliding mechanism or creating local scour. Large debris can ram the shaft, bending or dislodging it. The ultrasonic monitor was disabled terminating data collection when the frame suspending the apparatus was rammed by a large pieces of debris floating downstream during a peak flow event.

Artificial redds and tagged particles can be difficult to relocate because they are buried out of sight in the gravel (scour monitor devices can also become buried when excessive fill occurs). Attaching floating tags could help overcome this problem. Markers on the banks adjacent to the channel are needed to relocate buried scour monitor devices, artificial redds or tagged particles. These markers can be obscured or destroyed by high flows making it impossible to relocate monitoring sites. To assist with relocation, tagged particles are usually either marked with paint, have metal strips attached, or have magnets inserted into the particle. Abrasion of the paint or loss of tags can be a problem, however this usually only occurs after the particle is dislodged. Inability to find scoured artificial redds or tagged particles results in uncertainty as to whether scour actually occurred, or whether the relocation system was inaccurate.

Feasibility of methods (logistics, time and cost of sampling)

The studies with the largest sample sizes used either scour monitor devices or tagged particles. Both methods are relatively easy to use. The tube used to insert golf ball monitors must be pounded into the stream bed (14). This becomes increasingly difficult as particle size increases. Smaller diameter sliding bead monitors and scour chains can be inserted with a driving point system (10) that works better in stream beds with compacted substrate. The metal shaft monitors appear to be relatively easy to install. One tagged particle study (6) used a McNeil sampler to remove and reinsert tagged particles, restricting sampling to beds with gravel that would fit into the McNeil sampler. The cost of any of the scour monitor devices or tagged particle approaches does not appear prohibitive.

Artificial redds require more effort to construct and install. Studies using them (1, 4) had a small sample size. Construction of artificial redds required handling living eggs in plastic mesh bags (4) or artificial eggs frozen in disks of ice (1), making widespread application difficult under field conditions.

The ultrasonic monitor was the most expensive and logistically challenging method, requiring construction of a frame that is lowered into the stream at high flows to submerge the sensors in the water (2). Consequently, extensive time and effort was required to sample a single location on the stream bed. Hydraulic sampling of the stream bed to determine egg density is labor intensive, and produces results which may be difficult to associate directly with scour depth.

Collection of data on discharge and physical channel characteristics

Many of the studies used records from established gaging stations to determine peak discharge. In other cases, water levels were continuously recorded on site, and discharge measurements from nearby gages were used to establish a rating curve. Substrate data were collected using a bulk sample of substrate (surface and subsurface) or a pebble count (surface only).

RECOMMENDED MONITORING APPROACH

The following recommendations for a scour module are based on the literature review, personal experience and discussions with others.

Monitoring Parameters

Depth of scour in spawning habitat is the primary data that should be collected. Other recommended parameters include change in bed elevation (fill), peak flow discharge, substrate particle size (D_{50}) and channel gradient. This information will document scour conditions affecting incubating salmonids and allow scour to be interpreted in relation to physical input processes (hydrology and sediment transport) evaluated in of Watershed Analysis. Collection of additional data on physical channel characteristics such as gradient, LWD size and abundance and bankfull width would help to interpret differences in scour between segments and can be used to help identify reaches vulnerable to scour.

Sampling Design

There is extensive local variation in scour depth within stream reaches (Hassan, 1990; Schuett-Hames, et al., 1994). Typically, each year some salmonid egg pockets are destroyed by scour while others survive unaffected. Consequently, monitoring data collected at a single location or a small number of sites could provide a misleading picture of the overall effect of scour on a salmonid population. To interpret the significance of scour to salmonid populations, depth of scour data should be collected and interpreted at the stream-reach scale. The Watershed Analysis stream segment is recommended as the spatial unit of analysis for depth of scour. Stream segments identified on the basis of bankfull channel width, stream order, gradient, and channel confinement will allow depth of scour data to be integrated into the Watershed Analysis stream channel analysis.

Some within-reach variability in depth of scour appears to be related to differences in hydraulics associated with morphological features such as pools and riffles (Hassan, 1990; Schuett-Hames, et al., 1994). A better interpretation of depth of scour data can be obtained by differentiating the various types of spawning habitat available and stratifying sampling within stream segments by habitat type. Channel morphology and substrate size vary, so identification and stratification of habitat types will need to reflect conditions in each study stream. In channels with pool-riffle morphology, we recommend sampling a variety of typical spawning locations such as pool tailouts, riffle crests, and mid-riffle locations (Schuett-Hames et al., 1994). In steeper reaches where spawning habitat occurs in patches associated with obstructions (Kondolf et al., 1991), sampling locations representative of available gravel patches should be selected.

Scour should be monitored in suitable spawning habitat along cross-sections at sites selected to represent each spawning habitat type available in the reach. Conducting sampling along cross-sections allows systematic sampling of variation across the stream channel, and facilitates re-location of monitoring devices and collection of bed elevation information.

Depth of scour should be measured at 0.5-2.0 m intervals along the cross-sections depending on stream size (Table 2). Data on bed elevation, gradient, substrate, bankfull width should be collected at each cross-section.

Table 2. Recommended spacing of monitors along cross-sections.

Channel width (m)	Scour monitor spacing on cross-sections (m)
0 - 2.5	0.4
2.5 - 5	0.8
5 - 7.0	1.0
7.0 - 10	1.5
10 - 20	2.0
20 +	3.0

The number of samples (monitor locations) needed depends on the desired accuracy and confidence levels desired. The number of samples needed to attain levels of precision ranging from +/- 2.5 % - 20% at the 90 and 95 % confidence levels are shown in Tables 3 and 4, respectively. This information was derived by evaluating an existing set of depth of scour data from Kennedy Creek, Washington (Schuett-Hames et al, 1994). Note that the sample size varies depending on the percentage of samples expected to exceed the egg pocket depth criterion.

Table 3. Number of samples required to achieve different levels of relative precision for the estimate of *P*, the percentage of sites with a depth of scour exceeding a predetermined depth, at the 95% level of confidence.

Relative	Expected Percentage for *P*				
Precision	10%	20%	30%	40%	50%
±2.5%	553	983	1,291	1,475	1,537
±5.0%	138	246	323	369	384
±7.5%	61	109	143	164	171
±10.0%	35	61	81	92	96
±12.5%	22	39	52	59	61
±15.0%	15	27	36	41	43
±17.5%	11	20	26	30	31
±20.0%	9	15	20	23	24

Table 4. Number of samples required to achieve different levels of relative precision for the estimate of *P*, the percentage of sites with a depth of scour exceeding a predetermined depth, at the 95% level of confidence.

Relative	Expected Percentage for *P*				
Precision	10%	20%	30%	40%	50%
±2.5%	390	693	909	1,039	1,082
±5.0%	97	173	227	260	271
±7.5%	43	77	101	115	120
±10.0%	24	43	57	65	68
±12.5%	16	28	36	42	43
±15.0%	11	19	25	29	30
±17.5%	8	14	19	21	22
±20.0%	6	11	14	16	17

Sampling Methodologies

Scour. Use of golf ball or sliding bead monitoring devices is recommended to measure scour. These devices provide suitable accuracy, are reliable under peak flow conditions, and can be built and deployed at a reasonable cost. The measurements obtained from both monitor designs should be comparable.

Bed elevation. Bed elevation, relative to a permanent benchmark, should be measured at monitor locations along cross-sections. Measurements should be made at the time of monitor installation and after major storm events to document changes in bed elevation. Use of standard surveying equipment is recommended.

Substrate. Pebble counts (Wolman, 1954) should be used to document substrate particle size distribution along each cross-section at the time of monitor installation in order to examine the relationship between scour depth and particle size.

Peak discharge. Peak discharge may be determined by some measure of maximum stage, or level of flow, for a particular flood event. Maximum stage can be determined using a crest-stage gage or by identification of high water marks. Peak flow may be ascertained directly, using a flow rating curve, or indirectly, using detailed cross section and water surface profile data and flow equations. Measurement of maximum stage and peak discharge should be conducted in accordance with USGS procedures for stage and streamflow measurement.

Data Interpretation

To be meaningful for Watershed Analysis, scour data must be interpreted in the context of salmonid populations, peak flow events, channel characteristics and watershed conditions.

Depth of scour data should be interpreted by developing a frequency distribution curve showing the percentage of monitors scoured to various depths. This curve can be used to determine the percentage of monitors scoured to mean egg pocket depth (50 % probability of reaching an egg pocket) for the species of concern in the reach.

Variation in the depth of egg deposition occurs within and between populations of the same species, as well as between all the salmonid species of potential interest in Washington State. Depth of egg deposition appears to be influenced by the size of the female (van den Berghe and Gross, 1984), particle size, bed compaction, and velocity (Burner, 1951). Some of the variability in data on depth of egg deposition has been introduced by sampling methodologies (van den Berghe and Gross, 1984).

If information on the depth of egg deposition is available for stocks of interest, it should be used to determine mean egg pocket depth. If not, we recommend using default values for mean egg pocket depth developed from the literature (Table 5). To develop the default values, species were grouped by relative size, and conservative values for mean egg pocket depth were selected from the range of values reported in the literature.

Table 5. Recommendations for default mean egg pocket depth where stock-specific information is lacking.

Category	Species	Mean egg pocket depth (m)
Large-bodied salmonids	chum, chinook, steelhead	0.20
Medium-bodied salmonids	coho, pink, sockeye	0.16
Small-bodied salmonids	cutthroat, rainbow, bull trout, Dolly Varden	0.08

Depth of scour data should also be examined to identify patterns in relation to habitat types, substrate particle size distribution, peak discharge and stream gradient.

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