

**KEY UNCERTAINTIES IN GRAVEL
AUGMENTATION:
GEOMORPHOLOGICAL AND
BIOLOGICAL RESEARCH NEEDS FOR
EFFECTIVE RIVER RESTORATION**

Prepared by the CALFED Science Program and
Ecosystem Restoration Program
Gravel Augmentation Panel

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Acknowledgements

The Gravel Augmentation Panel would like to acknowledge the participants and presenters at the CALFED Rivers, Rocks and Restoration Workshop in July of 2004 for their assistance in calling out some of the key uncertainties facing the science and practice of gravel augmentation. We would also like to acknowledge the efforts of Jill Marshall (CALFED Science Program) and Rhonda Reed (CALFED Ecosystem Restoration Program) in organizing the workshop and supporting the panel in its work. Finally, the Panel's work has been greatly improved by the leadership, facilitation, and coordination of Rebecca Lave, who also served as editor and a contributing writer.

Executive Summary

Gravel augmentation is becoming a common management approach to address ecosystem restoration needs in the Central Valley, and a strategy in which CALFED is increasingly starting to invest. Because of this investment, the CALFED Science and Ecosystem Restoration Programs co-sponsored the Rivers, Rocks, and Restoration Workshop in July 2004 to discuss gravel augmentation. CALFED convened a technical panel to participate in the workshop and then produce a report identifying critical research questions and experiments to improve our understanding of gravel augmentation and management in the context of ecosystem restoration. The goals of this report are to:

1. Provide an introduction to gravel augmentation projects and the key issues involved in their design and implementation.
2. Identify the most pressing questions about the science and practice of gravel augmentation, describe the best available knowledge on each of these questions, and discuss the remaining uncertainties that need to be addressed.
3. Recommend specific studies, white papers, large-scale experiments, and coordination activities for CALFED to pursue in order to address these key uncertainties.

Panel members synthesized information and suggestions from workshop participants with a literature review and their own technical experience to develop a summary of important management questions (Chapters 5 and 6). These questions address both geomorphological issues (e.g., Can spatial and temporal effects of gravel augmentation be predicted?) and biological issues (e.g., What are population-level benefits of gravel augmentation to anadromous salmonids?). From these questions, the panel recommended studies, adaptive management experiments, and coordination that CALFED should consider implementing in the coming years (Chapter 8).

Key Uncertainties

A considerable amount of available research addresses gravel augmentation (e.g., coarse sediment transport processes, spawning gravel quality), but research with a specific focus on gravel augmentation is in its infancy. This report addresses key uncertainties about gravel augmentation, the most critical of which are summarized in this section. Some are large-scale issues that integrate geomorphological and biological questions, including:

- Can we predict the spatial and temporal effects of gravel augmentation on channel form, both on a reach (Section 5.1) and sub-reach (Section 5.2) scale?
- What are the potential long-term negative impacts of gravel augmentation on biological, physical and chemical processes? (Section 7.1)
- Can gravel augmentation improve non-spawning habitat for salmonids (Section 6.8), or create secondary benefits for other species of interest? (Section 7.1)
- What are the quantitative linkages between gravel augmentation, fluvial processes and form, habitat for aquatic animals of special concern, and the population dynamics of those animals? (Section 7.1)
- How far can river channels be scaled down and still retain critical habitat functions? (Section 7.2)

- How do we define and measure project success? (Section 7.4)
- Is gravel augmentation sustainable? (Section 7.5)
- What impact will climate change have on stream restoration projects in California? (Section 7.6)

There are also a number of smaller-scale geomorphological and biological uncertainties about gravel augmentation as a management strategy:

- Can immobile armor be mobilized with fine gravel addition? (Section 5.3)
- Can gravel augmentation serve as a substitute to flushing flows for removing fine sediments from the surface and subsurface? (Section 5.4)
- How does fine sediment infiltrate gravel deposits? (Section 5.5)
- How clean does gravel need to be to protect water quality (Section 5.6), without negatively impacting ecosystem health? (Section 6.6)
- How is sediment routed and stored in bedrock canyon streams? (Section 5.7)
- What factors influence salmonid use of introduced gravel for spawning? (Section 6.1)
- Does gravel augmentation influence scour risk? (Section 6.2)
- What short-term negative impacts to fish occur as a result of gravel augmentation? (Section 6.7)
- How accurate and precise is coarse sediment transport modeling in management applications? (Section 7.1)
- What are the best techniques for empirically estimating coarse sediment transport and computing a sediment budget for a given reach of river? (Section 7.1)
- What is the relationship between bed scour depth and discharge? (Section 7.1)
- What effects do gravel augmentation location and magnitude have on spawner distribution? (Section 7.1)

Answers to some of these key uncertainties may exist in the literature, yet they remain important issues for many scientists and practitioners attempting to implement and monitor gravel augmentation projects in the Central Valley.

Recommendations

The panel recommends that CALFED solicit and prioritize funding for scientific studies and restoration projects that address the key uncertainties identified in this report. These studies and projects should be hypothesis-driven, with clear statements of the hypotheses to be investigated and how the data collected will be used to test them. Highest priority should be given to studies and projects that further our understanding of the linkages between geomorphic processes and ecosystem response. Where objectives include creating benefits for salmon, priority should be given to projects that address population-level consequences, which may provide data to help prioritize among more narrowly focused studies. The panel further recommends finding mechanisms to institutionalize ongoing peer review of gravel augmentation studies and projects, especially those designed to address key uncertainties.

Many of the key uncertainties listed in the report will be difficult to address through single-site projects implemented by one investigating institution. The panel thus recommends that CALFED support broader studies following an adaptive management framework that are carried out both within and across drainage basins and scientific disciplines. The panel

recommends that CALFED take a leadership role in selecting critical scientific questions to address, assembling qualified teams of investigators, and coordinating development of experimental designs and project implementation. Ideally, these adaptive management experiments will involve not only field-based investigations but also theoretical, numerical and laboratory components.

In addition to specific studies to address areas of scientific uncertainties, the panel recommends that CALFED solicit several white papers relevant to gravel augmentation. The white papers' purpose would be to provide scientists and practitioners with a concise summary of available information to inform and improve gravel augmentation project performance, monitoring strategies, and overall cost effectiveness. The panel recommends that CALFED commission white papers on the following topics:

- The role of coarse sediment transport numerical modeling in coarse sediment management;
- Long-term sources of gravel;
- The relationship between gravel quality and fry production;
- Methods for reducing mercury contamination in dredger tailings;
- The use of ground and bathymetric topographical data in project design and monitoring; and
- Monitoring guidelines.

Lastly, the panel suggests that CALFED improve information-sharing and coordination among projects it funds by:

- Taking a proactive role in encouraging communication among researchers, consultants and agency staff involved in gravel augmentation projects by creating an on-line, searchable repository of project information, and by creating multiple avenues for sharing technical expertise;
- Committing resources for monitoring and reporting on project results; and
- Exploring ways to address the regulatory challenges facing restoration projects in California.

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Chapter I. Introduction

1.1. Objectives

This report was produced by an interdisciplinary panel of fisheries biologists and geomorphologists assembled by the Ecosystem Restoration and Science Programs at the California Bay Delta Authority, the governing entity for the CALFED Bay-Delta Program (CALFED). The panel members were:

- Bret Harvey (Redwood Sciences Laboratory, USFS),
- Scott McBain (McBain & Trush, Inc.)
- Dudley Reiser (R2 Resource Consultants, Inc.)
- Laura Rempel (University of British Columbia)
- Leonard Sklar (San Francisco State University)

Rebecca Lave (UC Berkeley and Design, Community & Environment) was a contributing author and editor, and facilitated the panel's work.

The panel's task was to produce a report for CALFED that would identify critical research areas and experiments to improve our understanding of gravel augmentation and management in the context of ecosystem restoration.

This report is not a summary of the presentations and discussion at CALFED's Rivers, Rocks and Restoration Workshop (see Chapter 2, below), which started the process, though it draws heavily on both. Nor is it intended to broadly describe the state of the science of gravel augmentation (see Bunte 2004 and the forthcoming CALFED white paper by Kondolf et.al. for a review of the state of geomorphological science on gravel augmentation below dams). Instead, the goals of this report are to:

1. Provide an introduction to gravel augmentation projects and the key issues involved in their design and implementation.
2. Identify the most pressing questions about the science and practice of gravel augmentation, describe the best available knowledge on each of these questions, and discuss the remaining uncertainties that need to be addressed in order to satisfactorily answer them.
3. Recommend specific studies, white papers, large-scale experiments, and coordination activities for CALFED to pursue in order to effectively address these key uncertainties.

This report consists of the following nine chapters:

- **Chapter 1** introduces the report.
- **Chapter 2** describes the Rivers, Rocks and Restoration Workshop and key ideas arising from it.
- **Chapter 3** sets forward an interdisciplinary model for conceptualizing the goals, design and results of gravel augmentation projects.
- **Chapter 4** reviews the steps necessary to design and implement a gravel augmentation project.
- **Chapter 5** addresses the key geomorphological questions raised by gravel augmentation.

- **Chapter 6** addresses the key ecological questions raised by gravel augmentation.
- **Chapter 7** describes additional important uncertainties that are not covered in other sections of the report.
- **Chapter 8** presents the panel's recommendations.
- **Chapter 9** lists the references cited.

1.2. A Brief history of Gravel Augmentation

Gravel augmentation downstream of Central Valley dams began in the late 1960's, and has until recently focused almost entirely on improving anadromous salmonid spawning habitat. Kondolf (2004) conducted a review of gravel augmentation projects in California, and found that at least 82 projects were conducted between 1968-2004, with a total of at least 400,000 yd³ of gravel added for spawning habitat improvements.¹ Many of these projects have been implemented by reconstructing spawning riffles and pool tails, in some cases accompanied by attempts to hold them in place with boulder weir grade control structures. These projects have had only temporary beneficial results, as placed gravels were usually scoured and transported downstream by subsequent high flows. Creation of spawning habitat is still the predominant rationale for gravel augmentation projects, with more sophisticated hydraulic models now being applied in an attempt to place gravel in a way that maximizes areas with preferred depths, velocities, and substrate for spawning salmonids (e.g., Pasternack et 2004).

1.3. Coarse sediment augmentation: moving beyond spawning habitat

More recently, the objectives of gravel augmentation in several rivers (e.g., the Merced, Sacramento, Trinity, and Tuolumne Rivers and Clear Creek) have been broadened to include improving dynamic fluvial processes and resulting channel form. These projects are sometimes referred to as "coarse sediment augmentation" to differentiate them from "gravel augmentation," because the size range of coarse sediment extends to larger particles (e.g., cobbles) than traditional gravel augmentation projects. Combining coarse sediment augmentation with high flow releases or spills is intended to increase coarse sediment transport and deposition, improve channel migration, and form complex bar features that will improve habitat for a variety of aquatic and terrestrial species. These projects often require much larger volumes of coarse sediment than traditional spawning gravel augmentation projects, and their geomorphic and ecological success is uncertain due to the limited experimentation to date. For ease of review, we use the term "gravel augmentation" in the remainder of the report to include both "gravel" and "coarse sediment", as described above.

¹ Additional research on this question by Stillwater Sciences found an estimated 800,000 yd³ of gravel added to date.

Chapter 2: the Rivers, Rocks and Restoration Workshop

2.1. Recap of Workshop

The Rivers, Rocks and Restoration Workshop (R³ Workshop) was held on July 13th and 14th, 2004 in Sacramento as a joint presentation of the CBDA Science and Ecosystem Restoration Programs. There were approximately 120 participants, including agency staff, academics, and consultants. The workshop was organized by Jill Marshall (Science Program) and Rhonda Reed (ERP) with the intention of encouraging discussion among participants, presenters and panel members. Thus each group of presentations was followed by a question period, and there was a discussion led by the five panel members at the end of each day.

The presentations were grouped into five main areas:

- **Gravel augmentation approaches and learning opportunities**, with presentations by Kevin Faulkenberry (DWR), Greg Pasternack (UC Davis), Carl Mesick (Carl Mesick Consultants), Mike Harris (Shasta RCD), Matt Brown (USFWS) and Andreas Kraus (Trinity River Restoration Program);
- **Linkages between physical processes and biota**, with presentations by Laura Rempel (University of British Columbia) and Frank Ligon (Stillwater Sciences);
- **Scale issues**, with presentations by Matt Kondolf (UC Berkeley) and Tom Lisle (USFS);
- **Design tools**, with presentations by Leonard Sklar (San Francisco State University) and Yantao Cui (Stillwater Sciences); and
- **Monitoring issues**, with presentations by Jennifer Vick (McBain and Trush) and Paul DeVries (R2 Resources).

These presentations are currently available online at:

http://science.calwater.ca.gov/workshop/workshop_071304.shtml.

2.2. Summary of Major Issues Raised at the R³ Workshop

The main issues discussed at the R³ Workshop included:

- **Does gravel augmentation create net habitat benefits?** Have the links between sediment introduction and population response been demonstrated, or simply assumed? Does gravel augmentation address the limiting factors for salmonids, or are other factors (rearing habitat, flow levels, etc.) more important?
- **Gravel augmentation: it's not just for spawning anymore.** A number of presenters argued that we should expand our understanding of the purposes of gravel augmentation projects beyond the creation of spawning habitat for salmonids towards a model of supporting multiple species and lifestages, as well as the restoration of geomorphic processes.
- **Too many projects are done on a "build it and they will come" basis.** Several presenters argued that many gravel augmentation projects are designed without careful consideration of the links between management action and desired affect, neither stating nor developing assumptions and hypotheses to guide their projects. As Greg Pasternack

described it, the limiting factor in advancing gravel augmentation is not basic science, but applied science experiments in the field.

- **Implementation is hard.** A number of presenters and workshop attendees commented on the difficulty of getting projects built, with regulatory compliance, building support among community members and agency staff, and the short construction season for in-channel work topping the list of problems.
- **Monitoring is harder.** Many presenters commented about the difficulty of designing and conducting pre- and post-project monitoring. Monitoring techniques need to be standardized to ensure comparability of results, but in every monitored project, there also needs to be careful matching among the hypotheses, designs and monitoring techniques employed. As Jennifer Vick put it: one size does not fit all; project proponents need to think carefully about what will be measured during monitoring and whether it actually answers the questions around which the project is framed.
- **The need for coordination across river basins.** Presenters and attendees spoke about the need for a central body to coordinate monitoring across river basins and disciplines to enable broad testing of specific hypotheses. Others mentioned the need for a range of reference reaches for long-term, intensive, multi-disciplinary study. The current CALFED funding process discourages adaptive management and long-term monitoring because of the short time-scale of funding.
- **The need for more interdisciplinary work, greater sharing of information, and an established forum for getting technical advice.**
- **Is gravel augmentation a sustainable practice?** Questions were raised about sources of gravel, and the sustainability of a practice that required constant infusions of new material.
- **How to get society more interested in, and supportive of, restoration.** Is the issue scientific illiteracy, lack of intelligible outreach by scientists, economics, or something else entirely?

Chapter 3: Ecosystem Context of Gravel Augmentation

Underlying hydrology (water) and geology (sediment, tectonics) are the primary governing variables of river ecosystems; how water, sediment, vegetation and human influences interact determines channel form (Figure 3-1). Correspondingly, channel form defines aquatic and terrestrial habitat within the river corridor, which in turn influences the biota. Figure 3-1 presents a hierarchical riverine perspective: SUPPLY → PROCESSES → FORM → HABITAT → BIOTA. Changes to the input variables (SUPPLY) in this conceptual framework usually cascade down to the biota, but this cascading effect is rarely considered adequately before change is imposed on the system (e.g., How will loss of coarse sediment supply impact aquatic habitat downstream of a dam?). The primary natural components of the SUPPLY tier are water and sediment, with some influence by large wood. The primary natural components of the PROCESSES tier are sediment transport, sediment deposition, channel migration, channel avulsion, nutrient exchange, and surface water-groundwater exchange. Sediment transport and deposition form alluvial features, including alternate bars and floodplain surfaces. In turn, these channel and floodplain features provide the physical location and suitable conditions that define habitat for aquatic organisms, including native fish species. The form of the channel (i.e., channel morphology) is thus a critical link between physical riverine processes and the native biota that the river corridor may support.

3.1. Alluvial Rivers

Alternating bars are considered basic units of alluvial rivers (Dietrich 1987), and this conceptual framework is useful in illustrating links between alluvial river form and aquatic habitat (Trush et al. 2000). Each alternate bar is composed of an aggradational lobe (point bar) and scour hole (pool) connected by a riffle. A variable flow regime causes spatial and temporal differences in sediment transport, scour, and deposition on alternate bar features to create morphologic and hydraulic complexity, which in turn produces diverse, high quality aquatic habitat (Figure 3-2), including:

- adult holding habitat in pools;
- preferred hydraulic conditions and substrates for spawning in riffles and pool tails;
- high quality embryo incubation environments in permeable, frequently mobilized spawning gravels;
- winter and spring rearing habitat in cobble substrates along slack-water bar surfaces, and in shallow backwater zones behind point bars;
- fry and juvenile velocity refugia and ephemeral rearing habitat on inundated bar and floodplain surfaces during high flows;
- abundant primary and secondary (food) production areas on the surface of gravels and cobbles, on woody debris, and on floodplains (terrestrial invertebrates); and
- large organic debris and nutrient input (logs, root-wads, leaf litter, salmon carcasses) that provide structural diversity as well as a primary source of nutrients for lower trophic levels.

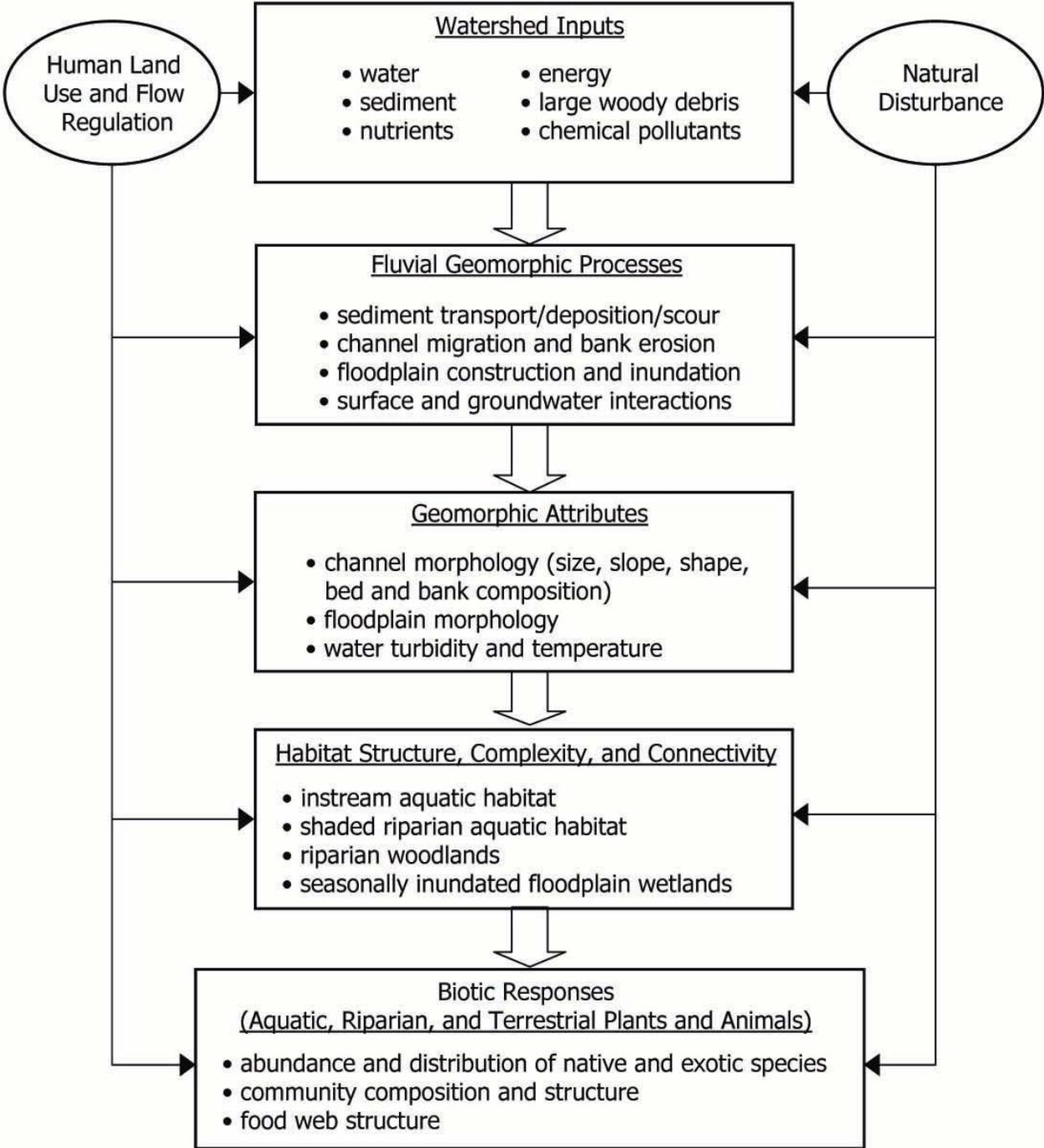
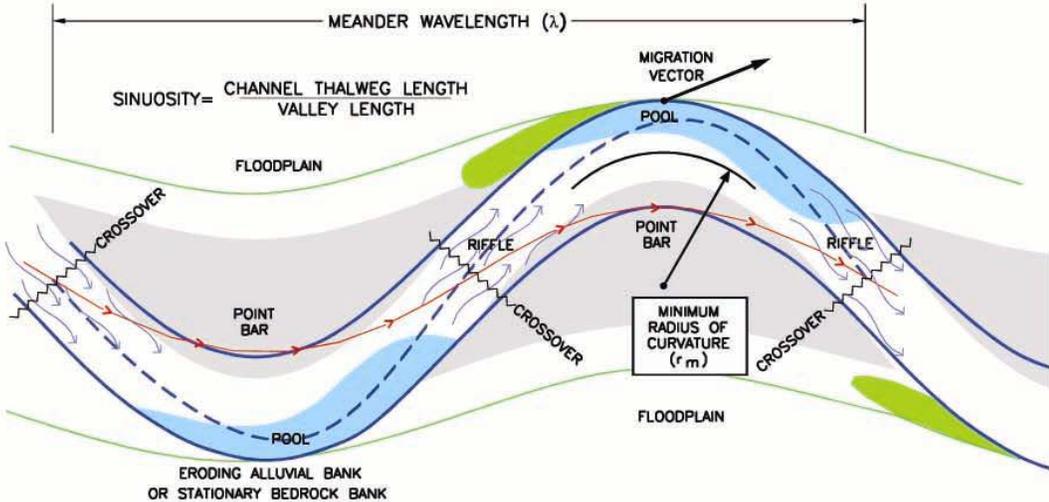


Figure 3-1. A simplified conceptual model of the physical and ecological linkages in alluvial river-floodplain systems, from Stillwater Sciences (2002).

GEOMORPHIC UNITS



CHINOOK SALMON HABITAT

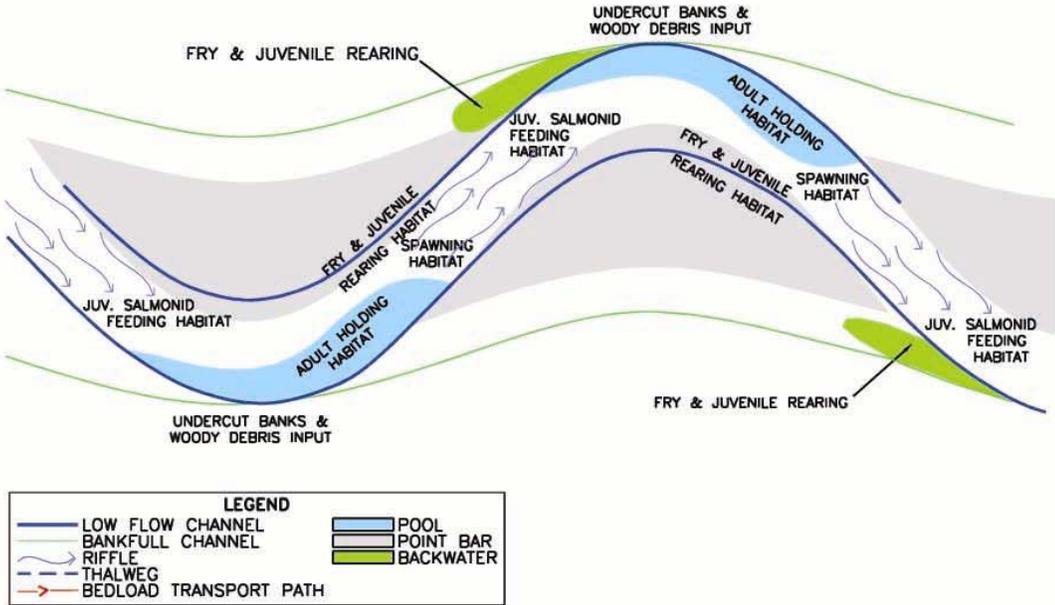


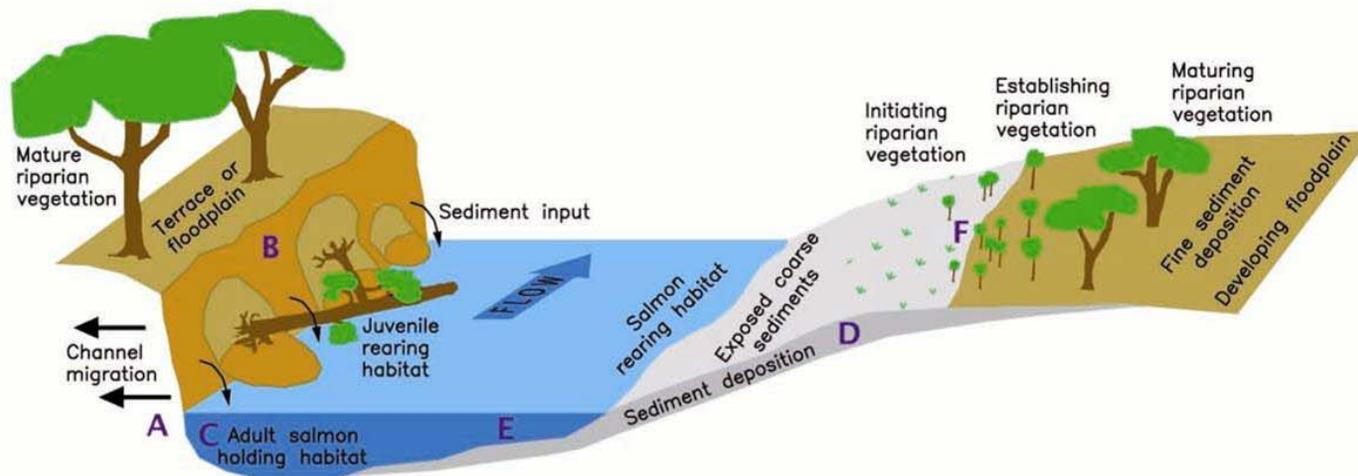
Figure 3-2. Idealized alternate bar sequence showing location of habitat features used by chinook salmon (modified from Dietrich 1987).

This correlation between physical processes and mainstem aquatic habitat is not always the primary driver of fish population survival (e.g., improved physical habitat doesn't necessarily increase fish numbers). Other influences, such as tributary habitat, inputs of suspended sediment to the mainstem, barrier effects, interspecies interactions (including predators), nutrient inputs, fisheries harvest management, ocean conditions, and climate change must also be considered when assessing factors limiting fish production.

A dynamic alternating bar morphology is only one indicator of a "properly functioning" or "healthy" alluvial channel. Floodplains, medial bars, and side channel networks are also key morphological indicators. These features may not be the direct consequence of alternate bar formation, but all are interdependent to varying degrees. Channel migration causing bank erosion, and subsequent sediment deposition on the inside of the downstream bend, maintain channel width and are fundamental fluvial processes that create and preserve an alternate bar morphology. As the channel migrates (over a time span of years to decades), cobbles and gravels deposit on the inside of bends in the gravel-bedded reaches, sand bars deposit on the inside bend in the sand-bedded reaches, large wood may enter the channel along eroding banks, and fine sediment deposits on developing floodplains along the backside of alternate bars (Figure 3-3). Riparian vegetation initiates on these new floodplain surfaces, and as it matures and the channel eventually migrates again, it enters the river channel as large woody debris.

3.2. Bedrock Rivers

While not discussed in detail during the R³ Workshop, gravel management is also an issue for bedrock rivers within the Central Valley. While quantifying the cause and effect relationships between gravel supply and biota is often more difficult for bedrock rivers, these relationships nonetheless exist. Salmonids spawn and rear in alluvial deposits within the bedrock dominated channel, and bars and floodplains are formed in certain areas by coarse sediment deposition. The hydraulic capacity of the high flow regime to transport coarse sediment in steep, confined bedrock channels is usually much larger than the sediment supply to the stream, suggesting that any gravels delivered to the stream are quickly "flushed" out of the system, leaving the channel devoid of any alluvial deposits. However, alluvial deposits do exist in nearly all confined and/or bedrock channels (e.g., Howard 1998, Montgomery et al. 1996). Much of the storage results from hydraulically shielded areas that allow coarse sediment deposition to occur. Figure 3-4 illustrates a conceptual model of coarse sediment storage in a bedrock river as a function of sediment supply under a given high flow regime (McBain and Trush 2004b). Dams rarely strip the channel of coarse sediment due to large roughness features (zone 1 in Figure 3-4) but they reduce storage in these "compartments" (zone 2). Gravel augmentation will likely quickly fill these storage compartments, yet additional increases of sediment once they are full may not result in appreciable increases in storage due to high transport capacity (zone 3). Coarse sediment supply would have to be greatly increased (greater than transport capacity) for storage to begin in the unsheltered portions of the channel (zone 4), eventually burying all exposed bedrock in the channel bed.(zone 5). This condition, in which the channel-spanning sediment cover is a thin veneer over bedrock, is common in hilly and mountainous terrain where coarse sediment supply has not been reduced by dams or other land use effects.



Conceptual linkages between channel migration and fish habitat. (A) A channel with adequate space to migrate erodes the channel bank on the outside of the meander bend during high flows, (B) encouraging mature riparian trees to topple into the channel. (C) The pool along with large wood on the outside of the bend provide structural complexity for good fish habitat. As bank erosion continues, the pool “migrates” laterally and downstream, but high quality habitat is maintained. (D) On the inside of the bend high flows scour and redeposit sediments (gravel in Reach 1, sand in downstream reaches), forming a shallow bar on the inside of the bend. (E) In Reach 1, this area provides slow-water rearing conditions for fry and juvenile chinook salmon, as well as habitat for aquatic insects (fish food), amphibians and reptiles. (F) Progressively higher up the gravel bar surface, receding water levels during the spring snowmelt allow riparian seedlings to establish. Newly established woody riparian seedlings are sporadically scoured out, but those established high enough on the bank become mature to eventually topple into the channel as the river migrates back across the valley (A). Large floods create scour channels on upper bar surfaces and inundate floodplains, providing juvenile salmon rearing habitat during higher flows.

Figure 3-3. Conceptualized channel cross section illustrating the role of active channel processes and a variable flow regime in forming complex aquatic habitat and areas for riparian vegetation to establish.

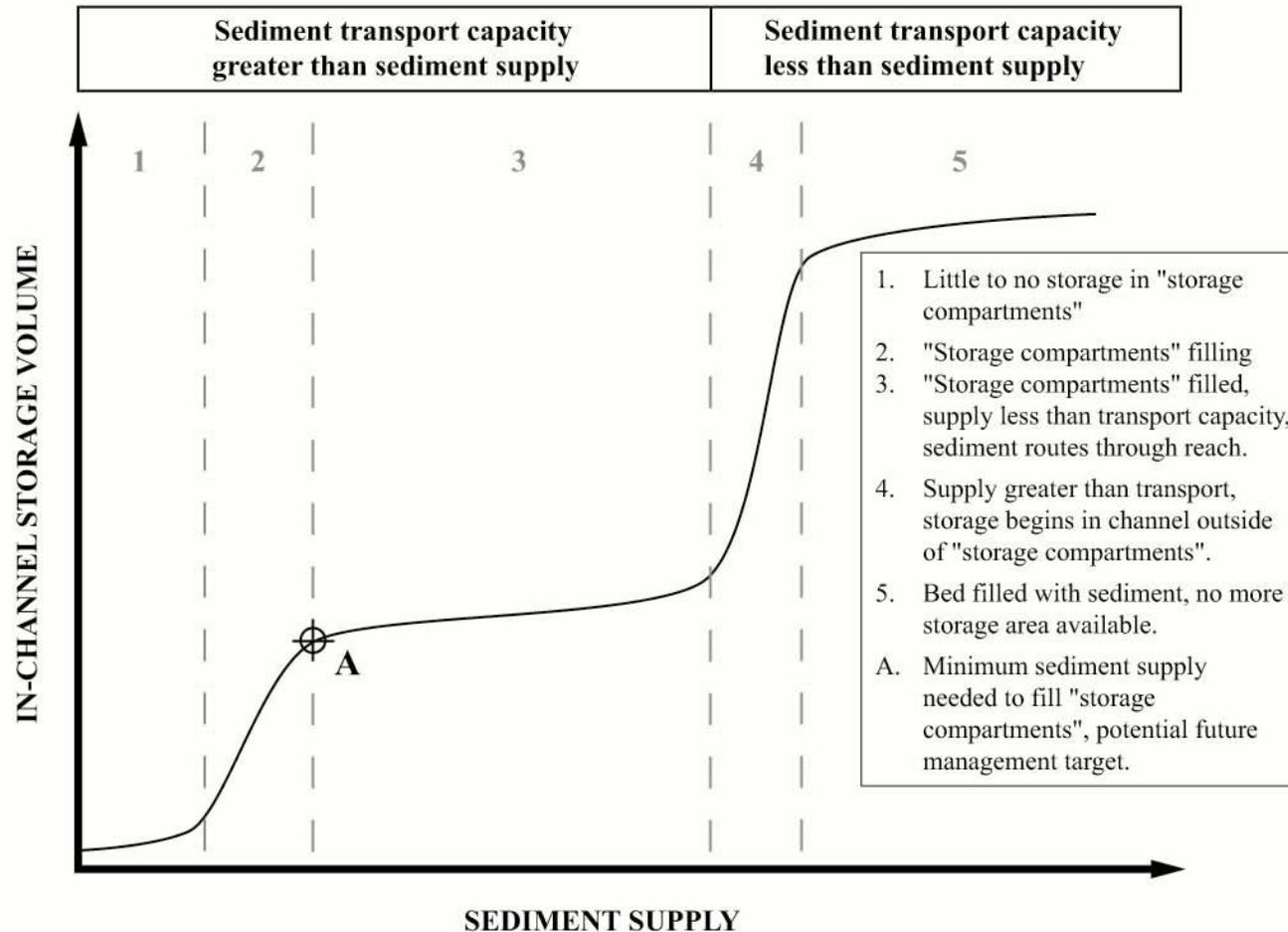


Figure 3-4. Conceptual diagram of a hypothetical relationship between in-channel sediment storage volume and sediment supply, showing how changes in sediment supply and transport capacity can affect in-channel storage volume (from McBain and Trush 2004a).

Gravel supply is an integral component of the conceptual models for alluvial and bedrock rivers described above. The loss of coarse sediment due to dams and gravel mining, while partially mitigated by the resultant reduction in high flows, has caused profound changes to Central Valley rivers. Most studies to date have focused on baseflows necessary for fisheries (habitat, temperature). As our understanding of the importance of river ecosystem processes improves, more consideration is being given to coarse sediment and high flow management in these rivers. Not all rivers afford the same opportunities for ecosystem rehabilitation via improvements in the high flow and coarse sediment regimes, and in these cases, coarse sediment augmentation takes a different role in rehabilitation. For any discussion on coarse sediment management issues, goals and objectives must be developed commensurate with physical, institutional, and political constraints within each river system.

3.3. Gravel Augmentation Linkages

In regulated Central Valley rivers, the loss of coarse sediment supply and reduced flow regime has reduced the magnitude, duration, and frequency of coarse sediment transport, channel migration, and coarse sediment deposition. Correspondingly, these changes in fluvial processes have caused profound impacts to the quality and availability of aquatic habitat. While large-scale habitat loss may not be the primary “limiting factor” to salmonid production on every regulated river, habitat loss is certainly a limiting factor to salmonids and other species. Gravel augmentation, when combined with prescribed future high flow events, attempts to improve sediment transport and deposition, channel migration, bar formation, bed scour and bed redeposition. Local physical habitat changes, such as improved availability and quality of spawning gravel, are to be expected. Reach-scale physical changes, such as increased spawning and rearing habitat, are also to be expected. Behavioral and biological benefits can also be expected from gravel augmentation, including reduced redd superimposition, improved spawner distribution, and improved invertebrate production.

Chapter 4: Developing a Gravel Augmentation Plan

Although, on occasion, past gravel augmentation projects have consisted of opportunistic dumping of coarse sediment into rivers, the design and implementation of current gravel augmentation projects is a complex process requiring careful consideration up front. This chapter provides an overview of the primary steps required to develop a well-planned gravel augmentation plan, starting from the crucial question of whether gravel augmentation can actually address the specific issues facing a stream, and proceeding through design, implementation and permitting.

4.1. Is Gravel Augmentation Needed?

Determining whether gravel augmentation or coarse sediment augmentation is needed requires river-specific ecosystem-scale analyses. When restoration is focused on increasing salmonid smolt production, the analysis should attempt to determine the factors limiting the populations of interest. Determining whether gravel augmentation is needed first requires an assessment of the factors that are limiting production because spawning habitat quantity and quality may not be limiting smolt production. Other factors such as predation, fish passage, high temperatures, and out-of-river conditions may instead be the primary limiting factor. Any limiting factors analysis should be revisited over time as restoration actions may shift them and our understanding of limiting factors may change. Conducting quality science to identify limiting factors with confidence is often difficult and costly, and thus may not be appropriate for every stream in the Central Valley. However, insights can be gained from existing analyses of factors limiting populations on other rivers (e.g., EA Engineering 1992, Tuolumne River) that may be applicable to the river of study. When restoration is focused on particular fish populations, gravel augmentation should be considered within an analysis that provides support for the hypothesis that increasing gravel quantity and/or quality offers the best option for increasing the abundance of those populations.

If the restoration vision for a given river is broadened to the rehabilitation of ecosystem processes, then the need for gravel augmentation is driven by the degree of change caused by flow and sediment regulation. Small diversion dams may allow coarse sediment to seasonally pass to downstream reaches, while larger dams usually trap 100% of coarse sediment supply from the upper watershed. Additionally, some Central Valley streams (e.g., Clear Creek) have tributaries downstream of the dam that contribute coarse sediment, partially or wholly mitigating the impact of a particular dam on the coarse sediment budget. Therefore, to determine the need for gravel augmentation when attempting ecosystem restoration, an assessment of the coarse sediment budget is needed with respect to the expected future high flow regime in order to identify whether coarse sediment deficits exist and, if so, where and at what magnitude. This assumes that restoring coarse sediment routing continuity and a balanced coarse sediment budget are primary restoration objectives.

These two hypothetical restoration scenarios (small-scale spawning gravel placement and large-scale gravel augmentation) simply provide illustrative examples of potential gravel augmentation visions that may be applied to Central Valley rivers. However, these examples

are not mutually exclusive (e.g., one may still implement large-scale augmentation to address spawning gravel limitations), and any gravel augmentation strategy developed for a river needs a careful analysis of limiting factors to key ecosystem values (salmonid production, riparian vegetation, amphibians, etc.).

4.2. Setting Objectives

There are several reasons why setting objectives for gravel augmentation is important. First, the restoration vision and associated objectives for a given river determine what gravel augmentation actions will occur. Due to a variety of constraints, some rivers may be limited to local-scale manipulations, where objectives might include increasing spawning habitat quantity by 25%, or improving spawning gravel quality to increase egg-to-emergence success to 70% within a specific reach. Gravel augmentation actions could include restoring or creating spawning riffles, replacing existing gravel with clean spawning gravel, and reshaping riffles to increase spawning habitat (preferred depths, velocities, and substrate). Other rivers may have fewer constraints, allowing a larger-scale restoration vision. Objectives to rehabilitate river ecosystem form and function may focus on gravel augmentation that increases channel migration, bar formation, floodplain formation, and aquatic habitat diversity. Objectives may include restoring coarse sediment routing continuity, increasing coarse sediment storage, increasing coarse sediment transport and deposition, reducing particle size, increasing channel migration, and balancing the coarse sediment budget over an appropriate length of time. Correspondingly, the scale and spatial extent of augmentation will vary greatly depending on the choice of objectives. Regardless of the scale of restoration intended with gravel augmentation on a given river, the geomorphic and ecological goals for gravel augmentation projects need to be clearly articulated and scientifically-supported.

The objectives will also guide monitoring. Monitoring should evaluate whether the project achieved its objectives (effectiveness monitoring), as well as adaptive management experiments that may have been conducted as part of the gravel augmentation effort. Monitoring protocols must be tailored to the project in question, but techniques must be standardized to allow cross-project information sharing, comparative analyses, and a regional-scale synthesis of project outcomes. Where restoration objectives focus on improving spawning habitat quantity and quality, monitoring at the site-scale may emphasize gravel quality and spawning habitat extent, and monitoring at the large-scale may focus on relating gravel augmentation actions to population-level benefits (e.g., changes to the stock-recruitment curve). In contrast, monitoring for larger-gravel augmentation projects may not only focus on population-level benefits, but also focus on reach-scale coarse sediment budgets, coarse sediment storage, and channel morphology for streams with fluvial process and form restoration objectives.

The third element that should be governed by the restoration vision and corresponding objectives is gravel augmentation design. How much gravel should be added, how often, and where? Where increasing spawning habitat is the primary objective, gravel augmentation volume and location may be determined by the available space and slope in existing riffles, and the frequency of augmentation determined by the frequency of high flow releases sufficient to scour the gravel away. Designs for these objectives typically focus on gravel

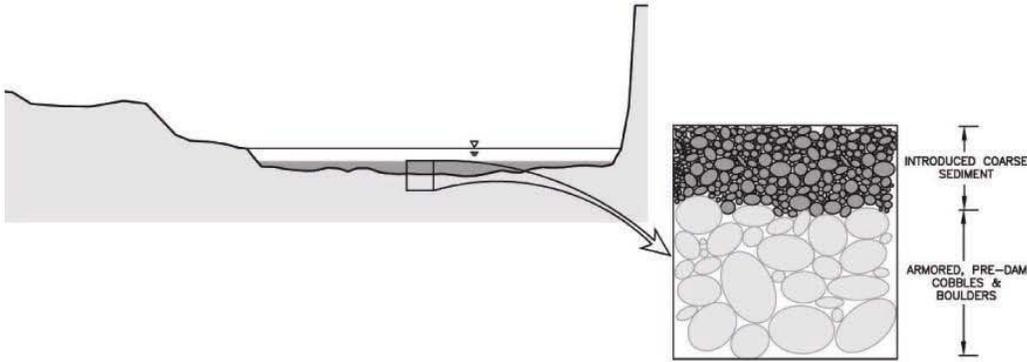
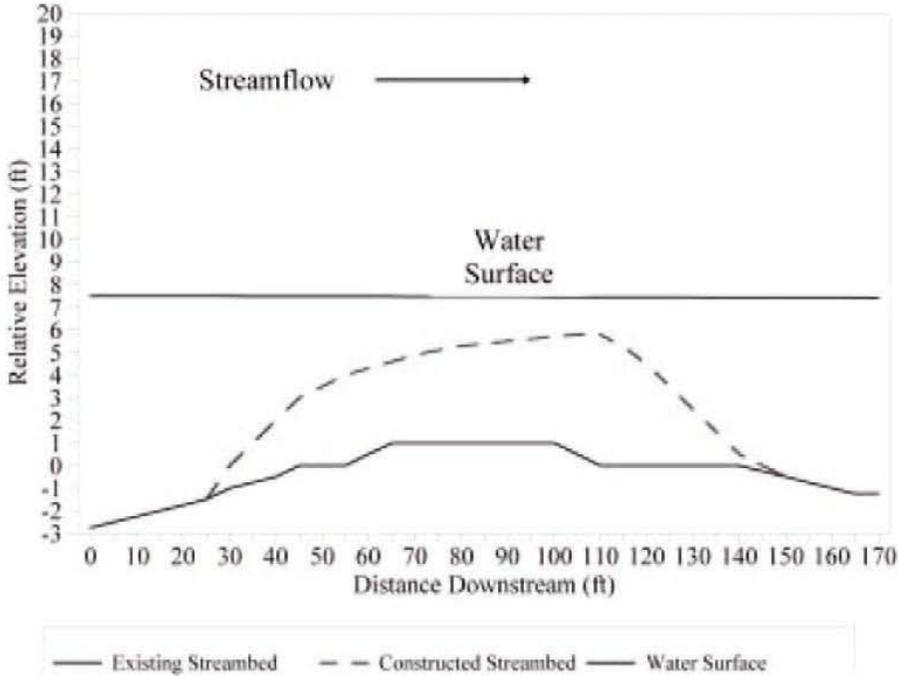


Figure 4-1. Direct placement of spawning gravel as a new pool tail and riffle (top, from Mesick 2004) and onto an existing riffle (bottom, from McBain and Trush 2003).

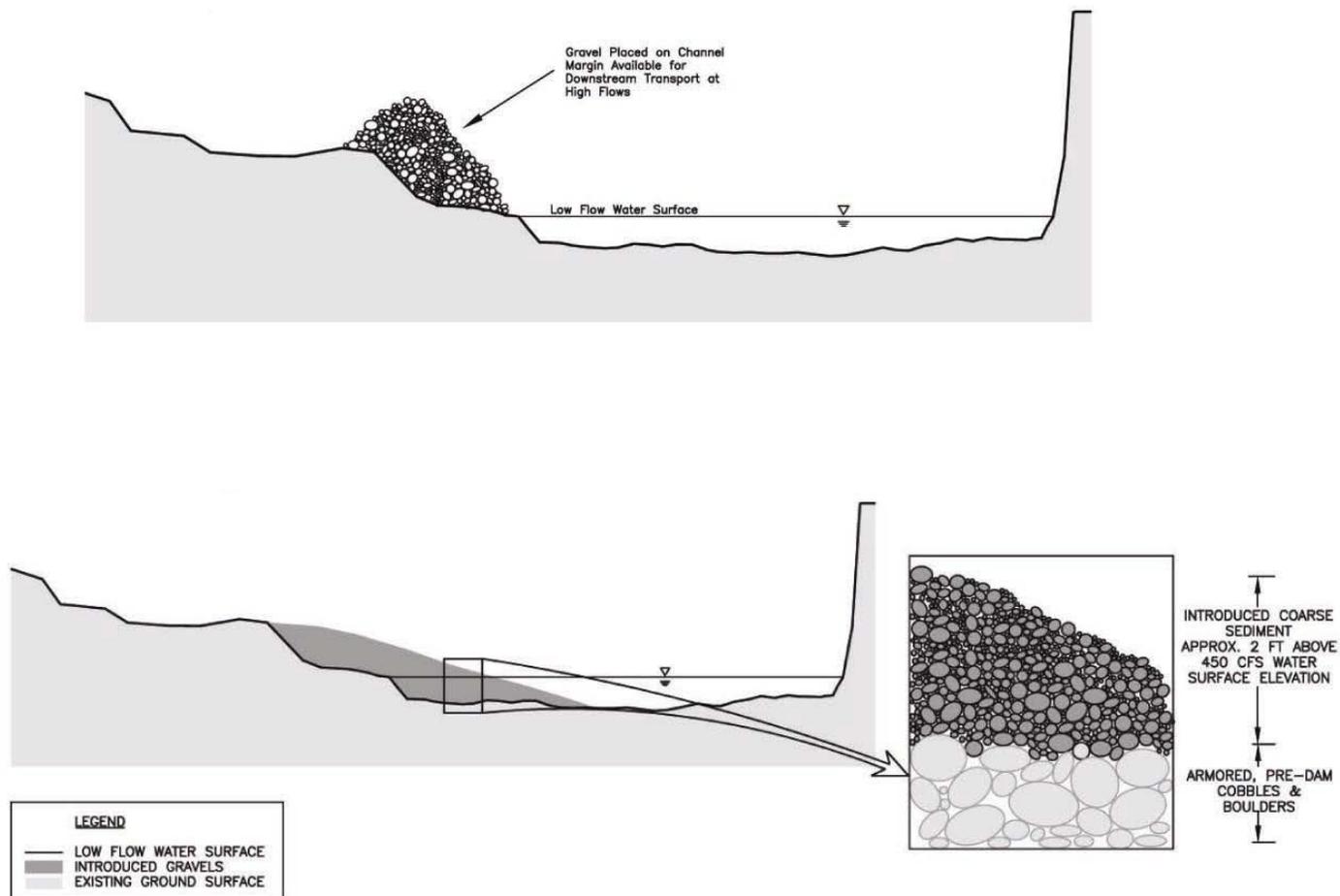


Figure 4-2. *Placing of gravel along the bank (top) or as bars (bottom) for recruitment at high flows and natural deposition in downstream reaches (from McBain and Trush 2003).*



Figure 4-3. Coarse sediment introduction below Whiskeytown Dam on Clear Creek, near Redding CA, using the high-flow recruitment method, with gravel end-dumped from the hillside above. The top photo is from April 2000. The bottom photo, from May 2003, shows most coarse sediment having been mobilized during intervening high flow releases from

placement within the low flow channel (e.g., Figure 4-1) to provide immediate habitat benefits (McBain and Trush 2004b, Mesick 2004).

Where the objectives include balancing the coarse sediment budget by restoring coarse sediment storage and routing continuity, augmentation volumes and locations will likely be determined based on which reaches have a coarse sediment deficit or lack coarse sediment continuity (e.g., downstream of mining pits). A combination of in-channel placement (e.g., Figure 4-1) and high flow recruitment placement (e.g., Figure 4-2, Figure 4-3) methods can be used depending on the site conditions. Recruitment piles and talus cones are typically placed in locations with high velocities during flood flows (heads of bars, outside of bends), such that the coarse sediment is transported and deposited downstream. Gravel placement as geomorphic features (e.g., point bars in Figure 4-2) is best done in areas where those features would naturally occur, such as the inside of meanders for point bars. Volume and location of placement are largely opportunistic, where funding, equipment access, land ownership, gravel availability and storage volume at each site dictate the overall volume initially introduced. Several recent gravel management plans attempt to introduce coarse sediment at a rate to balance the coarse sediment budget, yet this approach has not been tested to date in California.

4.3. Using Predictive Science to Evaluate Gravel Augmentation Actions

The Adaptive Management Forum for Large-scale Riverine Habitat Restoration Projects was critical of some restoration efforts in the Central Valley because predictive models were not adequately applied to restoration designs in order to better predict expected benefits, or to understand tradeoffs with different design components (AMF 2001). Applying stock-recruitment analyses to predict and monitor changes in smolt production, sediment transport models to predict transport and future augmentation volumes, and 2-dimensional hydraulic models with habitat suitability criteria (e.g., Pasternack et al. 2004) are examples of predictive modeling that can improve gravel augmentation designs in combination with adaptive management techniques. Additional analytical tools are discussed in the Chapters 5 and 6; suggestions for improving gravel augmentation adaptive management experiments are provided in Chapter 7.

4.4. Gravel Sources

Permitted mining operations have provided nearly all the gravel used in augmentation projects. These commercial operations historically excavated gravel from the river itself, and some still do. Most commercial operations now excavate gravel from deep pits in pre-dam floodplains and terraces, which can be captured during future high flows. As gravel mining becomes more expensive, accessing stores in reservoirs may become more feasible (see Section 7.5 for further discussion).

Alternative approaches are being developed where large volumes of dredge tailings are purchased for use in future for gravel augmentation and restoration projects. These sources have the potential to reduce commercial demand and restore dredge tailing sites as well as gravel augmentation sites. Managers of projects on the Merced River, Clear Creek, and the Tuolumne River have targeted dredge tailings as long-term sources of gravel for future restoration activities. While this may appear to be an attractive approach, there are

drawbacks. Restoration groups are required to “get into the mining business” to some degree, and these groups may not wish to take on this additional management, permitting, and implementation burden. Additionally, there is concern about potential mercury contamination in dredge tailings (see Sections 5.6 and 6.6 for more discussion of this issue).

4.5. Regulatory Issues

A resounding theme from the R³ workshop was the enormous regulatory burden placed on restoration practitioners (“we are treated equal to or worse than developers”). In addition to CEQA/NEPA compliance, numerous permits are needed from the Army Corp of Engineers, Reclamation Board, State Lands Commission, California Department of Fish and Game, NOAA Fisheries, Regional Water Quality Control Board, and others. These permits impose strict conditions on restoration activities (work windows, prohibitions) that greatly complicate and increase the cost of gravel augmentation efforts. Coordinated streamlining of the permitting process for gravel augmentation projects is desperately needed, based on input from workshop participants.

Potential mercury contamination is a major concern when reclaiming dredge tailings. When gravels were dredged for gold, mercury was used in the processing to recover finer gold. Some of the mercury was not recovered and remains in the dredge tailings. In addition, mercury naturally occurs in many areas of California, so mercury pollution in the Sacramento/San Joaquin System stems not only from its use in mining but also from natural sources dislodged during the mining process. Spot measurements may show mercury at near background levels, but there may be other nearby locations (“hot spots”) where mercury levels are elevated. The disturbance of contaminated dredge tailings may increase methylation of mercury, and thus its local distribution. Of perhaps even greater concern is the downstream transport of mercury to the San Francisco Bay-Delta where mercury concentrations are already dangerously elevated. Because mercury is usually bound to fine-grain particles (fine sands and silts), screening and washing gravels from dredge tailings removes nearly all potential mercury contamination. Washing gravel also reduces the effect of gravel augmentation on turbidity. Washing gravels, either from dredge tailings or pits, adds considerable expense to gravel augmentation projects, yet must be done in most cases - both mercury contamination and turbidity are regulated by Regional Water Quality Control Boards. Unwashed gravels might be useable where the gravel source has not been mined and potentially exposed to mercury contamination, and gravel is placed as a recruitment pile out of the low flow channel to minimize the elevation of turbidity. This topic is further discussed in Section 5.6.

4.6. Monitoring Considerations

As discussed above, a single standard monitoring protocol cannot be developed because monitoring needs vary based on the restoration and gravel augmentation objectives for a particular river. To examine the impacts of gravel augmentation on spawning habitat, monitoring may focus more on spawning gravel quality, spawning gravel quantity, factors limiting salmonid production, and biological response to gravel augmentation. To examine the impacts of gravel augmentation on geomorphic processes and form, monitoring may focus more on larger-scale issues, including coarse sediment transport and routing, coarse sediment budget, bar formation, and reach-scale habitat improvements.

Chapter 5: Key Geomorphological Uncertainties

5.1. Can the spatial and temporal effects of gravel augmentation be predicted?

The beneficial effects of adding gravel are difficult to predict due to the many uncertainties highlighted in this report. A key set of uncertainties involves predicting the spatial and temporal extent of the benefit. The problem can be broken into two parts. First, because the desired changes in bed texture or channel morphology are caused by the arrival of the newly added sediment (or the movement of pre-existing sediment newly mobilized by the gravel additions), we need to be able to predict how sediment additions move through the reach or set of reaches of interest. This is a component of the general problem of sediment routing. Second, we need to be able to predict how the channel morphology and bed texture will respond to the arrival of added sediment (Sections 5.2, 5.3 and 5.4). The ability to estimate how much of the channel will be affected and how long the effect will persist, coupled with the ability to predict the beneficial qualities of the changes induced, would allow the optimization of gravel augmentation project designs and would result in more accurate cost/benefit analyses.

5.1.1. Available Science

Gravel augmentation is a form of episodic sediment supply, in some ways analogous to a small landslide. Much work has been done in recent years to understand the fate of pulses of sediment that arrive suddenly to form a solitary wave of relatively mobile sediment. This includes detailed documentation of the evolution over several years of a large landslide that occurred in 1995 on the Navarro River (Sutherland et al. 2002), as well as other field studies of sediment pulses (e.g., Knighton 1989, Nicholas et al. 1995, Madej and Ozaki 1996). In addition, data from flume studies of sediment waves have been used to explore the controls on the relative importance of wave translation versus dispersion (Lisle et al. 1997) and to test and refine numerical models of disequilibrium bedload sediment transport (Cui et al. 2003a, Cui et al. 2003b). Several general conclusions emerge from this work:

- Wave dispersion dominates over wave translation. In other words, the topographic feature created by the pulse of sediment input stays relatively stationary in space, gradually diminishing in magnitude as sediment is transported downstream more rapidly than sediment is supplied from upstream. Part of what keeps the wave feature stationary in space is the trapping of sediment arriving at the upstream end of the feature by the low gradient or even ponded water surface behind the wave crest.
- Dispersion is favored by several factors, including: coarser input grain sizes than pre-existing bed size distributions; high Froude numbers characteristic of gravel-bedded channels; large wave amplitude relative to typical flow depths; weak rocks that tend to break down rapidly in transport; and topographically heterogeneous channel morphology, which provides a diversity of sediment storage sites with differing characteristic residence times.
- Translation is obviously favored by the opposite of the above factors, such that it is more likely to occur in sand-bedded streams and where the wavelength of the sediment wave is long and the amplitude is low. Note that dispersion of high amplitude waves may tend to create conditions favorable to some wave translation, although it may not be

detectable without heroic effort, as Sutherland et al. (2002) speculated in the case of the Navarro River landslide.

- Sediment transport rates increase dramatically after the arrival of the sediment input because of a steepening of the water surface slope on the downstream side of the wave, and due to the relatively loose and poorly sorted condition of the input sediments. A dramatic increase in sediment transport rates was observed even when the input sediments were coarser than the ambient grain size distribution (Sutherland 2002, Cui et al. 2003a). Transport rates then decline steadily with time, as the wave amplitude declines and the most easily moved grains are depleted.
- The effects of episodic sediment inputs may propagate downstream as a translating wave of altered bed texture even in the absence of any discernable topographic disturbance to the bed (Lisle et al. 2001). Although these may be precisely the type of changes gravel augmentation projects seek to induce, documenting the downstream migration of a pulse of bed fining or coarsening would require tremendous effort given the large background variability in facies textures due to lateral and longitudinal sorting.

5.1.2. *Knowledge Gaps*

The implications of the recent work on sediment pulses for gravel augmentation project design are ambiguous. Projects are commonly designed to benefit a limited reach of channel, and gravel transported to downstream reaches is often considered gravel lost from the site of interest. This is perhaps an implicit recognition of the dominance of wave dispersion over translation in gravel bed streams. However, many of the conditions favoring sediment wave translation are met in gravel augmentation projects, suggesting a largely untapped potential to design gravel additions to benefit more extensive reaches of channel.

For example, added gravel is typically finer than the ambient (commonly armored²) channel bed, and is also likely to be composed of relatively durable clasts that have survived previous incarnations as mobile bedload and the ordeal of processing and handling by gravel suppliers. In addition, the topographic waveforms created by placed gravel are commonly low amplitude and long wavelength, resulting in little change in the water surface slope. The same is likely true of the initial downstream topographic expression of sediments eroded from the toe of the angle-of-repose slopes of gravel injections (i.e. talus cones).

The rapid increase in observed bedload transport rates downstream of sediment wave crests is consistent with some observations of the performance of gravel augmentation projects (e.g., Scott McBain's Trinity River data, cited by Yantao Cui in his presentation at the R³ Workshop). This raises the question of whether a positive feedback between sediment supply and transport may limit the potential duration of the benefits of gravel additions. If adding more gravel serves to accelerate the removal of that same gravel from the reach of interest, then smaller, more frequent gravel inputs are likely to provide more benefit than larger, less frequent inputs.

The major practical question is how to manipulate gravel augmentation size and frequency to maximize the spatial and temporal extents of possible beneficial effects. The general

² Supply-limited transport conditions promote coarsening and strengthening of the bed surface, with fine sediment winnowed downstream or protected deep within the sub-surface layer. The surface layer is then referred to as "armored" or "paved" (Dietrich et al. 1989).

tendency toward sediment wave dispersion suggests a trade-off between the potential for long-lasting (temporal) and far-reaching (spatial) effects. Longer-lasting benefits probably will have to be more confined in space, and conversely, more spatially extensive benefits are likely to be shorter lasting. To the extent that sediment wave translation can be deliberately induced by careful gravel augmentation project design, the potential exists for maximizing the duration of project benefits, although not at a fixed location.

5.2. How does gravel augmentation affect channel morphology, such as pool/bar topography, channel width, lateral particle sorting, and riparian zones?

Under unimpaired conditions, coarse sediment was transported, routed, and deposited in a way that maintained channel morphology and supported high quality aquatic and terrestrial habitat. Subsequent regulation of flow and sediment greatly impaired coarse sediment supply and transport, and channel morphology was also changed (e.g., bed coarsening, narrowing of channel, reduction in pool depth). Gravel augmentation is intended to reverse many of these negative impacts to channel morphology and aquatic habitat. Several studies and pilot projects have indicated that gravel augmentation, if done with volumes and particle sizes commensurate with the regulated high flow regime, can rehabilitate fluvial processes and create a more desirable channel morphology. Expected outcomes of gravel augmentation on channel form include particle sorting that creates diverse substrate patches, creation of exposed bars, increased hydraulic complexity and shear zones, creation of backwaters and other complex alluvial features. These morphologic changes should increase aquatic and terrestrial habitat quality, quantity, and diversity. However, there is some concern that gravel augmentation efforts may cause detrimental changes to channel morphology under a regulated flow regime, such as reductions in channel width, pool filling, and channel migration, due to inadequate transport and routing of these added coarse sediments. Current numerical models provide reach-scale predictions of coarse sediment aggradation or degradation, but do not provide sub-reach scale predictions to address: (1) potential benefits to channel morphology from bar formation, channel complexity, and channel migration, and (2) potential impacts from pool filling or channel narrowing.

5.2.1. Available Science

Channel dimensions and particle size are scaled by the high flow regime (Leopold et al. 1964), and reductions in the high flow and sediment regimes typically result in reductions in channel width, increases in bed particle size, channel incision, and changes in riparian vegetation (Parker 1979, Williams and Wolman 1984, Dietrich et al. 1989). Regime equations can predict general changes in channel dimensions as a result of changes in flow, yet considerable variability remains, and these equations do not explicitly account for changes in sediment regime. Additionally, numerical models can predict general trends in longitudinal aggradation and degradation, channel migration, and sediment wave propagation, but not local or spatially discrete aggradation and degradation. Lisle (1986) has used empirical evidence to predict trends in depositional bar morphology as a function of high flow incidence into obstructions (e.g., the angle which flows “hit” an obstruction), but these predictions have not been applied to issues of gravel augmentation and subsequent deposition.

With respect to particle size, many studies have documented bed coarsening and channel downcutting downstream of dams (Parker and Klingeman 1982, Dietrich et al. 1989, Lisle et al. 1993), but less work has been done evaluating the effect of dams on coarse sediment particle sorting. McBain and Trush (1997) observed increasing particle size diversity over a small reach in response to increasing sediment supply, high flow events, and increasing channel width associated with removal of a riparian berm. Gravel augmentation, combined with higher peak flows and removal of floodway confinement, should increase the width of the bedload transport zone, channel migration and bar complexity, and particle size diversity.

5.2.2. *Knowledge Gaps*

The key knowledge gap is predicting how combinations of high flow management and gravel augmentation projects will result in changes in channel width, pool depths, bar formations, particle size diversity, and channel migration. We know that gravel augmentation combined with high flows will create bars and increase channel dynamics, and we know that gravel augmentation alone will likely reduce channel width and form bars, as well as potentially filling pools and inducing channel migration. However, precise predictions about habitat-scale changes in channel morphology remain elusive. Of all of these potential morphological changes, channel width is perhaps the most predictable. There is considerable empirical evidence about how gravel augmentation or channel reconstruction changes channel width under a given flow regime (e.g., McBain and Trush 1997, Graham Matthews and Associates 2004), but less is known about channel migration, bar formation, and pool filling associated with gravel augmentation. Channel migration models have been applied to evaluate changes in flow regime (e.g., Larson 1995), but not with respect to gravel augmentation. Given the importance of channel migration in creating alluvial features (bars, floodplains), better understanding of how gravel augmentation may change channel migration thresholds and rates would be valuable for evaluating potential impacts on instream habitat and adjacent land-uses.

These knowledge gaps above pertain to expected benefits to channel morphology, yet there are also knowledge gaps that make it difficult to predict potential negative impacts to channel morphology. Perhaps the most important aspect of our uncertainty on this topic is the potential of gravel augmentation to fill pools, given their importance in juvenile salmonid rearing habitat and adult salmonid holding habitat. One-dimensional hydraulic and sediment routing models are inadequate to accurately predict local pool scour/fill, but perhaps more recent two-dimensional or pseudo three-dimensional hydraulic models may prove more useful in predicting potential impacts of gravel augmentation volume and particle size on pool volume dynamics. These models may also provide insights into how more complex high flow hydraulics will increase particle size diversity at both the habitat scale and the reach scale.

5.3. **Can immobile armor be mobilized with fine gravel addition?**

Gravel channel beds downstream of dams are commonly mobilized much less frequently than in the pre-dam condition. This is the result of 1) a reduction in frequency of flows large enough to exceed the threshold of particle motion, 2) a coarsening (or ‘armoring’) of the bed due to preferential transport of the smaller fraction of the bed material grain size

distribution, 3) the lack of sediment supply from upstream due to coarse sediment capture by the reservoir, or, most commonly, 4) a combination of the above three factors.

Lack of regular bed mobility leads to poor quality spawning habitat, typically for one of two reasons. In some cases the bed material grain size distribution is in the desired size range but has high fines ('fines' here refers to sand and finer grain sizes) content because the beds are not regularly mobilized, preventing adequate throughflow to allow survival to emergence (see Sections 5.3 and 5.6 below). In other cases, the bed material is too coarse for spawners to move to build redds. Gravel augmentation projects are most commonly designed to address one of these problems.

The simplest way to achieve a desired grain size distribution and low fines content over a specific area of the bed is to cover the area with pre-sorted gravel imported from a source outside the reach of interest. To provide the intended habitat benefits, the layer of introduced gravel must be thick enough to bury the pre-existing bed at least to the depth of scour during redd construction, and deeper for the case of pre-existing high fines content and low permeability. Designers of gravel augmentation projects may choose to increase the depth of placed gravel still further to account for removal of gravel from the reach by active transport in the absence of replenishment from upstream or additional gravel augmentation. Thus, to improve spawning habitat over a large area may require a very large volume of imported gravel. When gravel is supplied by injection (streamside talus cones), the need for large volumes is most acute, because the rapid downstream dispersion of injected sediments greatly reduces the thickness of any single downstream deposit produced.

An alternative approach would seek to add gravel that is finer than the existing bed to increase the frequency of bed mobilization, rather than replacing the existing bed by burying it. In his presentation at the R³ Workshop, Frank Ligon discussed this approach. In the case of armored beds, gravel additions would be designed to take advantage of the interaction between the bedload and the bed surface to reduce the effective threshold of grain motion. For the case of fines-rich beds with adequate gravel grain size distributions, gravel additions would be designed to mobilize the bed frequently enough to flush a significant portion of the interstitial fines. The question of how this might be accomplished is treated in Section 5-4 below, and will not be dealt with further here.

There are several potential advantages to this alternative approach, in addition to the obvious benefit of reducing the volume of gravel required. Breaking up an immobile armor might expose a buried reservoir of finer gravel previously insulated from the erosive force of the flow by the overlying armor layer. This material would then be available for incorporation into a new, finer bed surface grain size distribution, and would contribute to an increased finer gravel supply to downstream reaches. This approach is particularly well-suited for gravel infusion projects, where gravel is supplied by creation of angle-of-repose talus slopes at the channel margin, because of the small volumes of new gravel reaching downstream beds at any given time.

5.3.1. Available Science

The linkages between the bed surface grain size distribution and frequency of mobility on the one hand, and size and quantity of coarse sediment supplied from upstream on the other,

are inadequately understood at this time. In part, this is due to the difficulty of accurately measuring bedload sediment flux over a sufficiently wide range of discharges to reliably estimate the long-term supply rate of sediment in discrete size classes. The adjustment of bed material grain size distributions to changes in sediment supply rates and caliber can be modeled numerically using size-class specific bedload sediment transport equations (e.g., Parker 1990). However, numerical simulations of bedload transport are typically limited to one-dimensional (downstream) representations of the channel, and do not explicitly account for the topographic and roughness effects of bars, bends and other morphologic features that contribute to the strong lateral sorting and heterogeneous textures of most gravel-bedded channels.

As a result, most of what we know about the role of sediment supply in controlling bed texture comes from laboratory flume studies. For example, Dietrich et al. (1989) observed a consistent and repeatable pattern of bed coarsening with reduced rate of sediment supply, even when the size distribution of the supply was held constant. Bed coarsening with reduced supply was not spatially uniform, rather the width of the zone of active transport narrowed toward the center of the experimental channel, leaving relatively coarse and immobile patches along the channel margins. Although their experiments were intended to simulate steady-state adjustments to slow changes in sediment supply, Dietrich et al. (1989) also explored the effect of transient pulses of added fine (sand-sized) bed load material on the mobility of the (pea-sized) gravel bed. Additions of small amounts of sand, which moved as bedload across a previously low mobility bed, lead immediately to a large increase in the rate of gravel transport to the sediment trap at the downstream end of the flume. Although the pulses of added sand tended to move downstream with a distinct front, the effect of increased gravel transport was felt downstream before the arrival of the sand-rich front. Similar observations were made by Whiting et al. (1988).

Another set of steady-state flume experiments offers insight into the role of fine bedload material in increasing mobility of the coarser fraction of the grain size distribution. In a series of papers, Wilcock and colleagues (Wilcock et al. 2001, Wilcock and Kenworthy 2002, Wilcock and Crowe 2003) report that the mobility of the coarse fraction (gravel-sized in these experiments) depended directly on the amount of fine (sand-sized) bedload material in the supplied sediments.

5.3.2. *Key Uncertainties*

Although the tendency for the presence of fine bedload material to increase the mobility of coarser material is well-demonstrated empirically, we lack a clear understanding of the physical mechanisms involved. Wilcock and colleagues (Wilcock et al. 2001, Wilcock and Kenworthy 2002, Wilcock and Crowe 2003) look to differences in the types of grain-to-grain contacts in gravel beds with large and small sand fractions. In sand-rich bed mixtures, large particles are held in place by many more grain contacts with sand-sized particles than in sand-poor bed mixtures. Thus, in the sand-rich case, when shear stresses increase to a level sufficient to mobilize sand from the bed surface, larger particles lose many of the grain contacts holding them in place and become more easily set into motion. A limitation of this explanation is that it assumes a consistent relationship between the amount of sand in the bed material and in the supply, as occurs under steady-state conditions. However, the

alternative approach considered here (pulses of fine sediment supplied to an immobile coarse bed) is inherently non-steady state.

Another potential explanation involves changes in the local bed roughness and availability of shear stress for sediment transport. Fine bedload material introduced to the surface of an immobile coarse bed will tend to fill in the low points, or pockets, between larger grains, effectively smoothing the bed surface. A smoother surface offers fewer and smaller protrusions into the flow, reducing the size of the turbulent wakes that extract momentum from the flow. This results in a steepening of the vertical gradient in downstream velocity in the vicinity of the bed, increasing the shear stress acting on the bed surface. Increased shear stress, in turn, will mobilize a great percentage of the coarse grains on the surface.

For this alternative strategy of supplying gravel finer than the intended resulting bed grain size distribution to be a practical tool in gravel augmentation, we would need not only a clearer understanding of the physical mechanisms, but also a set of predictive relationships that could be used in a field setting. Ideally, such relationships would predict the increase in the fraction of the bed area mobilized as a function of the grain size distributions of both the existing surface bed material and the augmentation material, as well as the effective increase in the rate of sediment supply by augmentation, assuming no change in discharge or channel geometry.

If this strategy proves viable for increasing the mobility of coarse armored beds, a number of other questions arise. For example, as the pulse of added sediment moves through the reach, would the coarse armor gradually develop again? Or, in the absence of coarse material replenishment, and with the potential exhumation of a formerly-buried finer subsurface size distribution, would the bed stabilize at a finer, less armored, condition? Could the release of buried finer-grained sediments result in a bed of poor spawning habitat quality, due to either low permeability or a too-easily mobilized surface resulting in frequent redd scour? Another potentially negative result of removal of an immobile armor layer would be significant long-term net erosion of the bed, resulting in reduction of the channel slope, increased bank instability and possibly (increased) exposure of bedrock in the channel bed.

5.4. Can gravel augmentation serve as a substitute to flushing flows for removing fine sediments from the surface and subsurface, thereby coarsening the size distribution?

High flow releases from reservoirs, so-called ‘flushing flows’, are intended to mimic the beneficial effects of natural floods. They are increasingly being used as restoration tools and prescribed as mitigation measures for dam re-licensing (e.g., Reiser et al. 1989). Among the key assumed benefits of flushing flows is removal of fine sediments (sand and finer) from gravel beds to improve spawning habitat (see Sections 5.5 and 6.3 for discussion of the linkages between fine sediment infiltration, bed permeability and spawning habitat quality). For fines to be removed, the gravel surface must be mobilized, and more sand must be transported away from the reach of interest than is brought in by the high flow. Otherwise, re-infiltration during the recession limb and subsequent low flows can return the bed to the same high-fines condition as existed previously. Moreover, unless there is a sufficient supply

of gravel from upstream, the flushing flow may produce a net removal of gravel along with fines, degrading the bed and creating no net improvement in spawning habitat.

Gravel augmentation has been proposed as a supplement, or even an alternative, to flushing flows for achieving a reduction in the fines content of the surface and near-surface bed. Adding gravel may provide at least three benefits relevant to removal of fine sediment: 1) it can compensate for the export of gravel from the reach due to high shear stresses during flushing flows; 2) addition of fine gravel may reduce the shear stress required to initiate bed motion, thus allowing more frequent bed mobilization without flushing flows or with lesser magnitude flows (see Section 5.3); and 3) clean gravel can coarsen the bed surface distribution simply by diluting the fines content of the resulting bed mixture

5.4.1. *Available science*

The recent development of mixed sand-gravel bedload sediment transport models (e.g., Wilcock and Crowe 2003) makes it possible to assess the relative mobility of the two size fractions. It is also possible to predict the net fluxes of both gravel and sand for different flow magnitudes and durations, provided the supply of sediment from upstream can be estimated. Mixed sand-gravel bedload transport models have been developed and tested using data from both flume experiments (e.g., Wilcock and McArdell 1993) and field studies (e.g., Haschenburger and Wilcock 2003).

Field and laboratory measurements of sand and gravel transport rates over a wide range of shear stresses suggest, however, that the beneficial effects of gravel framework mobilization on fines removal may be quite limited (Wilcock and McArdell 1993; Kondolf and Wilcock 1996). The problem is that once shear stresses rise beyond the threshold of motion for the coarse fraction, the potential bedload transport rates of sand and gravel are of similar magnitude when normalized by their relative fractions in the bed mixture. Thus, there is not a strong net removal of sand. Rather the bed erodes or aggrades essentially maintaining the pre-existing grain size distribution.

5.4.2. *Knowledge Gaps*

To achieve long-term net removal of sand from gravel beds, sand must be exported from the reach of interest at rates far exceeding the rate of sand supply from upstream. The most effective way to do this is to generate turbulence sufficiently high that sand is transported predominantly as suspended load rather than bedload. This can be achieved with large magnitude flushing flows, and/or by modifications to the channel cross-section. For example, narrowing the channel will result in deeper flow for a given discharge, increasing the shear velocity and thus the tendency for sand to be suspended. Where large magnitude flushing flows or substantial channel modification are possible, gravel augmentation is likely to be important in offsetting gravel transport out of the reach (the first benefit noted above). Large magnitude flushing flows and extensive channel modifications, however, are often not possible because of the high expense involved, flooding risks, and other site constraints.

A more limited approach, as suggested by Frank Ligon in his R³ workshop presentation, would focus on the second potential benefit noted above, using gravel augmentation to manipulate mobility thresholds on riffles. The goal would be to accentuate the preferential deposition of sand (moving as bedload) in pools on the recession limb of the hydrograph.

The idea is that enhanced gravel mobility on riffles will mobilize interstitial sand, but as the stage, and thus the shear stress, declines, gravel on the riffles will come to rest while sand will continue to move. Net export of sand from the riffle would occur because the supply of sand from upstream of the riffle would be intercepted by the upstream pool. Long-term net sand removal from the reach might then be accomplished by mechanical removal of sand from pools. Flushing flows would then be designed not just to reach or exceed the threshold of motion, but to extend the duration of the portion of the recession limb where sand export from riffles would occur. The amount of gravel added would also take into consideration the potential for coarsening through dilution (the third benefit noted above). This approach has some promise and should be investigated systematically.

Many fundamental uncertainties limit our ability to prescribe measures for removing sands from gravel beds. In addition to the question of how much mobility thresholds can be manipulated by augmentation of finer gravel (Section 5.3, above), much remains to be learned about how fines infiltrate into the gravel framework, how scour depths are influenced by fines content, and critically, how upstream supply rates of fine sediments can be accurately estimated and potentially mitigated to produce net export of sand from impacted reaches.

5.5. How does fine sediment infiltrate gravel deposits?

The availability and quality of suitably-sized bed sediment can be limiting factors to the spawning success of stream-dwelling salmonids. And while gravel augmentation may increase the availability of suitably-sized gravels, fine sediment infiltration may reduce the quality and usability of this gravel for spawning, jeopardizing the benefits of gravel augmentation projects. There is thus a need to identify factors governing the infiltration of fines into bed interstices, as well as to determine how these processes are affected by sediment supply.

5.5.1. Available Science

In this section, fine sediment in the streambed is referred to as the “matrix” material, and coarse bed material forming the interstices through which fine sediment passes is the “framework” material. Fine sediment can enter a gravel bed by infiltrating through interstices in the framework, or by depositing along with bedload in an active armor layer (surface seal) as the bed scours and fills. The distinction between these two processes is important in determining the amount and vertical distribution of fine sediment that accumulates in streambeds, and the channel conditions under which fine sediment is a problem for salmonid embryo survival (Lisle 1989).

In California’s regulated rivers, the size of sediment making up the riverbed (gravels) is typically not in phase with the sediment load in transport (sand and finer sizes). This is in part because dams have blocked the downstream transport of coarse sediment from upland sources, hence eliminating the supply of gravels and cobbles in transport. This is also because the size of sediment most commonly in transport has been reduced from pre-regulation conditions as a consequence of the reduction in flood magnitude and duration.

Supply-limited transport conditions promote coarsening and strengthening of the bed surface, with fine sediment winnowed downstream or protected deep within the sub-surface layer. The surface layer is then referred to as “armored” or “paved” (Dietrich et al. 1989), and patch dynamics among the surface grains are attributed with significantly increasing bed strength (Church et al. 1998). As a consequence, the surface has increased hydraulic resistance to flow and grains normally mobilized at a particular shear stress remain stationary. Furthermore, the armored surface layer is not reworked and mobilized by high flow events and is prone to fine sediment infiltration (Dietrich et al. 1989). For many salmonid species in California rivers, the embryo incubation period coincides with this period of high flow and sediment transport, making embryos vulnerable to smothering by fine sediment. The biological consequences of fine sediment deposition on embryo survival are further discussed in Section 6.3.

The depth to which fine sediment can infiltrate a stable gravel bed depends on the size of the fine sediment (matrix) relative to the interstices of the bed material (framework) (Frostick et al. 1984). Three general conditions may develop. If particles are larger than the interstices, they cannot infiltrate the bed surface and so are incorporated as surface material or transported further downstream. If particles are smaller than some interstices but larger than others, or are able to bridge gaps through interference with other particles, they become lodged in a layer just beneath the surface. They may form successively smaller gaps that trap successively smaller matrix materials, ultimately producing a ‘surface seal’ that prevents deeper penetration of fine particles. If particles are much smaller than the framework interstices (typically silt and clay), they readily infiltrate the bed surface and deposit at depth, gradually infilling the framework gravels.

While matrix size relative to the size of framework interstices is the most important factor determining whether fine sediment deposition creates a surface seal or gradually intrudes into the framework, it also depends on the transport process, with fine bed load (typically coarse sand) transported by saltation coming into more frequent contact with the bed than material transported in suspension (typically fine sand, silt, clay). The shape of the framework sediments (e.g., angular versus round) also affects interstitial spacing and hence fine sediment infiltration. The biological implications for these alternative processes of fine sediment infiltration are significant, as discussed by Kondolf (2000a). A surface seal created by relatively large fine sediment (usually 1-10 mm) may block the emergence of alevins occupying the sub-surface (Stillwater Sciences 2004), whereas smaller-sized intruding fines (usually <1 mm) that clog pore spaces reduce intragravel permeability and lead to embryo suffocation.

A highly heterogeneous framework will present few large pores; hence, infiltration of fines into the bed will be mostly restricted to the surface layer because of the lack of pore spaces. This condition promotes development of a surface seal. As stated by Lisle (1989), “because of the wide spread in particle sizes in most natural gravel beds, the formation of a surface seal after a bed has been cleaned of fine sediment [by spawning fish] appears to be inevitable once bed load transport begins”. A seal is not necessarily harmful to incubating embryos because it inhibits further fine sediment infiltration to depth and may maintain adequate intragravel flow to deliver oxygen and remove metabolic waste from redds. But a surface seal may effectively entomb embryos and prevent the escape of alevins from the sub-surface, as described above.

Reported entombment of alevins is often associated with redd superimposition because the process of secondary redd digging releases fine sediment from the bed, which entombs downstream redds (Carl Mesick presentation at the R³ Workshop). The timing of sediment transport events (high flows) that supply fine sediment relative to the incubation cycle of resident populations will be critical to the likelihood of fine sediment infiltration.

The organic content of the matrix sediment (e.g., algae) may influence the binding strength between matrix particles. A biofilm of organics, silt and clay can develop a surface seal that may be less penetrable than one made only of inorganic material. A stronger surface seal would have negative implications for alevins in the sub-surface and would be more likely to lead to mortality by entombment.

In addition to properties of the matrix and framework materials, other factors will influence fine sediment infiltration. These include:

- The timing of fine sediment inputs relative to periods of high flows. This determines whether the sediment is transported in suspension or settles out and infiltrates the framework. Timing is especially important with sediment inputs from human activities (e.g., agriculture, irrigation return flow) that may occur during periods of low flow compared with natural sediment inputs.
- Changes in local shear stress, for example from altered streamflows below dams, will produce changes in surface sediment texture and may make certain areas more or less favorable for spawning.
- The cleansing effect of salmon redd construction on the percentage of fine sediment in the bed material.

Once a particle has entered the interstitial spaces of the framework, its further vertical movement is controlled largely by its size relative to the size of the interstices and by the intensity of highly local water turbulence, which affects the trajectories of fine grains (Frostick et al. 1984).

Differences in fine sediment infiltration between natural gravel deposits and injected gravels have not been examined thoroughly, and will be influenced by many of the factors discussed above as well as:

- The size range of bed material, which affects pore size and permeability. Some projects have truncated the size distribution to inject only those particles >12.7 mm (1/2") in diameter. Such deposits will have relatively large pores within the framework that will readily trap fine sediment.
- The shape of the rocks, which also affects pore size and permeability. Gravel augmentation projects using crushed angular gravel may trap fine sediment more effectively.
- The thickness and configuration of the injected gravel deposits, which affect water depth and bed profile, and thus intragravel and downwelling flow through spawning gravels. Changes in these flow patterns as a result of gravel augmentation may account for the lack of use of seemingly high-quality spawning gravels.

The single study on this topic (Merz and Setka 2004) compared the spawning habitat characteristics of natural and “enhanced” gravel deposits (created through gravel augmentation) in the Mokelumne River. Approximately 1000 m³ of clean river gravel (rounded shape) was placed in berm and staggered toe-bar configurations perpendicular to stream flow along the 45-m enhancement area. The objectives were to increase velocity, reduce flow depth, and promote intragravel flow. Results showed that permeability and dissolved oxygen were higher through the enhanced gravel for a minimum of 12 months after gravel placement. Total suspended solids, turbidity, and water temperature all were lower in the enhanced gravel. Chinook salmon were observed spawning in the enhanced gravel within 2 months of placement, and for 2 years thereafter.

5.5.2. *Knowledge Gaps*

The interplay among bed sediment characteristics, sediment supply, and flow regime is an ongoing topic of research. Determining what flow regime (timing, magnitude, frequency of floods) and sediment supply conditions minimize fine sediment infiltration is critical if we are to achieve any long-term benefits from gravel augmentation projects. The character of the framework material and existence of an armor layer is a legacy of prior flows, whereas future flows and sediment transport processes can condition the bed and make it more or less favorable for spawning success.

Because the development of a surface seal of fine sediment appears inevitable in most natural gravel beds, the factors determining emergence success of salmon embryos incubating within a redd that develops a surface seal is a topic for further research (see Section 6.3).

The rate and degree of compaction that takes place within augmented gravel deposits remains uncertain, but has been qualitatively documented in one case (Merz and Setka 2004). This has implications for how processes of fine sediment infiltration may change over time as the added gravel deposits are worked by the flow. It also has significant implications for sediment budget calculations, because volumetric changes in sediment storage are typically attributed to either scour or fill, but instead may simply be due to local compaction.

Workshop participants expressed a need for standardized monitoring protocols for measuring permeability and intragravel flow. Kondolf (2000a) provides some suggestions (standpipe measurements, dye studies, examining channel geometry), but further work on this topic would be useful. In particular, apparent (intragravel) velocity is critical to successful embryo incubation and yet its measurement remains largely relegated to techniques originally developed in the late 1950s (Wickett 1954, Terhune 1958) involving dye or salinity dilution detection. Some promising progress was made in the 80s that evaluated the use of thermistors to detect and relate intragravel thermal gradients to apparent velocities, but no commercially available meters have been developed. Focused research is needed to develop a readily useable device for measuring apparent velocity (and ideally intragravel dissolved oxygen) under a variety of field conditions. Such a device would provide quantifiable information useful for evaluating the overall quality of the intragravel environment, as well as adding to the predictability of survival to emergence models.

5.6. Gravel augmentation effects on water quality: how clean does gravel need to be?

Current state regulations require that gravel be processed by dry-sorting and/or washing prior to augmentation in streams. The purpose of gravel processing is to minimize environmental impacts, either locally or downstream, due to elevated concentrations of turbidity and mercury. The presence of mercury in source sediments and the risk of mercury methylation leading to uptake in aquatic food webs pose a threat to human health as well. Sediment processing to reduce turbidity and mercury is costly, and there is uncertainty as to whether or not the procedure is both necessary and effective. This section is complementary with Section 6.6, below.

5.6.1. Available Science

The concerns over elevated turbidity (see Section 6.6) and mercury contamination are related because mercury is primarily associated with fine sediments < 2 mm in size (Ashley et al. 2002), which contribute to turbidity when transported in suspension. The majority of mercury transport in rivers is in association with suspended sediments (Domagalski 1998, 2001). This relation implies that reducing turbidity by dry-sorting and/or washing the gravel may also sufficiently reduce the risk of mercury contamination. A recent study by Stillwater Sciences (2004) has investigated this technique (described further below), although uncertainties remain. In general, the issue of turbidity is more straightforward than that of mercury.

5.6.1.1. Turbidity

Overwhelming evidence links elevated levels of fine sediment and turbidity to the reduced survival of incubating salmon embryos (see Section 6.3). Fine sediment deposition on and within the substrate reduces the permeability of gravel and intragravel flow (Section 5.5), adversely affecting embryo incubation.³ In free-flowing rivers, seasonal flooding and active spawning re-work the streambed to maintain permeability and high spawning gravel quality even in relatively turbid watersheds. But regulated rivers develop a coarse, armored layer that is hydraulically resistant to reworking by hydrologically-dampened flows. Such an armored layer also is prone to fine sediment infiltration (see Section 5.5). Increasing fine sediment inputs through gravel augmentation may exacerbate the problem if the source material contains a high proportion of fines.

Adult salmon spawners are effective at reworking and cleaning the bed sediment during redd construction (Goddesfeld et al. 2004), but this process may be relatively localized. In areas heavily laden with fine sediment, for instance downstream of a major sediment source, redd building may not effectively clean the bed sediment and may cause the resuspension of fines, thereby transmitting the problem of fine sediment infiltration downstream.

³ According to Merz et al. (2004), turbidity may be used as a surrogate for intergravel fines content. They found a strong correlation between intergravel turbidity and total suspended solids and total volatile solids within the spawning gravels of the lower Mokelumne River. They also found a strong correlation between intragravel turbidity and steelhead embryo survival to swim-up stage.

Turbidity also affects juvenile salmonid feeding rates and physiology, which in turn can reduce growth rate (Newcombe and MacDonald 1991). The potential impact of turbidity associated with gravel augmentation depends on the duration and magnitude of the turbidity. High turbidity of short duration may cause no impact to juvenile growth rates, yet moderate turbidity of long duration may cause behavior effects, or even lethal effects if the duration is long enough. Likewise, turbidity also affects feeding rates and physiology of fish that prey on juvenile salmonids. EA Engineering (1992) found significant reduction in rates of bass predation on juvenile Chinook salmon.

5.6.1.2. *Mercury*

The mercury in source sediments for gravel augmentation is likely to be elemental mercury, which is relatively insoluble and tends to sorb onto fine sediment particles, particularly silt and clay. Mercury is converted to methyl mercury mainly by sulfate-reducing bacteria that thrive in conditions of low oxygen, high organic content, and warm temperatures. Methyl mercury is a problem because it (1) readily crosses biological membranes; (2) bioaccumulates in exposed organisms; (3) biomagnifies in food webs; (4) is the primary form found in fish (95-99%); and (5) is highly neurotoxic (early life stages are most sensitive). Methyl mercury formation is very site-specific, and relatively small amounts of benign mercury can cause major problems if site conditions are favorable for methylation.

Mercury concentrations are highly heterogeneous and patchy, with concentrated “hot spots” that are often hard to detect, along with larger areas of particularly bad contamination (e.g., Bear and Yuba Rivers). Hot spots are likely to exist in all drainages because of the staggered periods of mining activity, various mining methods, and relatively primitive techniques used historically (e.g., reports of overturned dredges spilling the sluice contents). The heterogeneous distribution of mercury contamination makes it difficult to determine how contaminated the source material is.

Contaminated bed sediments adversely affect benthic organisms that live in or ingest sediment (Luoma 1989), and these organisms can represent a substantial environmental impact based on their associated bioaccumulation and toxicity characteristics (Jennett and Effler 1980). Such organisms then act as a pathway for contaminant transport up the food chain (Moore et al. 1991). The direct transfer of metals, including mercury, from sediments to organisms is considered to be a major route of toxic exposure for many species (Adams et al. 1992). This includes incubating salmon embryos, on which fine sediments adhere and through which intragravel flow is passed. Bed sediment is therefore a critical source of ecological toxicity in river systems (Moore 2002). Sediment processing (washing and/or dry-sorting) to reduce mercury loading by gravel augmentation is likely to be an important measure for minimizing toxic bioaccumulation. However, a cost-conflict arises from this “best management practice” because removing the fines is expensive. There is also the issue that gravel that is too clean may have some negative ecological impacts (see Section 6.6).

Stillwater Sciences (2004) provides useful information on this topic that highlights the heterogeneity and site-specificity of mercury problems. The study found a strong relation between mercury and fine sediments < 2 mm in sampled dredger tailings in the lower Merced River. Results confirmed the benefit of size selective sorting as a means of reducing future mercury loading to the San Francisco Bay-Delta. The combination of low mercury levels in sampled dredger tailing fines and the overall small mass of fines associated with sorted 13 - 150-mm sized gravel/cobble indicated that washing after sorting had no measurable effect on mercury leached from the exterior surfaces of gravel sizes commonly selected for gravel augmentation.

Recent studies by Stillwater Sciences (2004) and Slotton et al. (2004) have used species of invertebrates and fish as bioindicators of methyl mercury bioaccumulation. This technique holds promise for regulatory and remediation monitoring. Species ideally suited as bioindicators should (1) be widely distributed, (2) found locally in sufficiently high densities for sampling and bioassessment, and (3) have a relatively small home range. Stillwater Sciences (2004) examined hydropsychid caddisfly larvae and prickly sculpin (both relatively short-lived and easily sampled), and found that methyl mercury concentrations in these taxa were seasonally and spatially variable. For regulatory and remediation monitoring, Slotton et al. (2004) recommended that larger fish of human health concern also be included in monitoring programs for mercury. This approach may serve to reduce spatiotemporal variation in results.

5.6.2. *Knowledge Gaps*

A number of important uncertainties remain about the relationship between gravel augmentation and water quality. Strictly in terms of turbidity, what proportion of fine sediment in the source gravel represents the threshold value above which dry sorting or washing is required, and below which no processing is necessary (see Section 6.6)? How will fine sediment stored in the channel interact with injected clean gravels (see Sections 5.3 and 5.4)? How quickly will gravel quality degrade due to sand infiltration, and does the rate of infiltration differ depending on the processing method (dry sorting vs. washing) and the lower sorting size (<63 μm or <2 mm)?

There is also a good deal of uncertainty as to how the entry of methyl mercury into the base of the food chain affects bioaccumulation rates. This initial step may be the critical one for determining bioaccumulation rates. For example, concentrations in plankton have been documented at 10,000 times the ambient water concentration, while with each additional step in the food chain, methyl mercury concentrations increased only 3-fold (D. Podger, California Bay Delta Program, pers. comm.).

A reliable assessment method that relates sediment concentrations to risk of uptake in the food chain is desirable for regulatory monitoring and deciding upon the safety of source gravels for augmentation. Slotton et al. (2004) showed that seasonally averaged aqueous raw methyl mercury was the best predictor of aquatic insect and small fish methyl mercury levels. However, the form of the relation with raw aqueous methyl mercury varied significantly between sites.

A better understanding of how site chemistry (i.e. sulfates, organic carbon content, temperature, pH, etc.) influences the methylation potential of mercury-contaminated sediment is another important knowledge gap.

Yet another key uncertainty is what constitutes sufficient sampling effort for sediment testing, given that mercury concentrations are likely to be extremely heterogeneous. Stillwater Sciences (2004) concluded that the number of collected samples was not sufficient to exclude the possibility of localized hot spots. To address the likelihood of localized hot spots and the notion that large fish in the lower Merced River may already be exceeding recommended limits for the protection of aquatic life, the study recommended that aqueous methyl mercury concentrations be measured before, during, and after in-stream restoration activities to determine whether the activities increased methyl mercury levels.

One final question: is the cure worse than the disease? That is, does sediment processing (washing and/or sorting) to reduce turbidity and mercury contamination cause adverse environmental impacts that may reduce or outweigh their apparent ecological benefits? For example, the fine sediment must be stored or disposed of post-processing; the receiving waters from gravel washing are at risk of contamination; and aggregate mining to supply gravel for augmentation projects may mobilize tailings from the floodplain that were benign prior to disturbance.

5.7. How is sediment routed and stored in bedrock canyon streams?

Gravel augmentation projects are sometimes implemented downstream of dams in channels that are not, strictly speaking, alluvial (Trush et al. 2000), but rather are ‘bedrock-controlled’ (with either beds of exposed bedrock or locations in confined, bedrock canyons), or mixed bedrock-alluvial. Bedrock channels are found where active fluvial incision into bedrock is occurring due to active tectonic uplift or a long-term reduction in the supply of coarse sediment from upstream. Mixed bedrock-alluvial channels, with alternating exposures of bedrock and transient alluvial deposits, are common in actively incising, hilly and mountainous terrain (e.g., Howard 1998). Such partially alluvial channels also occur in lowland coastal streams (e.g., Ashley et al. 1988). In many channels, bedrock exposures and alluvial patches are interspersed at the scale of single-channel widths or less (e.g., Howard 1998), while other mixed channels are characterized by abrupt downstream shifts between fully alluviated or fully exposed bedrock (e.g., Montgomery et al. 1996).

Coarse sediment capture by reservoirs can lead to the conversion of alluvial channels to bedrock (e.g., Collier et al. 1996). This occurs particularly downstream of dams operated as run-of-the-river facilities, where high flows remain frequent but coarse sediment supply is essentially eliminated. Bedrock becomes exposed due to long-term bed degradation as active sediment transport removes the alluvial bed inherited from the pre-dam condition. Gravel augmentation can be a strategy to reverse this process, and restore at least partially alluvial conditions.

Bedrock channels are fundamentally different from alluvial channels in many respects. Despite a recent surge in attention by basic science researchers (e.g., Tinkler and Wohl 1998,

Whipple 2004), there remains a great deal that we don't know about bedrock channels, particularly regarding the dynamics of sediment transport and storage. For example, conventional bedload sediment transport theory (e.g., Parker 1990) assumes that a fully alluvial bed exists, providing an essentially infinite supply of sediment when transport capacity exceeds sediment supply from upstream. By definition, this is not the case in bedrock channels. Moreover, the motion of individual bedload clasts over exposed bedrock is likely to be different from transport across alluvial surfaces due to the increased rebound energy when clasts impact solid rock (Wiberg and Smith 1985). The roughness characteristics of bedrock channels also differ fundamentally from alluvial channels. In some cases planar bedrock beds are considerably smoother than equivalent alluvial channels, while in other cases highly irregular erosional bedrock forms create much rougher conditions (e.g., Howard 1998, Wohl and Ikeda 1998). In bedrock channels, the concept of the 'bankful discharge' as the channel-forming discharge often does not apply. In confined canyon channels, high magnitude, low frequency flows will be more important in shaping the channel than in alluvial channels. Given that many current and potential gravel augmentation sites are bedrock or mixed bedrock-alluvial channels, and that such channels differ from alluvial channels in fundamental ways, project designers and implementers need to better understand their characteristic forms and behavior.

5.7.1. *Available Science*

Recent attempts to understand the sediment transport and storage dynamics of bedrock channels have been driven primarily by basic questions about the role of sediment supply in controlling the rate of river incision into bedrock over geomorphic time scales (e.g. Sklar and Dietrich 1998, Sklar and Dietrich 2001, Dietrich et al. 2003). To model the influence of variable and episodic sediment supply into bedrock channels on the extent of partial bed alluviation, Sklar and Dietrich (1998) assumed that the fraction of the bed covered with transient alluvial deposits varies linearly with the ratio of the rate of sediment supply to sediment transport capacity. Flume studies (Sklar and Dietrich 2002) confirmed this basic linear relationship, but also revealed two aspects of non-linear behavior with potential importance for designing gravel augmentation projects in bedrock channels. First, a threshold of alluviation exists. For a fixed bed shear stress, small rates of sediment supply produced no alluvial deposits. Only after the sediment supply rate was increased to the point where a threshold concentration of bedload sediment was exceeded did stable alluvial patches form on the bedrock surface. Once the threshold for deposition had been exceeded, then a roughly linear relationship between sediment supply rate and extent of partial alluvial cover was observed. A second threshold was observed in the flume experiments, in which a run-away alluviation occurred once the bed reached a critical extent of alluvial cover. Thus, steady-state partial-alluviation was only observed for relatively low extents of alluvial bed cover.

5.7.2. *Knowledge Gaps*

The work to-date on sediment transport dynamics in bedrock channels has raised more questions than it has answered. A fundamental unknown is how to predict the sediment transport capacity of a bedrock channel. The flume experiments discussed above can be interpreted as showing that, during the growth in partial alluviation, transport capacity increases as sediment storage increases. Lisle and Church (2000) have proposed a similar view of alluvial channel sediment routing dynamics. In bedrock channels, a key uncertainty

involves the role of channel roughness in mediating bed condition, sediment storage and sediment transport capacity. Where underlying bedrock surfaces are highly irregular (in contrast to the relatively smooth, planar bedrock surfaces), partial alluviation may have the effect of smoothing the bed by burying low points and reducing the protrusion of bedrock high points. In this case we might expect a reduced threshold of initial deposition and suppression of the instability that leads to run-away alluviation. The McBain and Trush (2004) conceptual model, described above in Section 3.2, is consistent with a highly rough underlying bedrock channel bed topography. A better understanding of the role of bedrock roughness would allow better identification of reaches where gravel augmentation might be most beneficial, and where boulder placement might improve conditions for gravel patch formation (see Section 5.8).

For the practical concerns of designing gravel augmentation projects in bedrock channels, the existence of non-linear, threshold behavior offers both constraints and opportunities. To convert a bedrock-dominated channel bed to an alluvial bed will likely require a significant increase in the long-term rate of sediment supply. Frequent additions of small volumes of sediment to a channel with minimal alluvial cover may be insufficient to exceed the threshold of alluviation, and thus may have little or no beneficial effect. On the other hand, a small addition of sediment to a bedrock channel with abundant alluvial patches could push the channel across a roughness threshold and lead to a large increase in the extent of bed alluviation and habitat availability. In both cases, the episodic nature of gravel augmentation and bedrock channel response suggests that for a given net volume of added sediment, fewer larger additions will be more effective than smaller more frequent additions.

However, our generally poor understanding of bedrock channel dynamics makes it more likely that unforeseen negative impacts could result from large-scale gravel augmentation projects in these channels. For example, for channels with large extents of bedrock exposure, increasing the quantity of sediment moving as bedload will provide more abrasive tools to the flow and should increase the rate of erosion of the bedrock (Sklar and Dietrich 2004). Channel incision rates in relatively weak bedrock lithologies can be rapid enough to threaten engineered structures such as bridge abutments in developed areas (e.g., Tinkler and Wohl 1998). Conversely, catastrophic alluvial deposition and bed aggradation, such as observed in the flume studies (Sklar and Dietrich 2002), could result in a significant reduction in the channel flood conveyance and lead to an increase in flood risk in some situations. Finally, the habitat value of bedrock channels (e.g., Levine 2000) may be underappreciated, and conversion of channel beds from bedrock to alluvial-dominated may involve poorly understood tradeoffs in habitat value. In summary, where bedrock channels are concerned, we are in the uncomfortable position of being unable to make even approximate predictions of the possible positive and negative outcomes of gravel augmentation projects.

5.8. Can discrete roughness elements induce gravel deposition?

Channels downstream of dams that regularly release discharges capable of mobilizing gravel (due to small reservoir storage capacity and/or lack of flow diversion capability) commonly have beds composed of bedrock or alluvium too coarse to provide salmonid spawning

habitat. Although gravel capture by the upstream reservoir partly explains the lack of gravel-dominated patches downstream, in many cases these channels are located in steep or confined canyon reaches and were historically too coarse-bedded to provide spawning habitat. Rather, they primarily served as pathways for fish traveling to and from spawning habitat further upstream in the drainage network. With upstream migration blocked by the dam, these mainstem channels become the upstream-most available locations to create alluvial habitat. In such high shear stress environments, creation of channel spanning gravel deposits may require such large amounts of sediment addition as to be unfeasible (see Section 5.7). Even smaller deposits created by gravel augmentation may scour too frequently to provide meaningful habitat value.

Two related approaches could be used singly or in combination to create small but biologically useful gravel deposits in local zones of reduced shear stress. First, gravel could be placed and graded in specific locations where stable gravel deposition may have occurred prior to dam construction and the capture of upstream gravel supply by the reservoir. Second, discrete roughness elements could be constructed, using large woody debris (LWD) or boulder clusters, to create new low shear stress environments where gravel deposits would be stable. Gravel can either be placed in the region of expected low shear stress or the roughness elements can be designed to capture mobile gravel that might be supplied by a tributary that joins the mainstem below the dam, and by local bank and hillslope failures. However, placement of structures to retain gravel have had limited success on alluvial Central Valley rivers (e.g., Kondolf et al. 1996), and may only provide gravel retention benefits until the next large flood occurs. Structures are likely to be more successful on steeper, more confined streams where the structure can be properly anchored to large boulders, bedrock outcrops, and other non-mobile features.

Whether trying to identify existing sites of pre-dam gravel deposition, or attempting to design constructed hydraulic conditions favorable to gravel capture and retention, the key challenge is to balance the need for reduced gravel mobility with the biological requirement of adequate depth and flow velocity for spawning and redd survival. Achieving this balance is particularly difficult because of the wide range of flow magnitudes that must be accounted for. For example, roughness elements that create good hydraulic conditions for gravel capture and retention at moderate flows may induce enhanced scour at high flows. Similarly, a site at which gravel is stable at high flow might not have adequate flow depth or velocity for spawning at more moderate flows.

5.8.1. Available Science

Bed material grain size is strongly influenced by spatial variations in shear stress, whether those are due to regular planform and vertical morphologic patterns such as bar-pool units (e.g., Dietrich and Smith 1984), or are forced by local bank and bed irregularities (e.g., Lisle 1986). Much work has been done to identify and quantify the roughness effects of LWD (e.g., Manga and Kirchner 2000) and describe the effect of local LWD structures on bed surface texture (Peigay and Gurnell 1997, Thompson 1995). LWD not only reduces shear stress by extracting momentum through form drag, but can also partially dam the channel, reducing the water surface slope and thus the shear stress upstream. LWD is most effective in influencing shear stress and bed material texture in channels narrow enough for channel-spanning structures to be stable (Abbe and Montgomery 1996). Where forestry practices

have reduced the rate of supply of large trees to the channel, the resulting loss of channel-spanning wood structures has caused channels to shift from alluvial-bedded to bedrock (Montgomery et al. 1996).

Dams are commonly built on channels too wide for stable channel-spawning LWD structures, and LWD is typically easily mobilized in the high shear stress environments under consideration here (Braudrick et al. 1997, Braudrick and Grant 2000). As a result, boulder clusters are more likely than LWD to be useful for creating natural or engineered gravel deposition sites downstream of dams. However, considerably less is known about the interaction of water and boulders, particularly when the depth of flow is of the same order as the boulder diameter (Wiberg and Smith 1991).

At least one large-scale attempt is being made to use boulders as roughness elements to induce gravel capture and retention of placed gravel for spawning habitat creation on a mainstem channel downstream of a dam on the North Umpqua River in the Oregon Cascades Mountains (Stallman et al. 2004). As part of the design process, a number of key issues were first explored in a series of flume experiments (Sklar and Dietrich 2002). In those experiments, the coarse sediment moving as bedload tended to travel along a path that followed the high shear stress core in the center of the moderately sinuous channel. Model boulders were placed on the bed in various configurations to either directly capture bedload in the downstream wake, or to deflect sediment toward the banks and into lower shear stress, potentially depositional zones. Isolated, single boulders placed in the bedload transport path did not induced significant model gravel deposition. However, successful deflection and deposition of bedload was accomplished with a sequence of boulders oriented at an oblique angle from the flow center line. The field installation of boulder structures for this project made use of a similar configuration, in which oblique boulder spur dikes are intended to deflect mobile gravel toward the bank. High flow overtopping the boulder line is expected to generate a horizontal axis vortex, as occurs due to flow over dunes in meandering sand-bedded channels (Dietrich and Smith 1984), generating sufficient shear stress to move gravel out into a depositional zone in the downstream wake of the boulder structure. Gravel was placed in some but not all structures to test the ability of the structures to both capture and retain gravel. To date, the structures have not been fully tested due to a lack of high magnitude flows.

5.8.2. *Knowledge Gaps*

There are several key areas of uncertainty that prevent us from reliably predicting the influence of discrete roughness elements on bedload transport paths and the stability of both gravel deposits and placed boulders over a wide range of discharges.

- **Lateral sorting and patch formation.** We are not yet able to adequately explain the characteristic pattern of lateral sorting of bed sediments into discrete and distinct facies units. Work by Church and colleagues (Church et al. 1998, Hassan and Church 2000, Church and Hassan 2002) has shown some progress on this topic by demonstrating the significance of grain interactions that create reticulate stone structures, patches, and facies on the bed. Most numerical models of bedload sediment transport are only one-dimensional and thus do not consider lateral variation in bed texture or sediment transport rate. Patches of differing median grain size tend to mobilize at different flow stages and travel from patch to patch of similar texture as they move downstream. In

steep canyon channels, bar surfaces are often distinctly bi-modal (e.g., boulders and gravel) suggesting a superposition of grain size distributions, which move at very different recurrence interval discharges. A better understanding of the feedbacks between flow hydraulics, sediment transport, and bed morphology, which produce lateral sorting, and the role of discharges of various magnitudes and frequencies, is needed for reliable design of introduced roughness elements intended to alter patch texture.

- **Boulder mobility.** For boulder clusters to be effective as designed roughness elements they must be stable even at the highest flows the channel will experience. We presently lack a methodology for predicting the threshold of motion for particles with diameters on the same order as the flow depth. Boulders have often been observed to be more mobile than expected, due to several factors. First, when particles protrude high into the flow, water must flow around the grain, rather than over it. This results in an ‘inertial’ force in the downstream direction which can be much larger than the ‘drag’ force imparted to well-submerged grains that do not significantly deflect the flow. Second, if water spills over the top of the boulder, such that the water surface on the downstream side is lower than on the upstream side, additional forces arise due to the pressure difference across the boulder. Third, if boulders are placed on top of finer sediments, the friction angle between the boulder and bed can be very low, allowing the boulder to slide or roll downstream far more easily than if the boulder were placed in a pocket formed by particles of similar size. A physically rigorous methodology for predicting boulder mobility would need to account for each of these factors.
- **Two-dimensional sediment transport modeling.** Although two-dimensional hydraulic models are beginning to come into general use, and have been employed in modeling thresholds of bed stability and habitat conditions in gravel augmentation projects (e.g., Pasternak et al. 2004), models of active sediment transport that dynamically calculate resulting changes in bed elevation and morphology are not currently available. The depth-averaged approach in 2D hydraulic models does not capture the vertical components of velocity that are important in predicting the performance of roughness elements, particularly those designed to be overtopped by high flows. Two-dimensional models also require very high resolution topographic data, which limits their utility in non-research applications.

5.9. Where should talus cones be placed for best recruitment?

Talus cones and bank placement of coarse sediment are gravel augmentation strategies that depend on the river to mobilize, transport, and deposit the coarse sediment downstream. Talus cones are usually placed by end-dumping coarse sediment from a steep bank into the low flow channel, and can be created during either low or high flows. Coarse sediment is also sometimes placed on low terraces, or as small piles on the bank of the low flow channel. The placement of the talus cones or recruitment piles is important because geomorphic or habitat benefits will only be achieved if the river is able to recruit the coarse sediment.

5.9.1. Available Science

Successful placement depends on geomorphic and hydraulic understanding of where the high velocities needed to mobilize coarse sediment will occur during periods of high flow. We know that certain locations within a river corridor, such as bedrock outcrops, portions of

the outside of meander bends, upstream ends of point bars, channel obstructions, and other features are zones of high stream power during high flow events. Two-dimensional modeling can also predict these zones of high stream power. Locations to avoid placing talus cones and recruitment piles include the insides of meander bends, locations immediately upstream of high value habitat (to avoid aggradation damage), channel expansion zones, the downstream side of certain point bars, and floodplains. Examples of successful talus cone placement can be observed on Clear Creek (WSRCD 2000), where talus cones have been placed at three locations. Placement has occurred at one or more of these locations on a yearly basis beginning in 1996. Between June 1996 and June 2001, 47,000 tons were placed as talus cones. Gravel placed at the two downstream sites was mobilized and routed on a reasonable basis by tributary generated floods. However, the site immediately downstream of Whiskeytown Dam had multi-year periods where high flows did not occur, and the gravel remained in the talus cone for several years. Talus cone placement has also occurred on the Sacramento River (USFWS 1996) and the Trinity River (McBain and Trush 2001).

5.9.2. Knowledge Gaps

The issue here is not so much scientific knowledge, which is adequate, but geomorphic education in order to help project designers and implementers identify zones of high stream power or lateral channel migration that are suitable for coarse sediment placement.

Chapter 6: Key Biological Uncertainties

6.1. What factors influence the use of gravel?

The objective of most gravel augmentation projects is to increase the quality and/or quantity of aquatic habitat for fish use, primarily for spawning and embryo incubation and secondarily for fry and juvenile rearing. Although less often stated explicitly in project objectives, gravel augmentation also provides material for colonization by invertebrates, which in turn contributes to autochthonous production and food availability for fish. Many factors may influence the biological use of gravel substrates in rivers, and should be considered in the design and implementation of gravel augmentation projects to increase the likelihood for project success. We focus here on those factors that relate to fish use at a local and reach-scale, and highlight those that also apply to invertebrates.

6.1.1. Available Science

In naturally occurring habitat, salmonids select areas for spawning based in part on the grain size distribution of substrates. Field studies that measured the substrates used by spawning fish have shown specific size ranges of materials ranging from 0.6 -7.6 cm for trout and from 1.3 -10.2 cm for salmon and steelhead (Smith 1973, Hunter 1973, Bell 1986, Bjornn and Reiser 1991). Substrates in the range of 5 to > 7.5 cm provide important interstitial habitats for fry and juveniles. Substrates suitable for spawning generally cover the size ranges that promote high invertebrate production (Hynes 1970).

A second key factor in spawning habitat selection is the degree of substrate compaction and armoring. Salmonids construct redds (depressions) within the substrate framework into which eggs are deposited. Redd construction is accomplished via “hydraulic lifting” of the substrate materials via body and fin contortions of the female fish. Heavily armored substrates are not easily dislodged, and hence will not be used for spawning if other areas are available. Studies have also shown that salmonids exhibit a preference for certain water depths and water velocities coincident with suitably sized substrates when selecting spawning areas. Depth and velocity criteria have been developed for a variety of species (Bell 1986, Bjornn and Reiser 1991, Groot and Margolis 1991) and USFWS has developed spawning criteria specifically for IFIM modeling in the Central Valley (e.g., USFWS 1994). In general, larger fish occupy areas of higher velocity and larger substrate size for spawning than do smaller fish. For most salmonid species, areas affording suitable spawning depth, velocity, and substrate conditions are associated with pool-riffle transition zones (Bjornn and Reiser 1991). Riffle habitats in association with large gravels and cobbles are also the most productive for invertebrates (Hynes 1970).

A third factor that influences the use of gravel for spawning is hydrological stability. The spawning period of salmonids can range from several weeks to several months, depending on species and stock characteristics. The stability of flow conditions during the spawning period may influence the utility of potential spawning areas. Daily fluctuations in flow, as may occur with hydroelectric peaking or load-following operations, can result in rapidly

varying flow levels that deter or delay spawning, or may result in spawning in unfavorable areas. For example, redds that are created during high flow conditions (e.g., an up-ramp cycle) may subsequently become dewatered during the down-ramp cycle. Gravel supplementation in these conditions should be directed to areas that will remain wetted throughout the embryo incubation period.

A fourth factor that may influence gravel use by fish, particularly by juveniles for rearing, is habitat heterogeneity. According to Wheaton et al. (2004b), although optimal spawning habitat as defined by habitat suitability models was generally found in riffles, the proximity of habitat to structural cover (pools, large woody debris, boulder clusters and overhanging vegetation) and hydrodynamic shear zones was also important in providing refuge from predation and resting zones for energy conservation.

The availability of structural cover is another influence on spawning area selection. Some anadromous fish enter freshwater streams and arrive at spawning grounds weeks or even months before spawning. Cover is likely important in these systems to reduce predation risk and create bioenergetically favorable zones for resting. Bjornn and Reiser (1991) postulated that the proximity of cover may be a factor in selecting spawning sites by some species, citing several studies specific to brown trout in which spawning areas were located near undercut banks. However, there have been no definitive studies documenting salmonid spawning preference for areas with cover compared to areas without. Nevertheless, cover should be considered as an important element of gravel supplementation projects, especially if extended adult holding times are anticipated (as recommended by Carl Mesick, R³ workshop).

Some salmonids (e.g., chum salmon, Salo 1991; coho salmon, Sandercock 1991) tend to select spawning areas associated with groundwater upwelling. To the extent practical, gravel augmentation should target locations of known upwelling currents. Many salmonids select areas within streams at pool-riffle interchanges where the convexity of the channel morphology creates hydraulic downwelling forces as documented by Vaux (1968). These areas promote intragravel flow within the redd, which is important for the transport of dissolved oxygen to and metabolic wastes from incubating embryos. Creation of downwelling features in the context of gravel augmentation projects can be challenging because such features may dislodge or relocate following natural flow events. The exception to this may be systems in which flow releases are highly regulated and channel form is not expected to change. In these situations, some shaping of the channel to promote downwelling currents may be warranted. Another factor known to influence gravel use for spawning is water quality. Temperature and dissolved oxygen levels must be within acceptable ranges (Bjornn and Reiser 1991) to promote spawning and embryo survival.

6.1.2. Knowledge Gaps

Although much is known about factors influencing the use of gravel for spawning from a structural and hydraulic perspective, there are several poorly understood factors that may under some circumstances significantly influence gravel use. First, although cover type and availability have been postulated as key factors influencing gravel use for spawning, there have been no definitive studies conducted to test these hypotheses. The relative importance

of cover (e.g., boulder clusters, large woody debris, overhanging vegetation) as a factor influencing the use of coarse sediment for spawning warrants further investigation since cover type and availability may be important factors increasing the effectiveness of gravel augmentation plans. Cover, as a form of habitat heterogeneity, has already been shown to reduce predation and create hydraulically favorable resting areas for juveniles (Wheaton et al. 2004b).

Second, the olfactory senses of salmonids are keen and likely at a heightened state during migration and spawning. Homing instincts to natal streams have been well established for anadromous salmonids (Hasler 1976), and in general, returning adult salmon and steelhead are thought to cue in on stream-specific bouquets imparted by watershed characteristics. The extent to which native substrates impart odors that cue fish to specific spawning riffles is not yet understood (Mesick presentation, R³ Workshop). The question, then, is whether there could be preferential use of native introduced versus non-native introduced gravels by spawning salmonids. Pair-wise testing of gravel sources (native and non-native) could be done to test this hypothesis.

A corollary to the issue of gravel source and odor relates to the shape of the gravel, i.e. angular versus smooth or rounded, and whether gravel shape plays a role in the selection of spawning areas. A study by Meehan and Swanston (1977) indicated that fine sediment accumulation was more rapid in angular than in rounded river gravels. By extension, we may conclude that egg survival would be lower in angular as compared to rounded gravels, but we know of no studies that have tested this.

Also related to homing instincts are the questions of what factors determine the spatial distribution of spawning salmon, and what effects the location and magnitude of gravel augmentation have on spawner distributions. Because salmonids tend to spawn in highest densities close to dams, will gravel augmentation in downstream reaches more evenly distribute spawners and reduce superimposition losses? Or are salmonids hard-wired to use upstream locations, driven by homing instincts to access lost spawning habitat, and therefore augmentation sites in lower reaches will remain generally unused? If a greater proportion of spawning occurs in downstream reaches following augmentation, what are the implications for smolt production (e.g., poorer gravel quality, warmer water temperatures)?

6.2. Does gravel augmentation influence scour risk?

Scour has long been considered one of several key egg-embryo-alevin mortality factors that influence salmonid spawning success. The effect of scour (e.g., crushing and/or dislodgement of embryos or alevins) on survival and emergence is highly dependent on the hydrologic regime of a given system, in particular flood-flow frequency and magnitude, as well as channel substrate characteristics including grain size distribution, extent of armoring, and degree of embeddedness. Although gravel augmentation generally has no effect on a stream's hydrologic characteristics, it does create a spatial discontinuity in the existing channel substrate characteristics that could locally modify (increase or decrease) the risk of scour in a given system. The extent to which such local modifications may also more broadly affect reach-scale downstream channel form and function is also a question. Thus

the question of whether gravel augmentation influences scour risk is important because it is fundamentally tied to the question of whether the benefits of gravel augmentation may be offset by negative impacts that reduce rather than increase egg survival.

6.2.1. *Available Science*

Biologists have long recognized high flows and bed-scour as one determinant of egg survival to emergence (STE) success (McNeil 1964, 1966, Hobbs 1967, Lisle 1989), and as a potential limiting factor to populations in some systems (Seegrist and Gard 1972). Moreover, Kondolf et al. (1991) ascribed salmonid species distribution differences to seasonal patterns of bed mobility and scour in eastern Sierra Nevada streams. Natural spawning gravels that have been repeatedly used by salmonids are typically “well-settled” within the channel framework and hence are generally not vulnerable to large-scale mobilization and transport during normal runoff conditions, but can be during large floods. Conversely, newly added gravels that are simply “introduced” into a system (i.e. gravel retention structures not used) will be at least initially unconsolidated, and hence the risk of scour will be greater.

Scour has long been recognized as a potential limiting factor to STE, and previous studies have examined a range of topics including the development of measuring and monitoring techniques, scour depth relative to salmonid egg burial depths, the mechanics of scour relative to egg survival, and formulation of modeling approaches to predict scour frequency and magnitude in egg pockets. These topics are briefly summarized below.

- **Scour Measuring Techniques.** There have been a number of techniques developed and used to measure and monitor scour and deposition in gravel bed rivers. Many of these, including those of Platts et al. (1983), Tripp and Poulin (1986), Lisle (1989), and Nawa and Frissell (1993), are modifications of a type of scour chain or scour cord as used by Leopold et al. (1964). Nawa and Frissell (1993) also employed the use of sliding bead monitors borrowing from the method developed by Moring and Lantz (1975) that used buried ping-pong balls. More recently, DeVries (2001) has developed an electronic scour monitor as a means to measure temporal variation in scour depth.
- **Egg Burial Depths.** DeVries (1997) completed a comprehensive review of the literature and identified salmonid egg burial depths that should be considered relative to potential scour impacts. His synthesis of information led to the derivation of preliminary species-specific egg burial depth criteria that may be used to assess scour related impacts.
- **Mechanics of Scour Relative to Salmonid Spawning.** The spawning activity of salmonids serves to dislodge and locally and temporarily mobilize substrates. This action effectively “cleans” and flushes fine sediments from the gravels, increasing gravel permeability and intragravel flow. Montgomery et al. (1996) noted that the resulting salmonid-induced modifications in grain size, sorting, packing and bed topography may potentially affect bed surface mobility, thus the vulnerability of embryos to scour. This study revealed a close correspondence between egg burial depths (measured in two Pacific Northwest streams) and scour depths during typical annual high flows, suggesting population adaptation to the prevailing patterns of bed scour and hydrological regime. Since gravel augmentation projects have the potential to modify transport characteristics, they may correspondingly alter typical scour

depths experienced during annual floods. However, we are unaware of any studies that have specifically evaluated this.

- **Modeling Scour Probabilities.** The recent work of Lapointe et al. (2000) provides a predictive tool for evaluating the probability of egg scour during floods. They developed a substrate mobility index based on reach-scale geomorphic characteristics and flood hydraulics that provided relatively accurate predictions (R^2 up to 74%) of potential spawning zones undergoing flood scour. These types of models could be used for evaluating scour risk of gravel augmentation projects.

6.2.2. *Knowledge Gaps*

As particle size decreases with gravel augmentation, redd scour may increase, thus reducing alevin production. However, there are geomorphic benefits (e.g., preventing riparian encroachment) and habitat benefits (e.g., gravel cleansing) to periodic bed scour. What is needed is a defined analytical framework that links these various components together to provide a step-wise process for assessing and balancing scour-risk.

The work of Kondolf et al. (1996) on the Merced River provides perhaps the most cogent example of the problems that can occur with gravel augmentation projects when scour risk is not factored into the design. In that case, the design of the gravel supplementation program for certain areas apparently did not consider the range of discharges likely to occur at the site, the resulting sediment transport characteristics, and upstream sediment supply. The consequences were manifested in channel instability, bed scour, and transport of gravels downstream. Clearly, the potential for scour must be factored into the feasibility assessment of gravel augmentation projects.

There is currently no reliable model to predict local bed scour as a function of discharge or local shear stress. Models do a reasonable job of predicting local bed mobility but do not accurately predict local bed scour depth. A principal challenge is accounting for fluctuations in sediment supply from upstream, because local scour occurs when local sediment transport exceeds local supply. A predictive model, validated by measurements in a variety of field settings, would allow better evaluation of redd scour risk associated with gravel augmentation.

6.3. **What factors influence survival to emergence?**

Understanding the factors that influence embryo survival to emergence (STE) is fundamental to the development and implementation of successful gravel augmentation projects. Ideally, information about the combinations of physical, hydraulic and chemical parameters that promote successful STE, should be treated as the underlying biological design criteria for gravel augmentation programs. That is, if we know the combinations of physical, hydraulic and chemical parameters that promote successful STE, then the design goal of gravel augmentation projects should be, to the maximum extent possible, to optimize such conditions. Conversely, if we know that combinations of certain factors or processes tend to reduce STE, then the design of gravel augmentation projects should consider measures that reduce or minimize them. Understanding the factors that influence STE is also important for identifying key monitoring parameters that can be used both as indices of

STE (i.e. measurement of success) and triggers for maintenance actions (e.g., gravel replenishment, gravel cleaning, etc.). We believe that the difference between past successful and unsuccessful gravel augmentation projects may be partially explained by whether or not factors that influenced STE were considered in the design.

6.3.1. *Available Science*

With respect to salmonids and gravel augmentation, the major factors that influence embryo survival to emergence (STE) are those that influence intragravel conditions experienced by developing embryos and alevins, which include but are not limited to: the presence, intrusion, and infiltration depth of fine sediments; the timing of sediment deposition and scour relative to embryo development, gravel permeability; and intragravel velocity, dissolved oxygen, and temperature. Each of these factors is addressed below.

Previous studies have suggested that embryo survival is dramatically reduced when concentrations of fine sediments < 0.84 mm in diameter exceed about 10% (by weight or volume) in the gravel matrix (McNeil and Ahnell 1964, Reiser and White 1988). Studies have demonstrated that fry survival to emergence (STE) is reduced when concentrations of fine sediments < 6.4 mm in diameter exceed about 25% by volume or weight (Bjornn et al. 1977, McCuddin 1977).

Redd construction effectively cleans the gravel substrate of fine sediments. With time and under natural conditions, fine sediment concentrations in the redd will return to ambient levels reflective of watershed characteristics (Wickett 1958). The rate at which sediment infiltrates into the gravel framework varies with flow and can range from several months (under steady flow conditions) to a few days if subjected to frequent flow increases or flooding (Carling and McCahon 1987, Sear 1993). Sear (1993) suggested a differential risk of infiltration between small, relatively shallow redds (e.g., constructed by small trout), and larger redds in which the egg pockets are deeper. In the former, the risk of infiltration is in slack water and areas of low velocity; in the latter, the infiltration risk is associated with deeper, faster water which allows the penetration of fines to occur lower into the bed. Meehan and Swanston (1977) suggest that sediment accumulation may be influenced by the shape of the gravel, with angular gravel tending to accumulate sediment faster than round gravel.

As discussed in detail in Section 5.5, the depth to which fine sediments infiltrate within a redd depends on the diameter of the coarse bed materials, referred to as the framework (Carling and McCahon 1987). Beschta and Jackson (1979) noted that when fine sediments are large relative to pore spaces within the framework, they may settle into the surface layers of the substrate and may form a seal that prevents further intragravel infiltration of fines. Sear (1993) demonstrated that the size of infiltrated materials varies by location and depositional conditions. In marginal areas and areas of low velocity, the size of the infiltrated material will be relatively small, whereas in high velocity areas with increased bed shear stress, the materials that infiltrate will be relatively coarse, as small material will remain in suspension. The impact of sediment deposition depends on its timing in relation to embryo development. Reiser and White (1988) noted that salmonid embryos have differential developmental sensitivity to the effects of fine sediment deposition. Newly fertilized embryos (“green”, less than 48 hrs post-fertilization) are more sensitive to fine sediment

deposition than eyed embryos (exhibiting eye spots). This is likely because eyed embryos have a higher DO uptake efficiency due to the presence of a functioning circulatory system, rather than the reliance on passive diffusion processes in green embryos. Thus higher embryo mortality may result from sediment influxes that occur early in the embryonic development process compared with influxes that occur after the embryo's circulatory process becomes functional.

Multiple studies have demonstrated positive relationships between STE and gravel permeability (ability of particles in the redd to transmit water per unit of time). Chapman (1988) analyzed data from Koski (1966) and McCuddin (1977) and noted a positive trend in survival over a range of permeabilities extending from about 1000 to over 90,000 cm/hr. It can generally be stated that the higher the permeability the better the chances for increased STE. Related to permeability, the velocity of water moving through the gravel matrix comprising the redd has been related to embryo survival and the quality of emerging fry. The velocity of the water through the redd dictates the rate at which DO is delivered to, and metabolic wastes removed from, the developing embryos. Such velocities can be quite low and yet afford relatively high embryo survivals, provided dissolved oxygen concentrations are high. Relatively high survivals were reported by Wickett (1960) with intragravel velocities > 7 cm/hr, Phillips and Campbell (1961) at velocities > 20 cm/hr, and Peters (1962) at > 60 cm/hr. Reiser and White (1981) in laboratory tests reported that intragravel velocities as high as 1500 cm/hr continued to positively affect embryo survival. Intragravel velocities can be influenced by the shape and contour of the streambed, which can serve to promote the downwelling of surface flows into the substrate (Vaux 1962, 1968). Similarly, the concentration of intragravel dissolved oxygen within waters passing through the redd has been directly linked to STE and fry quality (Coble 1961, Phillips and Campbell 1961, Silver et al. 1965). Phillips and Campbell (1961) concluded that intragravel DO should average 8 mg/l for high survival of embryos and alevins. The interrelationships of DO with other parameters have been demonstrated by Tagart (1976) and Reiser and White (1981) who found direct relationships between intragravel DO and permeability, and inverse relationships between DO and percentages of fine sediments.

Water temperature affects the rate of embryo and alevin development and the DO capacity of the water. Bell (1986) reported that the general range of temperatures for successful incubation of salmonid embryos ranges from 4.4 to 14.4 °C. Intragravel water temperatures are influenced by surface water temperatures, the extent of groundwater interchange, and the thermal mass of the substrate (Bjornn and Reiser 1991).

Finally, there are several known biological factors that influence STE. These include: a) redd superimposition – higher density of spawners can serve to dislodge ova of previous spawners; b) intragravel predation – certain invertebrates and benthic dwelling fish have been known to prey on salmonid embryos; c) disease or fungus – fungus can spread from dead eggs to viable ones within a given egg pocket; and d) fitness of the spawning fish.

Recent research by Merz et al. (2004) sheds light on the possible benefits of gravel augmentation on STE. The study tested the hypothesis that spawning bed enhancement increases survival and growth of chinook salmon (*Oncorhynchus tshawytscha*) embryos in the Mokelumne River, a regulated California stream with a gravel deficit. They also examined 12 physical parameters correlated within spawning sites and how well they predicted survival

and growth of chinook salmon and steelhead (*O. mykiss*) embryos. Salmon embryos planted in enhanced gravels had higher survival to swim-up stage than embryos planted in unenhanced spawning gravels. Intergravel temperature and substrate size were strongly correlated with distance downstream from the lowest non-passable dam. Intergravel turbidity and total suspended and volatile solids were also strongly correlated. Merz et al. (2004) built multiple regression models with a combination of physical measurements to predict survival and length of chinook salmon (temperature, dissolved oxygen, permeability and substrate size) and steelhead embryos (substrate size, permeability, and redd depth and velocities). Survival models accounted for 87% of the variation around the mean for salmon and 82% for steelhead. Growth models accounted for 95% of the variation around the mean for salmon and 89% for steelhead. These findings suggest spawning bed enhancement can improve STE where spawning habitat is degraded. Additionally, measuring a suite of physical parameters before and after spawning bed manipulation may serve to predict benefits to target species.

6.3.2. Knowledge Gaps

Much work remains to fully understand the overall determinants of STE, the cause:effect relationships of sediment influx on aquatic ecosystems, and how to use that information in both a prescriptive and predictive way for gravel augmentation projects. Some of the research needs pertain to field assessment techniques of which the “state of the art” has not been updated since the early 1960s-70s. For example, one of the major determinants of STE is intragravel velocity. And yet, the field measurement of this parameter still relies primarily on the colorimetric or dye-dilution techniques described by Terhune (1958) involving standpipe insertion into the redd. However, a recent study by Zimmermann and Lapointe (in review) that focused on fine sediment infiltration included development and use of a hot wire intergravel velocity sensor to continuously monitor interstitial velocities in artificial redds. A similar instrument for measuring permeability and intragravel dissolved oxygen would likewise be useful.

An additional knowledge gap is the factors that determine the emergence success of embryos incubating within a redd that develops a surface seal of fine sediment (previously discussed in Section 5.5). The question is important because the development of a surface seal appears inevitable in most natural gravel-bed rivers, even after a bed has been partially cleaned of fine sediment by spawning fish. A surface seal is not necessarily detrimental to STE because adequate intragravel flow is maintained and further fine sediment infiltration is prevented. However, a surface seal may effectively prevent the escape of alevins from the sub-surface. An improved understanding of the factors determining STE in the presence of a surface seal is needed.

We also advocate continued research related to substrate sampling with a focus on *in situ* quantification and monitoring techniques that provide data directly linked to embryo survival. Improvements in the simplicity and accuracy of such techniques will provide a better understanding of factors that influence STE that may improve the success of gravel augmentation projects.

6.4. What metrics can be used to gauge gravel quality – embryo survival relationships?

Metrics for measuring the success of gravel augmentation as a function of embryo survival to emergence (STE) are needed to provide reliable estimates of resulting fry production. Data generated by these measurements could be used for cost benefit analysis of projects and also for life cycle modeling in order to evaluate population level responses to gravel augmentation. The two key questions about potential metrics are: 1) which are the best indicators of embryo survival to emergence (STE); and 2) of these, which are readily and accurately measurable in the field?

6.4.1. Available Science

Factors that have been commonly used to gauge the quality of gravels relative to STE have been extensively reviewed and summarized (Chapman and McLeod 1987, Chapman 1988, Reiser 1998, Kondolf 2000a) and include the percentage of fines (McNeil and Ahnell 1964, Hall and Lantz 1969, McCuddin 1977, Tappel and Bjornn 1983, Reiser and White 1988); apparent velocity (Shelton 1955, Gangmark and Bakkala 1958, Wickett 1960, Coble 1961, Phillips and Campbell 1961, Cooper 1965); intragravel dissolved oxygen (Coble 1961, Silver et al. 1965, Phillips and Campbell 1961, Merz et al. 2004), and gravel permeability (Wickett 1960, Tagart 1976, Reiser and White 1981, Merz et al. 2004). Another metric noted during the R³ workshop was porewater turbidity at depth (Matt Brown, USFWS). These metrics are briefly discussed below.

Perhaps the most often studied aspect of salmonid STE is the percentage of fine sediments present within the gravel matrix. Size classes of sediments cited as being deleterious to overall STE vary among studies: materials < 6.4 mm, which primarily affect emergence (McCuddin 1977); and materials < 4.6 mm (Platts et al. 1979), < 3.3 mm (Koski 1966), < 2.0 mm (Hausle and Coble 1976), and < 0.84 mm (McNeil and Ahnell 1964). Quantification of fines within the substrate usually entails the collection (using a core sampler or freeze-core sampler) of a bulk sample from the streambed from which grain size distributions can be determined via sieve analysis, a laborious process that cannot be carried out in the field. Intragravel fine sediment deposition has also been evaluated using sediment-trapping devices (Meehan and Swanston 1977, Mahoney and Erman 1984, Carling 1984, Wesche et al. 1989) that are installed directly within the matrix and periodically retrieved and analyzed. These approaches are more easily deployed in the field, but most still involve laboratory analysis to determine fine sediment concentrations. Reiser et al. (1989) explored development of a field-based method for measurement of intragravel sediments via standardization of trap media. Fine sediment accumulation in redds is a consistently good predictor of egg survival, but techniques for field evaluation within egg pockets are not readily available; most methods require substantial disturbance of the gravel bed.

Studies have also demonstrated that one of the major determinants of salmonid embryo survival within the redd is the intragravel velocity (apparent velocity) of the water that carries dissolved oxygen to and transports metabolic wastes from the developing embryos (Coble 1961, Cooper 1965, Peters 1962). Quantification techniques are largely those developed in the late 1950s (Wickett 1954) and early 60s (Terhune 1958) involving some type of dye or salinity dilution detection via a standpipe inserted into the gravel matrix, thus enabling direct

field measurements. Some promising progress was made in the 80s that evaluated the use of thermistors to detect and relate intragravel thermal gradients to apparent velocities, but no commercially available meters to monitor such have been forthcoming. A recent study by Zimmermann and Lapointe (in review) seems to have revitalized the hot-wire concept for measuring intergravel velocities. In their study, a hot-wire sensor was installed within an artificial redd and intragravel velocities were monitored continuously over a five month period. We believe apparent velocity remains one of the best metrics for gauging the suitability of the intragravel environment to promote egg survival, provided suitable field measurement techniques are applied to quantify intragravel velocities proximal to egg pockets.

The actual limiting factor in the successful development of embryos is intragravel dissolved oxygen, DO. Early measurement techniques involved either removal of a water sample from the intragravel environment and chemical analysis of DO, or insertion of a DO probe into the matrix via a standpipe. More recent advances include placement of DO monitors in the intragravel matrix to provide detailed measurements over varying periods of time. We consider intragravel DO to be complementary to apparent velocity and recommend the two be measured coincidentally.

A third key metric for STE is permeability, the ability of substrate particles to transmit water per unit of time. Wickett (1954), Pollard (1955), and Terhune (1958) were some of the earliest researchers to document the importance of permeability on embryo incubation. Field measurement techniques generally involve insertion of a standpipe into the gravel matrix and then pumping and quantifying the amount of water extracted over a specified time. Although permeability has been related to embryo survival (Chapman and McLeod 1987), direct measurements in the field can be highly variable due to the heterogeneous nature of the substrates. In addition, linking field measurements to predictions of embryo survival can be tenuous (as noted by Chapman and McLeod 1987), since measurement locations may not reflect conditions within the egg pocket. Nevertheless, we believe permeability remains one of the more field quantifiable metrics and one that should be considered for monitoring purposes.

An additional metric is measurements of pore water turbidity. This approach was mentioned at the R³ workshop by Matt Brown (USFWS) and generally consists of taking measurements of porewater at various depth intervals. We are unfamiliar with specific techniques available to assess pore water turbidity, but based on the discussion at the workshop believe further consideration of this technique is warranted.

6.4.2. Knowledge Gaps

Although much is known about what comprises the intragravel environment, standardization and modernization of field measurement techniques is needed. We subscribe to the premise of Kondolf (2000a) that there is no single metric to characterize gravel quality or to assess embryo survival. Researchers should consider a variety of metrics including those listed here. See Chapter 8 for further discussion on measurement and monitoring.

6.5. Does gravel augmentation preferentially help hatchery vs wild fish?

Gravel augmentation projects typically focus on increasing the amount of spawning habitat for “target” salmonid species, with no or little distinction as to whether the end-users are of hatchery or of wild origin. This is an issue in the era of Endangered Species Act (ESA) listings. We believe that the potential for gravel augmentation projects to negatively impact wild or native stocks, including ESA-listed species, in favor of hatchery stocks, should be evaluated.

6.5.1. Available Science

There have been a number of reports and studies that highlight differences between hatchery and wild salmonids (NRC 1996), but most have focused on interactions of juvenile fish (e.g., McMichael et al. 1999) rather than adult spawners. However, one can postulate that because of behavioral differences there may be circumstances under which gravel augmentation could prove more favorable to hatchery versus wild fish.

For example, it is possible that hatchery fish may be less selective than native salmonids in their use of spawning areas and therefore more likely to use newly placed gravels. Utter (2003) presumed that introduced fish (i.e. non-native) lack the detailed local adaptations particular to native populations such as maturation schedules, routes and timing of migrations, stamina, temperature tolerance, and disease resistance. We believe it equally possible that hatchery fish may be less selective in use of habitat features including spawning areas. This could include, for example, little if any sensitivity to gravel odors or requirements of “aging” or “seasoning” of newly placed gravels. Likewise, object cover may not factor into selection of spawning locations by hatchery fish. The implications relative to gravel augmentation projects are that those that are directed toward native species enhancement in systems supporting mixed stock (hatchery and native) populations could be inadvertently favoring hatchery fish. Further analysis of this is warranted.

Another aspect of gravel augmentation projects that could preferentially support hatchery fish is project location. Gravel supplementation that occurs downstream from a hatchery would more likely be used by hatchery fish than gravel placed above a hatchery. Hatchery fish are cueing in on the odors imparted by hatchery waters and are therefore likely to concentrate downstream from and adjacent to the hatchery facility. Gravel augmentation below a hatchery will thus likely be used more by hatchery fish than wild-native fish that tend to use upper segments of a watershed.

A third factor that could preferentially favor hatchery fish is that they are simply more abundant. Sheer numbers of hatchery fish using new gravels may displace wild fish to other areas. This could result from spawning behavioral differences associated with territoriality and redd spatial requirements, which we presume would be much lower in hatchery fish. In this case, the addition of gravel in systems supporting large runs of hatchery fish may provide little benefit to native stocks.

A final factor that might result in conditions that favor hatchery fish over wild fish in gravel augmentation projects is the timing of implementation. Hatchery and wild fish likely spawn at different times. Depending on when new gravel was introduced, the differences in

spawning periods may concentrate spawning within a specific area that is repeatedly used, predisposing redds to superimposition; this would negatively affect whichever stock spawned first, wild or hatchery.

6.5.2. *Knowledge Gaps*

There is relatively little known about this topic, as evidenced by the speculative nature of the discussion above. Although we have mentioned several instances where hatchery fish could potentially benefit from gravel augmentation more than native fish, in reality it is difficult to envision situations where native fish would be directly harmed. One of the central questions here is whether there are distinct differences between spawning area preferences of wild vs hatchery fish. If yes, then project designs should consider those in relation to the overall objectives of gravel supplementation.

However, rather than recommend specific studies to address this, we believe this could be evaluated as part of a monitoring and adaptive management framework of future and/or existing projects relative to stock usage. Importantly, this approach is consistent with Miller and Kapuscinski's (2003) recommendations relative to hatchery supplementation programs in general, in that programs should be considered as adaptive management experiments, with careful attention to monitoring and re-evaluation of goals and protocols.

6.6. **Can gravel be too clean?**

Regardless of the source of material (e.g., pit-run, off-site supply), a common practice in gravel augmentation projects is to clean or pre-wash the gravels prior to placement in the stream. This practice was developed to comply with state water quality objectives designed to prevent short-term turbidity issues, and, in some areas, mercury contamination. In addition, by removing the "fine sediment",⁴ the gravels presumably will provide a higher embryo survival to fry emergence rate; studies have shown that high percentages (> 10-15%) of fine sediments in gravels can reduce survival to emergence (McCuddin 1977, Koski 1966, Chapman 1988). Although the pre-wash practice can be viewed as successfully addressing regulatory compliance issues, there have been no studies that we know of documenting the biological benefits of, and therefore the need for, pre-washing gravels of all fine sediments. In fact, there may even be some unforeseen negative effects of using gravels that are too clean, among them project cost. We focus here on the ecological effects of gravel cleaning.

6.6.1. *Available Science*

Given that the preponderance of literature points to negative impacts of fine sediment on stream ecology (Waters 1995), the possibility that gravel may be "too clean" and thus negatively impact salmonid STE seems contradictory. However, there are potential negative ecological effects from overly clean gravel. One potential problem is that clean gravel may promote sediment intrusion at depth (See Section 5.6). Having some sediment in gravels may serve as a barrier or filter for finer sediments, thereby reducing the amounts reaching incubating embryos. By contrast, gravels with no or low amounts of sediments within the

⁴ Fine sediment as defined in this section are materials < 0.84 mm diameter.

framework may actually have a higher rate of fine sediment deposition at depth, essentially filling the matrix from the bottom up.

Another potential problem may be agitation of embryos during their “tender” period. Overly clean gravel has high permeability, which may allow relatively high intragravel velocities within the void areas of the gravel matrix. In natural redds, deposited eggs settle within and are supported by the combined mixture of gravels and coarse and fine sediments. Such materials provide a stable framework within which the embryos are protected throughout the incubation period. Salmonid eggs typically undergo an extremely tender period in their embryogenesis commencing about 24 hours after fertilization and water hardening up to the point when eye-spots first become visible (Leitritz and Lewis 1976). During this period, it is especially important for embryos to remain stationary and undisturbed. Overly clean gravels may actually create a redd environment where the potential benefits of higher intragravel flow velocities are offset by the resulting agitation of the early developing embryos (due to the absence of the fine and coarse sediment fraction in the supplemented gravels), resulting in increased mortality. This effect could be heightened in areas of high spawner density, where redd construction activity in one location may disturb the embryo-laden sediment-free gravel matrix in adjacent areas resulting in increased embryo mortality. We postulate that retention of some fine and coarse sediment fractions in these gravels could serve to dampen the effects of such agitation.

A third issue could be increased susceptibility to desiccation if the gravels are dewatered. Studies have shown that in redds periodically exposed to dewatering, as may result from hydroelectric peaking or load following operations, survival of incubating embryos depends on the residual moisture content of the exposed gravels. Becker et al. (1982) and Reiser and White (1981) demonstrated that higher embryo survivals occurred in redds containing some fine and coarse sediments versus those that were relatively clean and porous. This may not be a consideration for most gravel augmentation projects, which presumably are not located in areas with large flow fluctuations.

Notwithstanding these potential negative impacts, there is the fact that even the cleanest gravels will, with time, trend toward a sediment level that is in equilibrium with the watershed and geologic characteristics. Studies by Wickett (1958), Carling and McCahon (1987), and others have shown that gravel cleaning by fish during the redd construction process is transitory and that gravel quality returns to ambient conditions within several months. The same process would presumably occur with gravel augmentation projects.

6.6.2. Knowledge Gaps

We know of no studies that have directly tested the hypothesis that gravel cleaning prior to supplementation is biologically beneficial, or conversely, is detrimental under some circumstances. However, as described in Section 5.6, gravel cleaning to reduce levels of mercury in certain source sediments such as dredger tailings has been shown to be effective because of the strong relation between mercury and fine sediments < 2 mm (Stillwater Sciences 2004). A recent Stillwater Sciences study (2004) confirmed the benefit of size selective sorting as a means of reducing future mercury loading to the San Francisco Bay-Delta, although washing after sorting had no measurable effect on mercury leached from the exterior surfaces of gravel sizes commonly selected for gravel augmentation.

As long as cleaning represents a substantial cost to gravel augmentation projects, we believe further study is warranted. Perhaps a series of paired tests of “clean” versus “pit-run” gravels could be conducted within the same system to test biological responses and benefits to each. It may be that the overall benefits of clean gravels are fleeting, so long as mercury contamination is a non-issue, and that more consideration should be given to changing the regulations that mandate gravel cleaning.

6.7. What short-term negative impacts to fish occur as a result of augmentation?

If the short-term negative impacts of gravel augmentation on fish populations outweigh any longer-term benefits, the justification for gravel augmentation projects will be very much in question. The general issue of short-term negative impacts of gravel augmentation is also important from a purely regulatory perspective because water quality regulations without strong connections to biological consequences can determine the feasibility of augmentation projects. Regulators might de-emphasize short-term impacts where they cause no lasting harm in the context of the project's predicted long-term benefits, or demand strict adherence to specific regulations (e.g., turbidity increases limited to 20% above short-term background levels) that could preclude most gravel augmentation projects.

We focus in this section on the effects of elevated turbidity and the creation of unstable spawning gravels downstream of augmentation projects because these seem the most likely short-term effects of gravel augmentation projects on fish.

6.7.1. Available Science

A large body of literature addresses the effects of elevated turbidity on various aspects of fish biology. In general, this work focuses on physiology and the performance of individuals rather than populations. While gravel augmentation activities are unlikely to elevate suspended sediment to levels lethal to fish, a variety of sub-lethal effects are possible (Newcombe and MacDonald 1991), including: impaired respiration (Berg and Northcote 1985), increased physiological stress (Redding et al. 1987), and reduced feeding success via reduced reactive distance (the distance at which fish first detect food items; e.g., Barrett et al. 1992, Sweka and Hartman 2001a). These proximate effects may have consequences for fish growth. For example, the duration of moderate daily turbidity pulses (0 - 6 h, mean turbidity = 23 NTU) linearly and significantly reduced trout growth (as change in length or ln[mass]) in artificial stream channels (Shaw and Richardson 2001). This experiment suggested that direct effects on the fish (reduced prey capture efficiency and possibly physiological stress) were the main mechanisms driving the reductions in trout growth. In fact, the abundance of invertebrate prey in the channels was positively related to the duration of turbidity pulses.

Fish behavioral responses to elevated turbidity may also be relevant to gravel augmentation projects. Coho salmon avoided turbidities > 70 NTU in laboratory channels (Bisson and Bilby 1982), but did not respond detectably to levels of turbidity lower than 70 NTU. Other studies have shown that salmonids respond to moderate turbidity by increasing activity levels and reducing predator avoidance behavior (Gradall and Swenson 1982, Gregory 1993). At

least one field study supports the hypothesis that turbidity can lower predation risk (Gregory and Levings 1998).

Under some conditions, the tendency for fish to reduce predator avoidance behaviors under moderate turbidity conditions may offset the negative effect of turbidity on visual prey detection. In aquaria, juvenile chinook salmon tended to increase foraging rates under moderate turbidity (18 - 150 NTU) compared with either lower (<1 NTU) or higher (370 - 810 NTU) turbidity levels (Gregory 1994), although in several combinations of prey types and individual fish, prey capture rate declined monotonically with increasing turbidity, but often not until turbidity reached about 150 NTU. These and similar results (Rowe et al. 2003) indicate that non-visual prey detection may be relatively efficient in some settings, perhaps lessening the importance of the negative effect of turbidity on visual detection of prey.

In addition to generating turbidity, the short-term consequences of gravel augmentation projects might also include an increase in the availability of unstable spawning gravels. For example, if fish ready to spawn arrive at a site before streamflows have initially distributed the added gravel, they may encounter unstable spawning sites with appropriate depth, water velocity, and intragravel flow characteristics. Unstable spawning sites could negatively affect salmonid populations if redds are scoured before young emerge from the gravel. Adult salmon are subject to digging redds on unstable sites: redds of free-ranging chinook salmon in Klamath River tributaries placed on dredge tailings suffered significantly greater scour than redds on natural substratum (Harvey and Lisle 1999). One relevant issue here is the proportion of redds located on unstable sites. Because gravel augmentation projects are often proposed specifically to ameliorate a shortage of spawning gravel, one might predict that the proportional use of newly created gravel patches would be high, meaning their initial stability could be very important.

6.7.2. Knowledge Gaps

Based on existing information, it is not yet possible to determine whether short-term consequences of gravel augmentation outweigh potential long-term benefits. The apparent conflict between successful feeding by salmonids under high turbidity conditions in laboratory settings and observations of lower growth when subjected to relatively short pulses of modest turbidity in physically-simple streamside channels suggests that a better understanding is needed of the effects of turbidity on feeding success in natural channels. To the extent natural channels provide complex hydraulic conditions that might allow fish to use non-visual prey detection methods, the significance of elevated turbidity could be reduced. However, this scenario is probably least applicable to taxa such as chinook salmon, which focus on surface and drifting prey.

Given the ability to predict the consequences of elevated turbidity on fish survival and growth in natural channels, methods are needed to translate these effects on individuals into their consequences for populations. Incorporating any positive effect of elevated turbidity on survival (through reduced predation risk) is an added challenge in estimating the effects on populations. More empirical data on this linkage would be particularly valuable.

It is also worth considering the possibility of potential long-term negative impacts of gravel augmentation on biological, physical and/or chemical processes, because history is replete with examples of well-intended restoration efforts and interventions that have resulted in unforeseen and sometimes catastrophic consequences. Careful consideration should be given in the planning stages of gravel augmentation projects to potentially negative, unintended effects. Questions should include: what are the short and long-term construction impacts on existing biota (e.g., turbidity and habitat alterations described above)? Will gravel augmentation promote non-native fish proliferation? Will gravel augmentation destabilize the channel? What are the likely effects on other habitat features (e.g., reduction of rearing and holding habitats)?

6.8. Can gravel augmentation improve non-spawning habitats?

The goal of most gravel augmentation projects is to increase the area of usable spawning habitat for anadromous salmon, based on the assumption that spawning habitat is a limiting factor to salmon stock recovery. This is, however, not always the case (e.g., Clear Creek). Moreover, identifying limiting factors is problematic because of the complex nature of anadromous fish production, its linkages with watershed processes, and the importance of ocean conditions. In light of this, projects aiming to go beyond spawning habitat enhancement to restore additional habitats (e.g., juvenile rearing habitat, riparian habitat) and channel processes that together contribute to overall ecosystem function may have a greater likelihood for long-term success. It remains uncertain, however, what role gravel augmentation may play in improving non-spawning habitats.

6.8.1. Available Science

Gravel augmentation has the potential to improve non-spawning habitats given the extreme sediment-starved conditions of most regulated rivers. For example, increased gravel supply may increase (1) rearing habitat for anadromous fish, (2) habitats supporting resident non-salmonid fish species, (3) habitat for benthic invertebrates, which are an important food source for fish, as well as (4) riparian habitat for non-aquatic species, which also contributes terrestrial insects and wood to the channel. Such improvements will mostly be accomplished through the reestablishment of natural channel processes such as channel migration and the development of more complex channel features (e.g., gravel bars, side channels). Increased lateral channel migration can in turn increase floodplain-side channel-scour channel formation, thus improving riparian vegetation recruitment and expanding the zone of riparian habitat. Complex channel features increase the variety of habitats available to fish and other aquatic animals, providing a range of depth and velocity characteristics and zones of physical cover and hydraulic refugia (further discussed in Section 5.2). Increased gravel supply also will serve to rework and replenish bed sediments during high flow events, possibly mobilizing the underlying armored bed surface.

However, improvements to non-spawning habitats through gravel augmentation are contingent on a complex array of factors, in particular the geomorphic setting and contemporary regimes of water and sediment delivery to the channel. Ignoring these factors has been put forward as the primary reason for the failure of many previous restoration initiatives (Kondolf et al. 1996). Guidelines set forth by Kondolf (2000b) for evaluating

restoration project proposals are useful in this context, and are relevant to gravel augmentation proposals as well. These guidelines include giving due consideration to (1) the geomorphic setting at the watershed scale; (2) the natural and modified flow regime; (3) an accurate sediment budget to place the site in a larger context of sediment sources, supply, and transport; (4) large woody debris sources and supply; (5) channel form; (6) spawning gravel quality; (7) bed mobility; (8) intragravel flow through redds; and (9) bank, floodplain, and terrace vegetation.

A common problem with gravel augmentation projects is that the added material is soon blown out by high flow events, traveling either downstream and out of the reach, or laterally onto high elevation floodplain surfaces. So long as the material is unavailable to the active channel for reworking and distribution, habitat improvement cannot occur. The often short-lived benefit of gravel augmentation led Wheaton et al. (2004a) to recommend that “passive” gravel augmentation strategies be employed in conjunction with “active” approaches such as hydraulic structure placement in order to increase the residence time of the gravel and help stabilize the newly formed habitat. Hydraulic structure placement also can be effective for increasing hydraulic and structural complexity, which supports a wider range of species and life stages.

The generally shortened residence time of added material in many regulated rivers is attributed to flow regulation for flood management, but also to channel straightening and confinement by levees and bank revetments. As a result, both water and sediment move through the system faster and sediment retention time is consequentially reduced. Levees, coupled with reduced hydrologic variability, eliminate sediment storage and erosion on floodplains and inhibit sediment storage within and adjacent to the channel. They constrain channel dynamics and habitat development, and also reduce the residence time of nutrients. Gravel augmentation in highly constrained systems with high conveyance is thus not likely to make significant improvements to non-spawning habitat no matter how it is placed, unless the influence of such reach- and basin-scale constraints is somehow reduced.

6.8.2. Knowledge Gaps

Despite the interest in restoring more than just spawning habitat for salmon in California’s rivers, it remains unclear what specific habitat types are in need of enhancement. What other alluvial habitats are ecologically significant and desirable for enhancement, or are limiting to other salmonid life stages or species of concern? Explicitly identifying such habitats of interest is the first, and necessary, step.

Once limiting critical habitats are identified, other than those for salmon spawning, it is then worth asking questions such as: can gravel augmentation create secondary ecological benefits for non-salmonid species? Does gravel augmentation lead to increased side channel-floodplain formation, thus increasing channel complexity and improving riparian vegetation recruitment within the floodplain?

Finally, lack of long-term monitoring has prevented us from learning about the effects of gravel augmentation projects on sediment storage and transport rates, routing pathways, channel form response, and habitat development. Where does injected gravel go? Does it preferentially fill in pools, thereby further degrading habitat, or does it form spawning and

rearing habitats used by salmon (see Section 5.2)? Answers to these questions will better allow us to answer the question of whether gravel augmentation improves non-spawning habitat. A long-term commitment to monitoring gravel augmentation projects would help address this knowledge gap because processes of habitat development and channel adjustment are slow and dependent on geomorphically-effective floods to initiate channel change.

6.9. What are the population-level benefits of gravel augmentation for salmonids?

Where gravel augmentation is motivated primarily or substantially to benefit salmon populations, the ability to predict the impacts of gravel augmentation at the population level is critical. Unfortunately, to our knowledge there are no available examples that demonstrate the successful prediction of changes in fish populations in response to specific restoration activities, such as gravel augmentation. In addition to determining whether a given management action is likely to be beneficial at a meaningful scale or organization, tools to predict population-level responses to management activities are essential for setting priorities. For example, even where certainty is high that gravel augmentation will increase the number of fry produced by a given number of spawning adults, it would be highly desirable to be able to forecast how such a benefit would compare to other management alternatives (e.g., increased water releases), or ideally to forecast what combination of management activities would yield the greatest population-level benefit for a given expenditure of resources.

6.9.1. Available Science

The issue of forecasting the effects of gravel augmentation at the population level provides a specific example of the basic challenge of ecology -- to understand the distribution and abundance of animals -- and necessarily raises one of the most fundamental general issues in ecology: the degree to which density-dependent processes determine population size.

Because most salmonid populations are small compared to historic levels, research and management on these populations often assumes that density-dependent processes (those which tend to be associated with habitat quantity [Moussalli and Hilborn 1986]) are currently irrelevant in determining population size. Further, some recent analyses of time-series data of Pacific salmon abundance have failed to detect evidence for density-dependence (Kareiva et al. 2000), although additional research highlights the challenges of using this method (Zabel and Levin 2002). Focusing strictly on density-independent processes (those which tend to be associated with habitat quality [Moussalli and Hilborn 1986]), McHugh et al. (2004) recently provided a model of egg-to-smolt survival rate for Snake River chinook salmon as a function of five physical habitat variables: percent fines in spawning gravels, water temperature during incubation, riffle embeddedness, water temperature during parr rearing, and pool cobble embeddedness. The authors used empirical relationships between fish survival and the habitat variables established by existing research, and assumed independence among the univariate relationships with separate habitat variables. This approach garnered reasonable support in an analysis of chinook salmon survival in six Idaho streams (McHugh et al. 2004), although support was limited by the small number of observations. The focus on survival to emigration from spawning streams yields a relatively

tractable challenge that produces results with meaning for population modeling, and allows forecasting of changes in survival in response to various habitat changes.

However, evidence of density-dependence in salmon populations indicates that purely density-independent models cannot be applied universally. Interestingly, recent evidence for such density-dependence comes from tributaries of the Snake River supporting chinook salmon, in the form of density-dependent survival of juveniles (Achord et al. 2003). Achord et al. (2003) hypothesize that the density-dependence they document may result from greatly reduced salmon population sizes and the resulting loss of nutrients provided by adult salmon carcasses. Speed and Ligon (unpublished manuscript) provide another example of density-dependence with special relevance for gravel augmentation projects: Tuolumne River data provide strong evidence for density-dependence in spawning success driven by superimposition of chinook salmon redds. This mechanism leads to an overcompensatory Ricker relationship between spawners and recruits, in which the number of recruits peaks at a number of spawners well below the maximum observed. The influence of migration barriers such as dams on the probability of significant superimposition indicates that superimposition could be an important issue throughout the Sacramento -- San Joaquin Drainage, although the process may influence salmonid population dynamics in a wide variety of systems (e.g., Essington et al. 1998).

Available modeling methods allow incorporation of density-dependence at various life stages and analysis of alternative restoration scenarios. Greene and Beechie (2004) provide a recent example with a series of matrix models for chinook salmon. Ellner and Fieberg (2003) offer methods to evaluate the sources of uncertainty in such model forecasts. The models constructed by Greene and Beechie (2004) are necessarily general, in part because parameterization of the models requires the use of estimates of demographic rates from a variety of widespread sources, and habitat-specific estimates of density-dependent parameters are not available. One of Greene and Beechie's conclusions is that improvements in population size from freshwater habitat restoration will depend on specific mechanisms of density-dependence and whether restoration alters habitat quality or quantity.

Speed and Ligon (unpublished manuscript) offer a stock-recruitment-based model of chinook salmon population dynamics in the San Joaquin River system that utilizes extensive site-specific data, including the observed density-dependent relationship between spawners and recruits described above. Their approach, which parallels one described by Paulik (1973), also incorporates the influence of environmental conditions on annual variation in the stock-recruitment relationship. The Speed and Ligon approach allows forecasting of population responses to management alternatives by estimating how the alternatives will alter the shape and/or scale of the stock-recruitment relationship. The authors used this approach to forecast the consequences of using barriers to distribute spawners, of increasing survival of embryos to emergence by improving gravel quality, and of reducing environmentally-influenced density-independent mortality (perhaps through higher spring flows with enhanced turbidity). This work suggests in part that improving gravel quality would probably be the least valuable individual management action.

Individual-based models (IBMs) also show promise in linking habitat conditions and population dynamics. The basic IBM approach is to build a model of an individual organism, build a model of the environment, then simulate the interactions of the individuals with each

other and the environment. Patterns at the population level, such as density-dependent survival and growth, can emerge from these interactions (e.g., Railsback et al. 2002). Spatially explicit individual-based models are available for resident trout populations (Railsback and Harvey 2001), but to our knowledge they have not been applied to the entire lifecycle of anadromous salmonids.

6.9.2. *Knowledge Gaps*

Forecasting the population-level consequences for fish of habitat changes such as gravel augmentation offers a challenge critical to resource management that is not supported by a large body of research. Historically, population modeling and fish-habitat relationships have been treated largely as separate issues. Several current approaches show promise in linking population dynamics and habitat characteristics, but it is not yet clear how accurate their predictions are. Broader efforts to apply these approaches will speed the determination of their utility. Sensitivity analyses with these developing models will be useful in identifying critical knowledge gaps, but clearly better understanding of habitat specific demographic rates and density-dependent processes are urgently needed.

The fundamental structure of spatially explicit individual-based models is well suited for linking habitat features and biotic processes that determine population dynamics. Because these models can be applied to portions of the salmonid lifecycle, the ability to integrate individual-based models with those focused on higher levels of organization (e.g., stock-recruitment type models) will probably prove valuable.

6.10. **Can benthic invertebrates be used as an indicator of spawning habitat quality?**

Benthic macroinvertebrate assemblages are widely used as a measure of the condition of aquatic systems. The relatively easy, rapid, and effective means by which invertebrates can be sampled makes them an appealing potential alternative biological indicator for gauging the success of gravel augmentation projects. The use of benthic invertebrates to assess enhancement or restoration projects is a relatively new research frontier and available studies (Merz and Ochikubo Chan 2004, Ochikubo Chan et al. in prep) suggest that benthic invertebrate community structure may be used as a reliable indicator of spawning habitat quality. If so, benthic invertebrate assessments may represent a reliable surrogate indicator of habitat quality that is less prone to problems of environmental variability and sampling bias than alternative measures specific to anadromous salmon.

6.10.1. *Available Science*

Invertebrates are more convenient for study than fish because they are less mobile, ubiquitous in geographic distribution, highly abundant, and demonstrate a broad range of tolerances to environmental conditions (e.g., chemical pollution, suspended sediment, bed sediment size composition, near-bed velocity). Invertebrates also respond on a convenient time-scale for assessing gravel augmentation projects due to their life cycle (usually one year), unlike fish with a relatively long life cycle, or algal composition that can change in a matter of days. An added advantage to invertebrates is that while anadromous salmon are affected by environmental conditions over a large spatial area and across several aquatic environments, invertebrates carry out their short life cycle within a relatively small area.

Hence, the species assemblage and abundances of invertebrates at a particular site are highly reflective of site conditions (Richardson and Jackson 2002).

The use of particular species or invertebrate community structure as indicators of the condition of aquatic systems has exploded in the last decade (e.g., Taniguchi and Tokeshi 2004). One of the first and most widely used approaches is *RIVPACS* (**R**iver **I**nvertebrate **P**rediction and **C**lassification **S**ystem), which was developed in the UK to assess biological quality of rivers and streams (Clarke et al. 2003). Equivalent software packages have been developed in other countries (e.g., Australia).

The generic RIVPACS-type approach is termed the '*reference condition method*', which uses minimally disturbed sites as predictors of the expected invertebrate community at test sites. The reference approach has been adopted for biomonitoring in several regions of North America including the Fraser River basin in British Columbia (Reece et al. 2001, Reynoldson et al. 2001), and is favored by some resource agencies in California (particularly the U.S. Forest Service).

Alternatively, there are benthic indices that have been developed for particular regions, the majority of which are multimetric in nature and referred to as '*Biotic Indices of Biotic Integrity*', B-IBI' (e.g., Engle et al. 1994). Although both the reference condition approach and B-IBI typically are applied in impact assessment (e.g., water quality degradation from industrial pollution or heavy metal contamination), they should be equally effective for gauging the positive benefits of habitat rehabilitation and gravel augmentation projects.

The basis of the B-IBI approach is that the additive or synergistic effects of multiple stressors (pollution, habitat degradation) or habitat changes (gravel augmentation) are reflected in changes in taxonomic composition and structure of the stream invertebrate community. Particular benthic metrics (e.g., density, diversity) are chosen based on their predictable relation to measures of such habitat changes. Ideal metrics also are relatively easy to measure and interpret, are sensitive to a range of biological stresses, and can discriminate between impacts and the background "noise" of natural variation. Resh and Jackson (1993) provide an extensive list of single metrics used in bioassessment. In a multimetric approach to biological assessment, the metrics that exhibit the strongest response to human-caused impacts are combined into a single score, the Index of Biotic Integrity. Typically, multiple metrics combined in a multivariate model provide the greatest predictive power.

The appeal of B-IBI is the provision of a simple numerical representation of the "condition" of the system, with obvious advantages to regulatory personnel. The federal EPA Rapid Bioassessment Protocols for use in streams for periphyton, benthic invertebrates, and fish are an extension of the B-IBI approach (Cooper 1965). Harrington (1999) describes the current bioassessment procedures for California streams, which are an adaptation of the EPA standards.

As mentioned above, preliminary results from Ochikubo Chan and colleagues (Merz and Ochikubo Chan 2004, Ochikubo Chan et al. in prep) show promise for the use of benthic invertebrates as indicators of spawning habitat quality. Based on a two-year sampling period,

both mean invertebrate density and mean invertebrate dry biomass were correlated with the density of naturally spawned chinook salmon redds in the Mokelumne River.

6.10.2. *Knowledge Gaps*

The main knowledge gap is whether or not a predictable index of spawning habitat quality can be developed based on benthic invertebrate community structure (a “Benthic Index of Spawning Habitat Quality”). Such an index should be robust across a wide region. Commitment to a research program would be required to identify the particular benthic metrics (e.g., various measures of diversity, biomass, density, relative taxonomic abundances) that most consistently predict spawning habitat quality. One goal would be to develop an invertebrate-based assessment procedure to evaluate the success of spawning riffle and habitat creation by gravel augmentation.

6.11. **What factors influence the use of gravel by benthic invertebrates?**

Implicit in most gravel augmentation projects is the goal of broad-scale ecosystem recovery through improvements to physical habitat structure and ecological function. Benthic macroinvertebrates are a critical element in aquatic ecosystems, serving as an important food source for fish and performing multiple ecological roles, such as organic matter processing. Across all stream habitats, they constitute the bulk of species diversity and account for the majority of secondary productivity (Richardson and Jackson 2002). Hence, invertebrate colonization and use of newly injected gravel may strongly affect the success of gravel augmentation projects. Factors influencing the use of gravel by benthic invertebrates are discussed below.

6.11.1. *Available Science*

Much is known about the colonization and use of naturally occurring gravel habitats by invertebrates, and several recent studies also have examined the use of artificially created gravel habitats in streams (e.g., Ebrahimnezhad and Harper 1997, Merz and Ochikubo Chan 2004). Results from relevant studies are summarized here.

- **Substrate Composition.** Gravel and cobble-sized substrate with a rough surface topography creates microhabitats of reduced hydraulic stress for foraging (Holomuzki and Biggs 2003), which serve as refugia from predators (Fuller and Rand 1990) and disturbance events (Gore et al. 1998, Lancaster 1999). Rough bed topography also facilitates the retention of drifting organic matter that is the food-base for invertebrate communities and a necessary precursor to community persistence (Maridet et al. 1995, Kiffney et al. 2000, Negishi and Richardson 2003). The proportion of fine sediment (sand or silt) in the streambed is negatively correlated with invertebrate density and biomass (Wood and Armitage 1997). Sediment porosity and groundwater flow will influence the extent of hyporheic habitat that is used by certain invertebrate species for various life stages (e.g., Capniidae) and as a refuge during flooding (Matthaei et al. 1999).
- **Food Availability.** Population persistence depends on food availability, and invertebrates exploit a variety of food sources including algae and detrital leaf litter. Detritus retention in streams increases with substrate size (Kiffney et al. 2000, Negishi and Richardson 2003), provided a source of leaf litter is available from riparian areas. Intact riparian habitat provides a reliable source of organic matter, as well as woody

debris for instream habitat complexity, and shade to regulate water temperature. Algae and aquatic plants are exploited by many invertebrate taxa, and have been shown to establish rapidly on newly placed gravel where habitat conditions and water quality are suitable (Merz and Ochikubo Chan 2004).

- **Water Velocity.** Aquatic invertebrates are highly adapted to flowing water and use many strategies to persist, including behavioral (burrowing, streamlining, swimming) and morphological adaptations (hooks, claws, suckers, silk threads, dorso-ventral flattening). Hence, velocity itself is not a limiting factor for invertebrate colonization and the use of stream habitats. On the contrary, species diversity is positively correlated with velocity (Lake 2000), and riffles typically support the highest invertebrate biomass, density, and diversity (Richardson and Jackson 2002). Ebrahimnezhad and Harper (1997) found that species diversity associated with artificial riffles was negatively correlated with water depth (depths ranging from 10 to 70 cm) but positively correlated with velocity (15 to 60 cm/s).
- **Flow Regime.** Invertebrates respond to flooding by moving to less hydraulically stressful habitats or they risk accidental dislodgement and mortality. Hence, resilience to flood disturbance depends on habitat complexity and the provision of refuge from floods. Invertebrates may take refuge amongst sheltered refugia within the channel (under woody debris, large boulders, stable rock clusters; Lancaster 1999), burrow deep into the substrate (Matthaei et al. 1999), or migrate to shallow, newly inundated floodplain habitat during high flows (Rempel et al. 1999). Similar strategies are used to avoid desiccation during periods of low flow. The predictability and frequency of flow changes are major determinants of community structure, due to differences in species' resilience to flow disturbance. A flashy flow regime, as may occur with daily hydroelectric peaking, will preferentially select species with good colonization ability (Poff and Ward 1990) and may prohibit other species from establishing.
- **Water Quality.** Water quality is a major determinant of invertebrate community structure due to highly species-specific tolerances. As such, invertebrate community composition is used widely as a biological indicator of site conditions (discussed in Section 6.10) and for detecting impacts from pollution. Impacts to water quality associated with gravel augmentation (e.g., turbidity, mercury contamination) may offset possible benefits to invertebrate production, or lead to an adverse change in community composition that favors invasive or tolerant species.
- **Habitat Structure.** There is a positive relation between habitat heterogeneity in streams and the diversity of aquatic communities (Power 1992, Lancaster and Hildrew 1993, Wallace and Webster 1996, Rempel et al. 2000). Much of the heterogeneity is derived from diversity in flow conditions and substrate types and most evidence points to riffle habitats as the most productive channel unit in streams.
- **Colonization Mechanisms.** Invertebrates are highly successful at colonizing both natural and artificial gravel habitats. The primary mechanism is by drift (Ciborowski 1983, Mackay 1992); studies report rapid colonization (within hours) of newly inundated habitats in gravel-bed streams (Ebrahimnezhad and Harper 1997, Rempel and Church 2003, Merz and Ochikubo Chan 2004). In one study, community structure and abundance was similar to reference sites as early as 6 weeks post gravel augmentation (Merz and Ochikubo Chan 2004).

6.11.2. Knowledge Gaps

Despite the relatively large number of studies on factors influencing the use of gravel habitat by macroinvertebrates, several knowledge gaps remain.

First, it is not yet known whether community structure associated with artificial riffles is similar to natural sites, or if gravel enhancement projects favor particular species. “Weedy” species that are particularly mobile and with good swimming ability often arrive first at newly created riffles (e.g., *Baetis* sp.) whereas others are slower to disperse (e.g., *Chelifera* sp.). If particular species are favored, are they of biological importance and perhaps representing an important food source for fish species of interest (therefore yielding a net benefit), or are they “unfavorable” and perhaps outcompeting species of higher food value?

Second, does gravel augmentation have any benefits for productivity? Does newly injected gravel increase reach-scale productivity by creating additional habitat for invertebrate production? Or are colonizing invertebrates relocating from unenhanced sites and therefore not increasing stream production?

Does gravel augmentation create temporary or long-term benefits? Merz and Ochikuo Chan (2004) showed higher invertebrate density and biomass at newly injected gravel sites compared to unenhanced sites, but also indicated that benefits may only be temporary because of the transient nature of injected gravel deposits in most streams. Are there adverse long-term effects of gravel augmentation to invertebrate production or community structure?

An additional uncertainty is whether there is an available upstream source population from which sites may be colonized. Dams are barriers to the downstream dispersal of invertebrates, and also alter the sediment budget and natural variability of flow regimes. These physical changes may restrict the distribution, dispersal, and persistence of species in stream reaches, and may override any positive effects of small-scale gravel augmentation on invertebrate production. However, where gravel augmentation causes changes in a relatively small proportion of the streambed, rapid colonization of “new” substrate would be expected (Mackay 1992).

Chapter 7. Additional Knowledge Gaps

In Chapters 5 and 6, we discussed many of the key scientific uncertainties or knowledge gaps that limit our ability to effectively design and evaluate gravel augmentation projects. In this chapter, we focus on questions critical to the science and practice of gravel augmentation that have not yet been addressed in this report. For the most part, these are over-arching questions that will require a strategic approach integrating efforts across disciplines, projects, and research studies. Several of these uncertainties were discussed at the R³ Workshop:

7.1. **What are the quantitative linkages among gravel augmentation, fluvial processes and form, habitat for aquatic animals of special concern, and the population dynamics of those animals?**

Conceptual models have done a reasonable job of describing qualitative linkages between gravel augmentation and habitat improvements (see Chapter 3), yet few studies have made quantitative linkages. It is accepted that adding gravel and increasing high flows in certain combinations will modify channel morphology, but whether the modified channel offers more favorable habitat for spawning and rearing, and whether more favorable fish habitat translates to increased biological production remains uncertain. Given the large cost and imposition on human infrastructure, arguments to improve geomorphic processes and form based on qualitative relationships to biology may be insufficient to convince society to invest in this approach without more quantitative evidence.

7.2. **How far can river channels be scaled down and still retain critical habitat functions?**

Although detailed consideration of other restoration techniques is beyond the scope of this report, gravel augmentation is likely to be most effective when used in concert with strategies such as environmental high flow releases, flood control releases, and channel downscaling (structural alterations of channel cross-section and planform geometry towards expected future dimensions for the prevailing high flow regime). Channel attributes that could potentially be manipulated as part of downscaling include width, roughness, sinuosity, slope, bankful depth, as well as gravel supply and particle grain size. However, we do not know how much a channel can be downscaled before it loses critical ecosystem functions. For example, there are practical limits to how much bed grain size can be reduced and still provide spawning habitat. Similarly, because the total elevation drop in a river cannot be changed, increases in channel slope in one place must be compensated for by reductions in slope elsewhere. There is an urgent need to quantify the range of potential variation in channel attributes that would still allow significant ecosystem function, including identification of the thresholds and other physical limits on channel downscaling, and the tradeoffs between possibly conflicting ecosystem objectives.

7.3. What are the best available techniques for estimating coarse sediment transport, and how useful are they for management?

Sediment transport through a channel cross-section or reach can be empirically estimated by constructing rating curves from direct measurements using bedload samplers or traps, or by repeat surveys (bathymetric or cross-sectional) to measure topographical change. Each approach has advantages and disadvantages, and neither is clearly preferable for all flow and river conditions. Because bedload motion and transport rates are highly variable in space and time, even moderately precise measurements by direct sampling require significant physical and logistical effort. Moreover, cross-sections most convenient for sampler deployment (e.g. bridges) often do not represent typical, reach-averaged conditions. Transport estimates based on topographical change integrate over longer time periods than direct sampling and thus may be more representative, but they may greatly underestimate transport because not all sediment motion results in detectable changes in bed elevation. Moreover, this approach is sensitive, and limited to the spatial and temporal resolution of available topographic surveys. Several conditions of regulated rivers favor the topographical method for sediment budget estimation: the null sediment input volume below a dam is known, which closes the sediment budget equation, and low flow conditions allow for detailed surveys by LIDAR or ground methods.

Airborne laser swath mapping (LIDAR) potentially offers a source of topographic data of vastly improved density and precision, although data filtering and processing challenges remain. Technological advances in direct flux measurements, such as acoustic sensors and use of transponders, also offer promise. Overall, the critical need at this time is a summary of methodology guidelines for estimating coarse sediment transport under the range of expected conditions in the Central Valley, and guidelines for quantifying the uncertainty in sediment transport estimates.

Numerical modeling can be used in coordination with field data collection to extend and refine field-based estimates of transport. These models continue to improve, but no consensus exists on how, if at all, to use them appropriately for river management. Some practitioners will not apply sediment transport or routing models to management problems, while others perhaps rely too much on modeling accuracy. Sediment transport modeling is a research frontier and still in its infancy. There remains a lack of agreement on the appropriate transport formulae to use, which are likely to be system-dependent, and problems with model calibration because of the lack of accurate field data. A concise summary of the application, accuracy, and precision of applicable models to typical gravel augmentation problems is needed, a process begun by Yantao Cui at the R³ Workshop. (All of the R³ Workshop presentations are available online at: http://science.calwater.ca.gov/workshop/workshop_071304.shtml.)

7.4. How do we define and measure project success?

If a goal of the CALFED Ecosystem Restoration Program is substantial rehabilitation to the form and function of rivers in the Central Valley, how do we measure form and function? What physical or biological criteria can objectively evaluate whether a project has attained

this goal? Is project success defined by substrate characteristics (low proportion of fine sediment, high gravel permeability, scour depth), habitat characteristics (riffle-pool spacing, proportion of riffle habitat, channel geometry), bedload transport, and/or residence time of gravel deposits? Or is there a more appropriate, quantitative measure or set of measures by which project success can be measured?

7.5. Is gravel augmentation sustainable?

Restoring active geomorphic and ecosystem processes downstream of dams by adding gravel to mitigate coarse sediment capture in upstream reservoirs is inherently a never-ending process. If gravel augmentation is to play an increasingly important role in ecosystem restoration in Central Valley rivers in coming decades, the issue of gravel sources must be addressed. Gravel extraction in the Central Valley is predominately from floodplain and terrace pits, and entails significant environmental risks including pit-capture by mainstem channels during floods (Kondolf 1998). Competition for a decreasing gravel supply between restoration practitioners and the commercial gravel industry already occurs and is likely to grow, increasing costs for augmentation materials. Dredger tailings may provide a long-term alternative source of gravel for augmentation projects, with the added benefit that reclamation of tailings sites can provide restoration of floodplain and riparian habitat, but use of unprocessed tailings is accompanied by risks of mercury contamination and turbidity. Ultimately, in the absence of dam removal, the only long-term sustainable sources of gravel are reservoir deposits, because they are formed by the sediments that would be delivered to downstream reaches if the dams did not block their passage. Significant regulatory and technological obstacles will have to be overcome to access these sources.

7.6. What impact will climate change have on stream restoration projects in California?

A last looming challenge is climate change. The most recent and comprehensive study of the impacts of global warming on California (Hayhoe et al. 2004) predicts a dramatic decline in the winter snow pack in the Sierra Nevada and an overall reduction in annual precipitation. These predictions, coupled with continued human population growth, suggest several negative consequences for ecosystem restoration on Central Valley rivers. These include additional stress on ecosystems that cannot adapt rapidly to a warmer climate, changes in the pattern and magnitude of runoff with resulting impacts on flood control releases, less available water and greater costs for environmental flows, and renewed pressure to build more storage dams. Many of these expected consequences of climate change will directly affect the feasibility and impacts of gravel augmentation projects.

Chapter 8. Recommendations

In this chapter we present four categories of recommendations: 1) specific research priorities; 2) large-scale adaptive management experiments; 3) ‘white paper’ reviews of broad topic areas, which summarize what is now known rather than seeking to create new knowledge; and 4) information and coordination activities.

8.1. Priority knowledge gaps to address

We recommend that CALFED solicit and prioritize funding for scientific studies and restoration projects that address the key uncertainties discussed in Chapters 5, 6 and 7, with highest priority given to studies and projects that build our understanding of the linkages between geomorphic processes and ecosystem response. Where project objectives include benefits to salmon, we recommend that priority be given to projects that address population-level consequences. Effective approaches that influence the population level should dictate the highest priorities among more narrowly focused studies. All of the studies and projects that address the key uncertainties listed above should be hypothesis-driven, with clear statements of the hypotheses to be investigated and how the data collected will be used to test them. In addition, we recommend institutionalizing ongoing peer review of these studies and projects to ensure that high standards for scientific rigor are maintained throughout the course of project implementation.

8.2. Adaptive management experiments

Many of the key uncertainties and knowledge gaps identified by workshop participants and discussed in Chapters 5, 6 and 7 will be difficult to address through projects or studies at a single location or implemented by a single investigating institution. An unprecedented opportunity exists for multiple CALFED-supported projects and studies to be designed and implemented in a coordinated way, both within and across drainage basin boundaries and scientific disciplines. The goal would be to implement an experimental design to test specific hypotheses such that each component project alone would cover only a fraction of the range of the independent variable or variables being investigated, but together the full range of possible conditions and responses would be encompassed. A simple example might be to test the hypothesis discussed in Section 5.3, that additions of fine gravel can mobilize a static armored bed. The independent variable might be the ratio of median grain diameter of the added gravel to the median diameter of the pre-existing armor. A number of gravel augmentation projects on several different rivers would together explore the effect of ratios between 0.5 and 0.05. This approach may be the only way to fully test basic science hypotheses in an applied context, because some projects will inevitably ‘fail’ if the independent variables are varied widely enough. In the present example, it may be that only ratios of 0.10 to 0.14 produce the desired effect; obtaining this important result would come at the cost of most of the projects failing to observe a beneficial effect. Taking an adaptive management approach will ensure that the new insight gained can be applied to those

projects with initially poor outcomes, so that the twin goals of advancing the science and restoring ecosystems can ultimately be achieved together.

We recommend that CALFED take a leadership role in selecting scientific questions to address through coordinated adaptive management experiments, assembling teams of investigators, coordinating development of experimental designs, and overseeing project implementation. Ideally, these adaptive management experiments would involve not only field-based investigations but also theoretical, numerical and laboratory components. One way to develop the institutional capacity for large-scale coordinated investigations, both within CALFED and among the recipients of CALFED funding, would be to select one or more reference basins where intensive monitoring and experimental research could take place. Focusing the work of many researchers and restoration practitioners in the same system, and investing in the infrastructure for systematic long-term monitoring, offers perhaps the best opportunity to fully develop and test linked models for how ecosystems respond to rehabilitation of fluvial geomorphic processes.

For example, experiments with gravel augmentation in Clear Creek could provide a coordinated set of studies in a single basin, which might include predictive modeling and corresponding monitoring to evaluate (1) coarse sediment transport rates, routing, and budget, (2) gravel quality improvement, (3) changes in channel dynamics and form, (4) changes in particle size and coarse sediment transport rates, (5) changes in aquatic habitat in alluvial reaches, and (6) coarse sediment transport, routing, and storage in the bedrock canyon reach. Clear Creek has the advantages of being relatively small (improving experimental control), including both a bedrock and an alluvial reach, still experiencing large flood events, and having been the site of large-scale gravel augmentation since 1996. The primary drawback is that the outlet works are too small to permit controlled high flow releases, and that the flood events that do occur are uncontrolled spills through the “glory hole” spillway.

8.3. White papers

Many of the questions posed by the R³ Workshop participants are not scientific unknowns, but their answers are scattered among many different sources. Gravel augmentation practitioners could thus be assisted by selected compilations of information. The panel recommends that CALFED commission several peer-reviewed white papers that present the current state of the science and opportunities for improvements in the following subject areas:

8.3.1. Gravel quality and fry production

Prepare a white paper that summarizes the science of gravel quality as it relates to fry production (e.g., permeability → embryo emergence success), and makes recommendations on monitoring approaches for Central Valley rivers based on particular restoration objectives.

8.3.2. *Role of coarse sediment transport numerical modeling in coarse sediment management*

Prepare a white paper that summarizes the applicability of different modeling approaches based on restoration goals, illustrates reasonable levels of resolution of applicable models, and recommends combinations of modeling and empirical approaches to improve coarse sediment management.

8.3.3. *Gravel sources*

Prepare a white paper on long-term alternative sources of gravel, including a comprehensive inventory of dredge tailings sites and examination of the potential for accessing reservoir deposits or routing sediment around dams.

8.3.4. *Mercury*

Prepare a white paper that summarizes research conducted to date on potential short- and long-term impacts of using dredge tailings for restoration purposes. For each of the several potential uses of dredge tailings, the white paper should make recommendations on processing approaches needed prior to use in Central Valley rivers, including the issue of what to do with residual fine sediments, which may be laden with mercury.

8.3.5. *Ground and bathymetric topography*

Prepare a white paper that evaluates a number of methods for gathering topographic data, including LIDAR, and makes recommendations on which methods are most useful for particular purposes.

8.3.6. *Monitoring Guidelines*

At the R³ Workshop it was clear that while there is consensus that monitoring should be improved, there is no consensus on how to do so. Using standardized approaches to gather and analyze data will facilitate cross-project information sharing and comparative analyses. However, the available techniques are not so advanced that no further innovation is needed. In addition, there needs to be careful matching among the hypotheses, designs and monitoring techniques employed in a particular project. As Jennifer Vick stated in her presentation, one size does not fit all; monitoring approaches should be tailored to the objectives and physical circumstances of particular restoration projects. We therefore recommend that CALFED prepare a white paper that establishes guidelines for monitoring gravel augmentation projects to help practitioners select appropriate and cost effective monitoring strategies and techniques, and to ensure minimum thresholds of project follow-up while still allowing for emerging best practices.

8.4. Further Recommendations: Communication, Monitoring, and Regulatory Compliance

In addition to the recommendations listed above, we recommend that CALFED institute the following actions:

8.4.1. *Be proactive in encouraging communication among researchers, consultants and agency staff involved in gravel augmentation projects.*

One of the clearest lessons from the R³ Workshop was that there seemed to be very little cross-project communication and data sharing among people working on gravel augmentation projects in California. This results in projects “reinventing the wheel” to identify and address common problems and technical issues, and limits the potential scope of problem solving to small-scale, individual projects. While we recognize that scientists and practitioners receiving CALFED support have a responsibility to cooperate and coordinate, CALFED should assume a leadership role for those projects it funds. We recommend two approaches to this:

8.4.1.1. *Create a database of CALFED Projects.*

Create a centralized database for all gravel augmentation projects, which would include gravel injection and monitoring data. Database entry would be a required deliverable of all CALFED-funded projects, and the database itself would be searchable and publicly accessible. At minimum, all documents produced, including design studies, implementation reports, and monitoring results, would be posted on-line on the CALFED website.

8.4.1.2. *Create multiple avenues for sharing technical information.*

Expand CALFED’s program of sponsoring informal technical forums, such as the R³ Workshop, in order to foster greater information exchange among the CALFED Science Program, CALFED Ecosystem Restoration Program, and contracted scientists and practitioners. CALFED could also create directories of individuals and organizations grouped by fields of expertise, and sponsor email list-serves on specific restoration strategies such as gravel augmentation.

8.4.2. *Commit resources to conducting monitoring and reporting on its results*

A high quality monitoring program should be a mandatory component of all CALFED projects. Such a program should apply standardized techniques to ensure that results are comparable with other projects in order to facilitate information sharing and, as described above in Section 8.3.6, should be tailored to the objectives of the particular project. Some programs may be comprehensive and others may focus on a specific objective (e.g., gravel quality). To assist project managers with planning and executing a quality monitoring program, we recommend that CALFED commit resources to monitoring and information gathering. In the past, very few restoration projects in California have been subject to post-project monitoring and objective project evaluation (Kondolf 1998). As a result, opportunities to learn from past experience and to improve future project design have been lost. While comprehensive monitoring of every gravel augmentation project is unrealistic, some degree of monitoring and post-project assessment should be required. Alternative strategies are available, such as “nested” or “pulsed” monitoring designs, which maximize the information obtained while effectively allocating resources. In addition, both workshop participants and presenters suggested that CALFED secure long-term, dedicated funding for monitoring-focused projects that either extend beyond the lifespan of a single project or monitor across projects and river systems.

8.4.3. *Explore ways to address the regulatory challenges faced by restoration projects in California.*

The challenges of conducting and completing environmental compliance for restoration projects have increased over the years, making timely and cost-effective implementation more difficult. When CALFED was initiated in 1996, there was an effort to develop “one-stop shopping” for restoration project regulatory compliance, but unfortunately this was never implemented. Workshop participants repeatedly lamented the growing regulatory challenges, calling for a streamlined regulatory process for restoration projects. We believe that the time is ripe to revisit the question of whether CALFED can offer regulatory compliance assistance and coordination.

Chapter 9: References

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