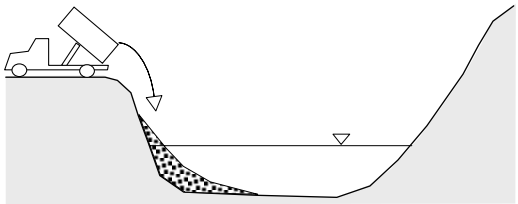
State of the Science Review

Gravel Mitigation and Augmentation Below Hydroelectric Dams:

A Geomorphological Perspective

Report submitted to the
Stream Systems Technology Center

USDA Forest Service
Rocky Mountain Research Station
2150 Centre Avenue
Fort Collins, CO, 80253



by

Kristin Bunte

Engineering Research Center
Colorado State University, Fort Collins, CO 80523

October 2004

Abstract

In many salmon-bearing Pacific coast gravel-bed rivers, closure of hydroelectric dams cut off gravel supply to streambeds below. Gravel mining and changes in the post-dam flow regime further disturbed the streams, leaving them in a geomorphologically and biologically dysfunctional state. Habitat for spawning and other salmon life stages became severely degraded, and salmon populations drastically declined over the past several decades. Gravel augmentation – the artificial addition of spawning-sized gravel to a stream – has been used by hydraulic engineers, fluvial geomorphologists, and fishery biologists as a means to mitigate the poor quantity and quality of spawning and other salmon habitat. As gravel augmentation is a relatively new and rapidly evolving discipline, the majority of information used for the present study stems from projects proposals and project reports available on the internet and compiled by a handful of consulting companies or government agencies. A variety of approaches has been used to augment and mitigate the gravel scarcity below hydroelectric dams. Major ones are:

- River segment-wide gravel augmentation and sediment management plan to restore geomorphological and biological functioning of the stream,
- Intensive multi-reach stream restoration,
- Detailed hydraulic modeling to arrive at the optimum gravel augmentation solution for a specified reach (SHIRA),
- Direct creation of spawning habitat by one-time gravel additions in stream areas with low erosion potential, and
- Passive gravel augmentation at a logistically convenient location to create spawning habitat where the added gravel naturally deposits.

Approaches to gravel augmentation differ greatly in the their spatial scale and focus, emphasizing either the breadth of the geomorphological context considered, the comprehensiveness of river restoration work to establish geomorphological and biological functioning, the immediacy with which the remedial action takes effect, the effects of intragravel processes on redds and the spawning success, the optimization in project results that can be achieved through detailed hydraulic modeling, or the simplicity (planning wise, logistically and financially) of the project approach. However, there seems to be a recent trend towards mingling different approaches in one project.

Based on the tasks in an adaptive management approach that many gravel augmentation projects follow, this study presents the steps and tools involved in gravel augmentation projects. Pre-project analyses are the basis of the iterative process of problem statements, goal setting, and the development of conceptual models and end in the formulation of a design plan. A detailed overview is provided of different tools used in gravel augmentation projects and the computations performed to arrive at the final gravel augmentation plan to be implemented. Steps involved in project monitoring and evaluation, as well as the importance of both for learning from the project outcome are then discussed. A summary and conclusion highlights the main points of this study.

Table of contents

Abstract……2
Table of contents……..3

1. Introduction 8
1.1 Anthropogenic stream disturbances downstream of hydroelectric dams 8
1.2 What is gravel augmentation? 8
1.3 Gravel augmentation: since when and by whom? 9
1.4 Sources of information regarding "gravel augmentation" 9
1.5 Scope of work and organization of the study 10

2. Gravel augmentation approaches in different spatial scales 13
2.1 Overview and Organization 13
2.2 Approaches within the local scale 15
2.2.1 Hydraulic structure placement 15
2.2.2 Riffle augmentation by direct gravel placement 15
2.2.2.1 Equipment used for gravel placement without direct stream access 17
2.2.2.2 Big, flat, erosion-resistant gravel deposit 17
2.2.2.3 Riffle supplementation and lengthening 18
2.2.2.4 Pool tails and riffles in long straight pool reaches 18
2.2.2.5 Riffles with several downstream humps 19
2.2.3 Artificial spawning channels 20
2.2.4 Complex spawning area design based on hydraulic and sediment transport modeling (SHIRA) 21
2.2.5 Spot fixing, filling of ponds, pools and scour holes, and bar shaping 22
2.2.6 Passive gravel augmentation (indirect gravel placement) 24
2.2.6.1 Dumping at place of convenience and/or entrainment 24
2.2.6.2 Spawning gravel supplied by wing dams 26
2.3 Multi-reach river restoration effort 27
2.3.1 Expanding the bed of a narrow and incised channel 28
2.3.2 Carving a design channel into gravel deposits 30
2.3.3 Narrowing an overly wide bed with gravel fill 30
2.3.4 Channel lining with spawning gravel 30
2.4 River segment-wide Gravel Augmentation and Management Plan 31
2.4.1 Two-step approach: short-term active transfusion and long-term passive replenishment 32
2.4.1.1 Short-term transfusion 33
2.4.1.2 Long-term gravel augmentation 33
2.4.2 Downstream gravel conveyance 34
2.4.3 Other measures 34
2.4.3.1 Establishment of a post-dam seasonably variable flow regime 34
2.4.3.2 Clean water supply: reduction of fines and other harmful substances 35
2.4.3.3 Purchase of riparian land 35
2.4.3.4 Project support through involvement of public and stakeholders. 35

3. Adaptive Management in gravel augmentation studies 37

4. Project steps and tools ... 43
4.1 Straightforward, geomorphologically unchallenging gravel augmentation ... 43
4.2 Highly complex and geomorphologically challenging gravel augmentation ... 44
4.2.1 Channel change in response to altered water and sediment supply ... 44
4.2.2 Necessity of understanding the underlying problem ... 45
4.2.3 Long-term or short-term solutions? ... 46
4.2.4 Steps and tools in complex and geomorphologically based gravel augmentation projects ... 46
4.2.5 Identifying the problem through assessment and comparison of pre-project and pre-dam conditions ... 47
4.2.5.1 Field maps, aerial photographs, balloon photos and historical documents ... 50
4.2.5.2 Pre-dam and post-dam hydrographs ... 50
4.2.5.3 Pre-dam and post-dam geomorphic features and sediment supply ... 50
Visual analysis of stream features ... 50
Cross-sections surveys and analyses ... 51
Surface particle-size distribution (pebble counts) ... 51
Pre- and post-dam mean annual gravel load ... 52
4.2.5.4 Additional effects from anthropogenic instream and watershed disturbances ... 52
4.2.5.5 Does lack of spawning gravel quantity and/or quality necessitate gravel augmentation? ... 53
4.2.6 Establishing goals and objectives for a gravel augmentation project ... 53
4.2.6.1 Goals depend on the project settings ... 53
4.2.6.2 Setting measurable project goals and objectives ... 54
4.2.7 Establishing a conceptual model ... 54
4.2.7.1 Interaction between fluvial processes, sediment supply, transport and conveyance, and salmonid habitat ... 55
The five-tiered alluvial ecosystem ... 55
Scour and fill versus aggradation and degradation ... 58
Bankfull flow, pool-riffle-bar units, gravel transport paths, and fish habitat ... 58
Habitat quality and quantity for all life stages ... 60
4.2.7.2 Gravel augmentation in the context of a geomorphologically functioning stream ... 61
4.2.8 The project proposal ... 63
4.2.9 A note on project documentation ... 64
4.3 Field investigations and computations ... 64
Fieldwork throughout the project ... 66
Successful field work ... 66
Criteria for selection of project field sites ... 66
A note on measurement accuracy and consistency ... 67
4.3.1 Topographic surveys ... 67
4.3.2 Geomorphological survey ... 68
4.3.2.1 Geomorphologically based estimate of initial gravel transfusion volume ... 68
4.3.2.2 Selection of sites for gravel augmentation ... 69
4.3.3 Bed mobility and scour depth ... 69

4.3.3.1 Critical flow for incipient motion 70
Computation of incipient motion 70
Tracer experiments 71
4.3.3.2 Scour experiments 72
4.3.4 Bedload transport 73
4.3.4.1 Measurements and computations to determine annual load 73
Direct measurements of bedload transport 73
Bedload equations and bedload transport modeling 74
Bedload discharge, annual and mean annual load 75
4.3.4.2 Pre-dam mean annual load 75
4.3.4.2 Post-dam transport and amount of gravel to be supplied 76
Q^{-}, Qb^{+} 76
Q^{o}, Qb^{--} 77
Q^{-}, Qb^{+} 77
Fining of post-restoration gravel surface increases long-term gravel augmentation needs 77
Measure at locations with sufficient sediment supply 77
Use an experimental approach 78
Augmented gravel sizes to match stream competence 78
4.3.5 Areal extent of post-dam spawning habitat 78
4.3.5.1 Field surveys based on fish habitat criteria and redd counts 79
4.3.5.2 Analyses of aerial photographs 79
4.3.5.3 Historical extent of spawning habitat 79
4.3.5.4 General salmon related information 80
4.3.6 Quality of spawning gravel 80
4.3.6.1 Size distribution of spawning gravel 80
Fish needs 80
Stream needs 81
Characteristic particle size parameters: D_{84}, D_{50} and the percent fines. 81
Collection of unstratified bulk sampling 82
Truncation of samples at some large particle size 82
4.3.6.2 River-segment wide assessment of fines 83
4.3.6.3 Gravel permeability and intragravel flows 84
4.3.6.4 Effect of intragravel flow conditions on spawning success 84
4.4 Modeling and design development 85
4.4.1 Criteria for site selection 85
4.4.2 Topographic modeling 86
4.4.3 Hydraulic modeling 86
4.4.3.1 One-dimensional models (e.g., HEC-2, HEC RAS) 86
Use as a testing tool 87
Use as a design tool 87
4.4.3.2 2-D hydraulic models 87
Creating and testing different gravel augmentation designs (SHIRA) 88
Modeling critical flow for incipient motion 92
Design evaluation 93
4.4.4 Gravel bedload transport modeling 93
4.4.4.1 A bedload equation coupled with a 1-D hydraulic model 93
Computation of annual loads and gravel augmentation needs 94

General problems in bedload transport modeling 94
4.4.4.3 Stillwater Sciences' EASI-model based on the Parker bedload equation 94
Variability in results and sensitivity to slight variations in model input parameters 95
Important information for gravel augmentation 95
Modeling channel designs that fulfill geomorphological and biological functionality 95
Long-term post-project conditions and channel responses are difficult to foresee 96
4.4.5 Modeling downstream gravel movement as bedload waves.... 96
4.5 Changes in the seasonal flow regime 96

5. Project implementation 98
5.1 Sites for gravel augmentation and computation of gravel volumes 98
5.1.1 Site selection in local scale projects.... 98
5.1.2 Gravel amounts 99
5.2 Gravel sources and preparation 99
5.2.1 Gravel costs.... 99
5.2.2 Gravel sources and acquisition 100
Commercially purchased gravel from instream mining 101
Government owned gravel quarries 101
Floodplain 101
Mining tailings 101
Terraces - potential transportation problem 101
Stream re-building 102
Gravel conveyance 102
Re-excavating and re-using gravel 102
Gravel from a different stream 102
Extracting gravel from the upstream delta 103
5.2.3 Preparation and placement of spawning gravel 103

6. Monitoring and evaluating project effects 105
6.1 Monitoring purposes and timing 105
6.1.1 Pre-project assessments 105
6.1.2 Baseline monitoring 106
6.1.3 Implementation or compliance monitoring.... 107
6.1.4 Effectiveness monitoring 107
6.1.4.1 Frequency, timing, and temporal extent 107
6.1.4.2 Long-term monitoring 108
6.1.4.3 Parameters to be monitored 108
Direct influence from gravel augmentation: stream morphology, habitat conditions and spawning gravel quality 109
Geomorphological and fish habitat parameters 109
Spawning gravel conditions and biological parameters 109
Number of salmon, spawners and redds are unclear indicators of project success 112
Relationship between created habitat and habitat use 112
6.1.5 Validation monitoring.... 113
6.2 Analysis, evaluation and adjustment.... 113
6.2.1 Evaluation timing and purposes.... 113
6.2.2 Post project evaluation: quality control and learning 113
6.2.2.1 Degree of documentation increases degree of learning 114

6.2.2.2 Potential and danger of long-term project evaluations 114
6.2.2.3 A gravel augmentation project is still an experiment 115
6.2.2.4 What ought to be known about gravel bedload movement before adding gravel to a stream 116

7. Summary and Conclusion 118
7.1 Different approaches to gravel augmentation projects 118
7.2 Adaptive management and project phases 122
7.3 Final caveats 123

8. References 125

Appendix A: General information on California gravel augmentation studies 135

Appendix B: Legislative text of CVPIA (3406)(b) programs that include gravel augmentation 144

1. Introduction

1.1 Anthropogenic stream disturbances downstream of hydroelectric dams

Hydroelectric dams cut-off all gravel supply, such that bed scour, bank erosion and tributary supply become the only post-dam gravel sources (Kondolf and Matthews 1993). Depending on the reservoir size, the post-dam flow regime may severely decrease highflows (down to 10-20% of normal) if water demand is high, while low flows may be increased (by 50-100%) if water demand is low at that time. Dams thus alter the timing of the flow regime such that release flows do not match salmon flow needs. Smaller dam may have less effect on the flow regime but still trap all the gravel.

Floods that may occur in the post-dam flow regime scour and transport all gravel from the bed for which there is flow competence, eventually leaving behind a paved streambed consisting of cobbles and boulders that are immobile even during the few post-dam flood events, except perhaps the very largest ones. As gravel in the size suitable for spawning of anadromous fish is not replenished by upstream supply, it becomes scarce or is completely absent. At the Toulumne River, at least 44% f the spawning habitat was lost between 1988 and 2000 (McBain and Trush 2001).

In California, where naturally gravel- and gold-rich streams entered the Central Valley from the Sierra Nevada, streams have also been drastically disturbed by other anthropogenic effects such as gold dredging and gravel mining (Kondolf and Matthews 1993; Kondolf 1995a; 1997). Hydraulic mining for gold dredged sediment from the stream bottom, washed it for gold, and then deposited it the in long rows on the floodplain. These rows elevate the floodplain surface, while the resulting channel is often narrow, deep and armored and has high shear stress. Encroached vegetation stabilized the banks and prevented channel adjustment to flows. Other anthropogenic effects that disturb salmon spawning habitat and decrease the rearing success are instream and near-stream gravel mining that create deep pits within and next to the channel. When the narrow berm separating the stream and pit is breached (which it often does), the lateral pond is annexed by the stream. Both instream and near-stream features act as gravel sinks and impede downstream gravel conveyance, while captured side ponds harbor predators to young salmon. Gravel augmentation is required to restore the salmon spawning habitat lost from these impacts.

1.2 What is gravel augmentation?

Gravel augmentation or gravel replenishment means artificially adding gravel suitable in size distribution for salmon spawning and fry emergence to a streambed that lacks such gravel. Approaches that have been used for gravel augmentation projects over the last one or two decades vary in spatial and temporal scale, complexity, focus, methods, and success. The general aim is improvement of spawning habitat, but more recently also the restoration of the geomorphological and biological functioning of the stream such that spawning habitat is formed and maintained. Gravel augmentation projects are generally

aimed at gravel-bed streams in which salmon used to spawn but where spawning habitat was destroyed by anthropogenic influences.

1.3 Gravel augmentation: since when and by whom?

Gravel augmentation for the purpose of spawning habitat improvement has occurred episodically by various government agencies since the 1960ies and 1970ies (e.g., starting at the Trinity River, CA., in 1976; (McBain and Trush 2003 a, Appendix B)). Gravel additions in a wider scale came into effect after 1992, when the Central Valley Project Improvement Act of 1992 (CVPIA) under its title 3406(b) requested that all reasonable efforts be made to obtain a sustainable salmon population that would be doubled by 2002 (Appendix B). Among the reasonable efforts to increase spawning success was gravel augmentation, and first gravel replenishments under this program seem to have taken place since 1996 or 1997. Table A2 in Appendix A lists projects that are currently (or have been very recently) funded under this program. Table A3 in Appendix lists entities involved in (California) gravel augmentation studies, and Table A4 in Appendix A lists amounts of gravel augmented into California streams under the CVPIA (3406(b)).

As numerous gravel augmentation projects are currently underway, a document that provides an overview of different approaches that describes underlying concepts, steps and tools necessary to design a gravel augmentation project and discusses monitoring strategies may be useful for those who practice gravel augmentation or seek information about it.

1.4 Sources of information regarding "gravel augmentation"

A literature search on "gravel augmentation" was the first task of this study. Searches in the catalogues from a large number of Colorado academic libraries, as well as in larger data bases such as Web of Science and Science Direct were unsuccessful. The search terms "*gravel augmentation"*, "*gravel replenishment"*, "*gravel addition"* and *"aggregate addition"* provided no published articles on this subject. Even an article-by-article search through several years' issues of journals that likely might publish studies related to gravel augmentation (e.g., *Regulated Rivers; River Management, River Research and Application*[1]; Water Resources Research, Earth Surface Processes and Landforms, Geomorphology, Journal of Hydraulic Engineering, Environmental Management*, International Journal of River Basin Management*)* gave meager results only. Results of gravel augmentation studies are only just beginning to appear as journal articles (e.g., Pasternack et al. 2004, Wheaton et al. 2004 a and b).

To obtain information on gravel augmentation it was necessary to find out *where* is it currently practiced, *who* provides funding, and *who* carries out projects. An internet search lead to web sites of funding agencies and those sites had links to annual work plans, project proposals and their reviews, and sometimes, though rarely, project reports. Of the large number of documents contained on the internet on *gravel augmentation*,

[1] *Journals marked with an asterisk had one or more papers that addressed gravel augmentation, at least indirectly.*

many are more programmatic and less technical than desirable as informational sources for a detailed report on gravel augmentation. Technical information on gravel augmentation had to be discovered and pieced together. A more detailed source of information on gravel augmentation are the project proposals submitted to Calfed and particularly the proposal reviews. However, information is spotty and has to be extracted from voluminous documents.

Ongoing studies – few reports – few results

As most of the projects are not completed, final project reports are available from only very few projects. Interim reports identifying preliminary results have either not been published yet or are rarely available on the internet in connection with the funding agency. Some work plans mention a planned report as a 2004 task.

The most technical and helpful information for this study was obtained form a few recent project reports and proposals written by geomorphologically and biologically oriented, and experienced consulting companies. Some of these documents were available on the internet. Others were requested (and obtained) directly from the entities carrying out a gravel augmentation project. The most informational sources were:

1. Reports and peer-reviewed journal publications on modeled and optimized designs of gravel augmentation by Pasternack et al. (2004) (UC Davies), and Wheaton et al. (2004 a, b) at the Mokulmne River, CA.
2. Peer-review journal articles by G.M. Kondolf and coauthors pointing to problems regarding stream restoration projects, monitoring, and post-project evaluation.
3. Final reports, draft reports, and/or project proposals written by consulting companies and government agencies on various approaches to gravel augmentation:
   a. McBain and Trush (2000a, 2001, 2003a, b, c and 2004a) on the Trinity and Tuolumne Rivers in CA.
   b. Stillwater Sciences (2001a, b and 2002) on the Merced River in CA,
   c. California Department of Water Resources (2001, 2002) on the Merced River, and
   d. Carl Mesick Consultants (1999, 2001, 2002 a, b, c) on the Stanislaus River in CA.

1.5 Scope of work and organization of the study

A variety of different approaches is used for gravel augmentation depending on the intended spatial and temporal scale and focus of the project. This document provides an *overview* of approaches, methods and tools most commonly used in gravel augmentation projects. However, not all methods and tools ever used to assess salmonid spawning habitat or applied to gravel augmentation projects could be considered, nor are the descriptions of the methods detailed enough to serve as a manual for an inexperienced user. In the often multi-disciplinary approach, help needs to be sought from those experienced in their particular part of the field.

This document is written from a geomorphological perspective and places most of its focus on gravel augmentation projects that emphasize the link between geomorphological and biological functioning of the stream.

The document is structured as follows: After the introduction (Section 1), an overview of different approaches used for gravel augmentation projects is compiled (Section 2). The project strategy of adaptive management is explained (Section 3) because it provides the outline for most of the recent gravel augmentation projects. The structure of this study follows the steps outlined by adaptive management and discusses in sequential order the tasks to be performed during the pre-project phase as well as the main project phases of a gravel augmentation project. An overview is given of different field measurements, computations and model runs that might be performed in different gravel augmentation projects (Section 4). Project implementation and gravel sources are addressed (Section 5). Section 6 discuses monitoring strategies (timing, intensity, documentation and duration). Careful monitoring is necessary not only to evaluate the project success, but also to learn from the outcome of gravel augmentation studies (Section 7). The report finishes with the summary and conclusion (Section 8) and a reference list (Section 9).

A large portion of this report (46 p) is devoted to an overview of methods and tools commonly used in gravel augmentation projects (Section 4). However, it is beyond the scope of this report to provide descriptions that are detailed enough to serve as a guideline on how to accurately use these methods and tools, nor have enough references been compiled to cover all field measurements and computations.

Steps and tasks as well as methods and tools used in gravel augmentation projects vary depending on what kind of an approach is used. Please note that this study focused on approaches that are mainly based on concepts of fluvial geomorphology. Matters of fisheries biology are discussed shortly and with no differentiation between different salmonids, while matters of riparian vegetation are neglected. Unless otherwise noted, a river-segment wide stream restoration and gravel management plan is assumed as the background for many discussions.

One should keep in mind that technologies and concepts presently used in gravel augmentation projects are still in the process of vigorous development. This report (Bunte 2004) therefore presents a snapshot in time (mainly the 2000-2003 status) that may need updating as new results are published. One of the innovative developments is the trend of uniting within one gravel augmentation project various approaches that hitherto had emphasized their distinctiveness. Projects focusing on restoring long-term geomorphological and biological functioning include measures to provide spawning habitat immediately (McBain and Trush 2004a), while projects focusing on immediate habitat creation include a geomorphological perspective (Carl Mesick Consultants 2001). Similarly, 2-D hydraulic modeling and 1-D sediment transport modeling are not necessarily stand-along approaches but may be part of any gravel augmentation project.

A report of this length that provides an overview of approaches, steps and tools should ideally have an alphabetical index in the end to quickly find the text location that

discusses specific items. The lengthy table of contents that includes many unnumbered subheadings is a substitute.

2. Gravel augmentation approaches in different spatial scales

2.1 Overview and Organization

Gravel augmentation projects for spawning habitat improvement cover a variety of different approaches that differ in:

- Spatial scale (individual riffle to entire stream segment),
- Temporal scale (one-time effort to perpetual episodic replenishment),
- Method of gravel placement (direct placement or natural deposition of supplied gravel),
- Basis of know-how for gravel placement (e.g., personal experience, attributes for geomorphological and biological functioning, hydraulic and sediment transport modeling, physical and biological intragravel processes),
- Depth of understanding of physical and biological functioning of the stream system,
- Complexity of the situation and the problem, broadness of scope, costliness of the project,
- Degree to which gravel addition is combined with other measures that aim at improving salmon habitat in all life stages.

Although not necessarily so in each case, there is a tendency for newer projects to span increasingly larger spatial and temporal scales, to use both active and passive gravel augmentation, to employ complex hydraulic and sediment transport modeling, to have an increased scope of view, to be based on increased comprehensiveness and depth of understanding both of salmon-related processes as well as fluvial processes and how they link to biological processes, and to combine gravel augmentation with other measures that improve salmon survival.

Among the different parameters by which gravel augmentation projects can be distinguished, spatial scale is probably the easiest for organizing the different approaches, and it is used for this report. The various gravel augmentation approaches are sorted into three major, nested spatial scales: local, multi-reach, and river-segment wide (Fig. 2.1).

- Local gravel augmentation (within a reach, 5-7 stream widths long, or multiple individual reaches)
  - Hydraulic structure placement,
  - Riffle augmentation,
  - Spot fixing, pool filling and bar shaping, and
  - Passive gravel augmentation (will eventually cover a stream segment).
- Multi-Reach Stream Restoration (covering several reaches, perhaps 20-50 stream widths long),
  - Channel shaping for annual gravel mobility and geomorphic functioning,
  - Channel lining with spawning-size gravel, and
  - All of the above.

- River Segment-Wide Gravel Augmentation and Sediment Management Plan (10-100 km).
  - Establishment of downstream gravel conveyance,
  - Passive gravel augmentation,
  - Enhancement of flow and flow regime,
  - Reduction in supply of fines,
  - Establishment of habitat for all salmon life stages,
  - All of the above.

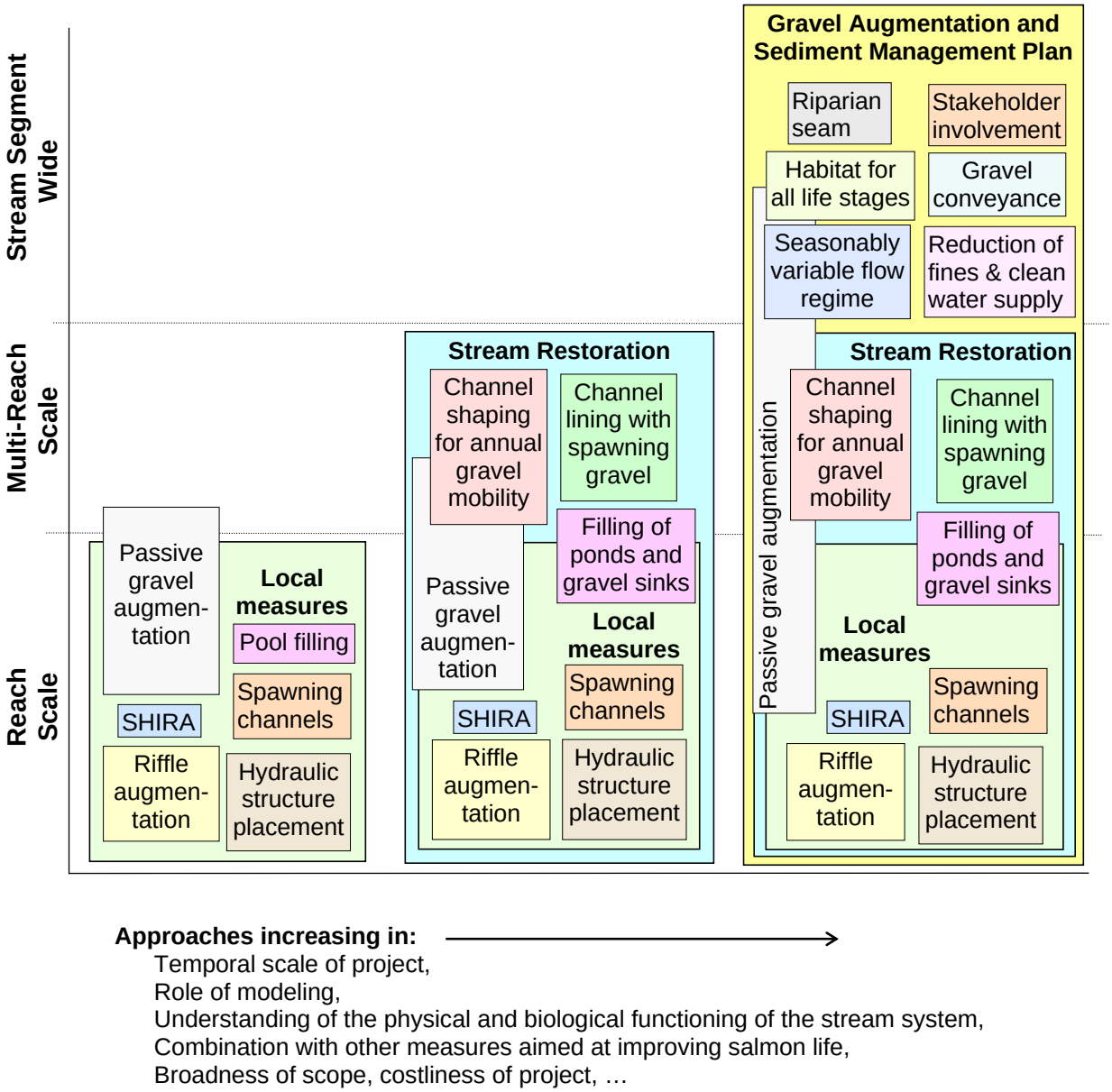


Fig. 2.1: Schematic diagram showing gravel augmentation projects at three spatial scales and for increasing complexity. The spatial differentiations shown in this schematic diagram are not absolutely fixed, but intermediate forms may exist.

2.2 Approaches within the local scale

Local gravel augmentation projects comprise measures of different activity levels. A semi-active approach makes use of natural gravel deposition at locations of low erosion probability or around strategically placed hydraulic structures. Active approaches place gravel more or less directly at the location where spawning habitat is to be improved, while passive approaches rely on stream flow to distribute and form gravel deposits suitable for spawning from gravel artificially supplied from upstream.

2.2.1 Hydraulic structure placement

Hydraulic structures are a semi-active way of gravel augmentation in which structures of different size are placed into the stream to capture and deposit gravel around them. The gravel may be naturally transported to these sites or be artificially supplied by gravel augmentation. Flow hydraulics around obstacles protruding into flow cause both scour and deposition. Gravel and sand bedload may deposit in the wake (downstream) and at the stoss (upstream) side unless a vortex scour develops there. These deposits can provide patches of useful spawning habitat. To enhance the number of these spawning deposits, boulders and large woody debris large enough not to be transported by regular floods can be placed strategically into the stream. The amount and sizes of gravel collected around obstacles to flow (and thus the size and gravel composition of the spawning area) depend not only on the upstream supply of gravel available for deposition, but also of the strength of flow and the specific hydraulic conditions that develop around an obstacle of a specified size and shape. The outcome of this endeavor may therefore not be easily predictable and can vary between years.

Larger structures like low weirs may be constructed from a stream-spanning row of large rocks or a log to cause a gravel deposit on the upstream side. Depending on the size of the scour pool downstream from the obstruction, a riffle-like deposit may form on the pool exit. Similarly, artificial boulder deposits across the stream (riffle template) cause gravel accumulation. Gravel accumulation also occur at the upstream and downstream of partially stream-spanning structures such as deflector wings which are constructed of gabions or logs and extend at an 45 degree angle in a downstream direction (Whyte et al. 1997). The problem of placed structures is that they may wash out or be undermined by high floods.

2.2.2 Riffle augmentation by direct gravel placement

In the riffle augmentation approach, spawning-sized gravel is placed mechanically onto a riffle, a group of riffles, or individual riffles within a longer reach, using heavy construction equipment for gravel placement and distribution (Section 2.2.2.1). The aim is to create a riffle surface that provides good spawning habitat. This may be achieved by shaping the bed surface and using gravel sizes such that surface and subsurface flow conditions will develop that are favored by spawning fish and lead to a high spawning success.

Direct placement of gravel offers the opportunity to mold a specific design shape and experiment with different designs to find the ones that attract the most spawning fish and that are most erosion resistant. Other advantages of direct gravel placement are that it creates habitat immediately and opens a possibility to evaluate known and newly invented riffle designs to enhance the quality of spawning habitat. As spawning riffles can be designed directly tailored to fish spawning needs, spawning fish seem to adopt the newly augmented site and there is typically immediate success (Carl Mesick Consultants 2002 a, b, c). Acceptance may be so overwhelming that redd superimposition reduces the spawning success. However, sometimes, fish do not accept seemingly perfect spawning gravel. This might happen if gravel used for augmentation comes from a different stream and smells wrong for salmon.

If the upstream water supply and flood frequency is known and the probability of large flood events is low, the riffle can be designed on which the augmented gravel just starts to be mobile at post-dam bankfull flows and that anticipated particle transport distances are small. However, the immediate success of the spawning riffle may not be long-lasting. During larger floods, the augmented gravel may wash out due to a lack of upstream gravel supply and the spawning riffle needs to be rebuilt. Contrarily, if gravel remains permanently immobile, fine sediment and algae may clog interstitial spaces which reduces intra-gravel flows and oxygen content and consequently diminishes the spawning success. If flows are particularly low during a spawning season, the augmented gravel may be above water and unavailable to spawners. Direct riffle augmentation is therefore best suited for environments with relatively stable flows. In order to reduce the danger of washout and achieve a natural deposit, gravel may be placed just upstream of the augmentation area with the aim that flows will naturally disperse the gravel (Spawning Gravel 2004).

The project manager needs to evaluate the probability of a large flood and weigh the risk of loosing the augmented gravel against the beneficial effects of the increased spawning habitat while it lasted. The lower the flood and erosion probability, the higher the benefit and the more likely it is that money spent for the augmentation was well spent. In some instances, spending money and effort to obtain a spawning site with a two-year life expectance may be justifiable, in other cases not. There is also the unsolvable dilemma between too much and too little gravel movement.

Several strategies have been developed to overcome the various difficulties encountered in direct gravel augmentation. Placement of spawning gravel in locations with low erosion susceptibility such as in low gradient riffles or spawning channels decreases the erosion problem. Extending exiting pool tails or riffles through added gravel increases the size of the spawning area, while creation of riffles with multiple humps increases the number of locations with downwelling flows and accommodates a larger number of spawners per unit area. Hydraulic and sediment transport modeling allows testing numerous and complex riffle designs. The ones that provide the largest and most hydraulically suitable spawning areas over a wide range of flows while being stable at bankfull flow, and have economical gravel use, can be selected for implementation. These different approaches are described in more detail below. Direct gravel placement is usually a cost approach, particularly if it follows a design shape and requires local stream access to be established. A less costly

approach is indirect placement or passive gravel augmentation: gravel supplied at some convenient upstream site is naturally entrained, transported and deposited (Section 2.2.6).

2.2.2.1 Equipment used for gravel placement without direct stream access

Although mechanical, direct placement can more or less accurately implement a design plan, using heavy construction equipment such as bull dozers, front end loaders and backhoes is expensive, requires accesses to the stream and damages riparian areas and interstitial microorganisms and may compact the newly placed gravel. If this stream-bed disturbance is unacceptable, and/or if making access for trucks and heavy equipment is unfeasible, gravel may be placed by more remote methods. A discussion of alternative gravel placement methods that includes helicopters, cable ways and various conveyor belt systems (portable, truck-mounted, crane mounted and attached to dump truck) is provided by Kimball (2003). It includes a description of methods, limitations, horizontal placement distance, discharge rate, and the price per ton for 1,000 tons of gravel placed. Using a gravel price of $25, the placement costs range from about $50 to $100 per ton.

2.2.2.2 Big, flat, erosion-resistant gravel deposit

In order to reduce the potential for gravel entrainment and prevent loosing the augmented gravel to erosion, riffle augmentation projects tend to focus on low gradient and wide streambed areas (Fig. 2.2.2.2). Examples are the Merced River below the New Exchequer Dam with its Riffle 1B (Kondolf et al. 1996; CDWR 2002b) and Riffles 1A and 1B at the Stanislaus River below Goodwin Dam and the Knights Ferry Replenishment Project where excavated stream-channel areas left over from gravel mining were used as sites for gravel augmentation (Carl Mesick Consultants 2002a, b, c).

Spawning gravels may also be placed in stream locations naturally suited for gravel retention, such as low-gradient areas with only little upstream sediment supply and a relatively stable flow regime (Whyte et al. 1997) (e.g., downstream of reservoirs and lakes or at stable groundwater outflows (avoid low oxygen content)). A sediment retention structure such as a weir may be needed to keep the added gravel from being transported away.

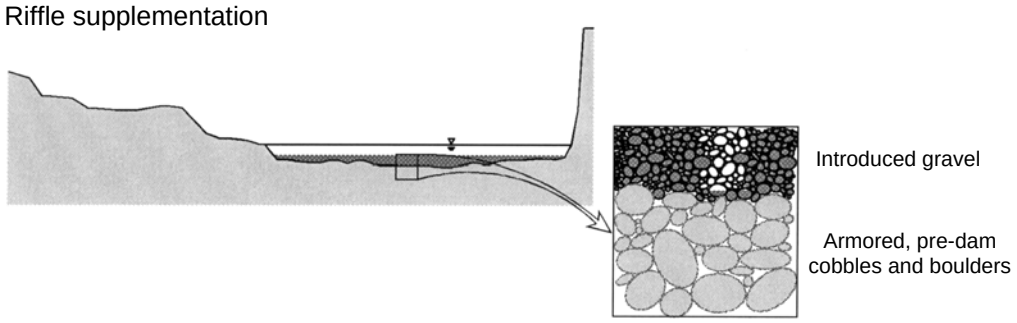


Fig: 2.2.2.2: Direct placement of spawning gravel onto a riffle (copied from McBain and Trush (2003b), slightly altered).

2.2.2.3 Riffle supplementation and lengthening

Spawning gravel may have eroded off a riffle, leaving a remnant that has only a small area with spawning-sized gravel. If the height of the riffle crest is not to be changed, gravel can be added to either the upstream or downstream side of the riffle (riffle lengthening). Upstream augmentation supplements an overly steep pool tail (Fig. 2.2.2.3a). Downstream augmentation in the form of a wedge decreases the riffle steepness and extends the spawning area at the lower riffle (Fig. 2.2.2.3b) (McBain and Trush 2001).

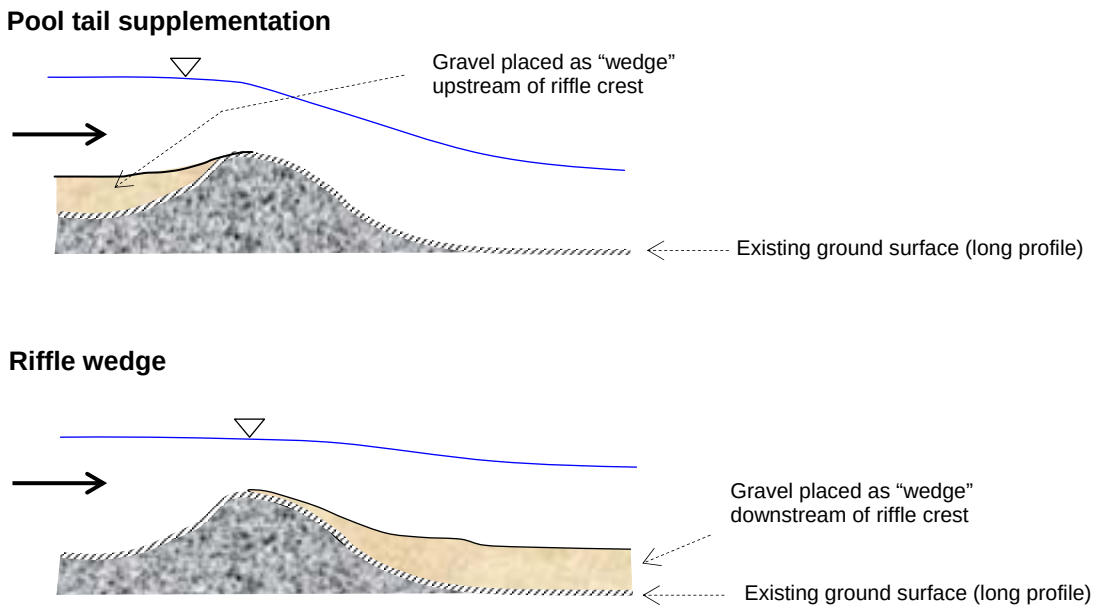


Fig. 2.2.2.3: Spawning gravel augmentation to upstream side of riffle as a pool tail supplementation (a) and the downstream side of a riffle as a riffle wedge (b) (redrawn and slightly altered from McBain and Trush 2001).

2.2.2.4 Pool tails and riffles in long straight pool reaches

Riffle lengthening (Section 2.2.2.3) applied to short riffle-pool units may cause a reduction of the pool habitat that should be avoided. Creating a low and low gradient spawning riffle in a long pool or glide (Fig. 2.2.2.4) that otherwise does not provide much habitat (McBain and Trush 2004a) averts this problem. The new riffle provides not only immediate spawning habitat, but elevates the upstream water surface which may improve hydraulic conditions for spawning habitat at the upstream steep riffle. Placement of a riffle into a long pool or glide also shortens an overly long riffle-pool spacing to better fit the post-restoration flow and sediment transport regime.

Longitudinal profile

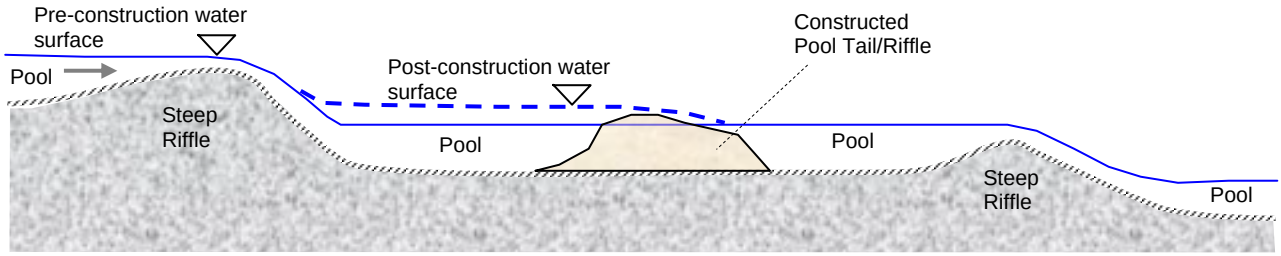


Fig. 2.2.2.4: Pool tails and riffles in long straight pool reaches (redrawn and slightly modified from McBain and Trush 2004a)

2.2.2.5 Riffles with several downstream humps

The freedom in gravel placement by mechanical riffle augmentation permits creating spawning riffles that are based on fisheries biologists' knowledge of good spawning habitat according to habitat suitability curves (appropriate combination of flow depth and flow velocity), downwelling and upwelling flow, intragravel flow velocities, and high intragravel oxygen content. An example of gravel placement with the aim to maximize the number of areas with downwelling and upwelling flow per stream length is shown for the Robinson Reach in the Merced River, where the riffle surface was structured by either one, two, or three humps (CDWR 2002a, 2003) (Fig. 2.2.2.5). The height of the hump does not appear to matter much. Car Mesick Consultants (2002b) observed that intragravel flow and dissolved oxygen did not vary in riffles shapes with high, moderate or low crests, nor did the number of spawners per riffle.

While gravel-augmented riffles usually seem to be adopted by spawning fish (right away and increasingly so over time), the immediate success of direct placement may not be long-lasting. All of the gravel augmentation designs on riffles discussed above suffer from the dilemma that gravel mobility on the augmented riffle is essential, but potentially destructive. The solution is to achieve periodical gravel movement and immediate replacement of the scoured gravel by an upstream sediment supply. A scour-and-replacement exchange occurs in streams with equilibrium gravel transport conditions and ensures geomorphologically and biological functioning of the riffle as a spawning site. To facilitate this functioning, a general gravel augmentation and sediment management plan may be needed that not only create suitable spawning habitat but attempts to maintain it over the long run by establishing continued downstream gravel conveyance and geomorphic/biological functioning of the stream (Section 2.4).

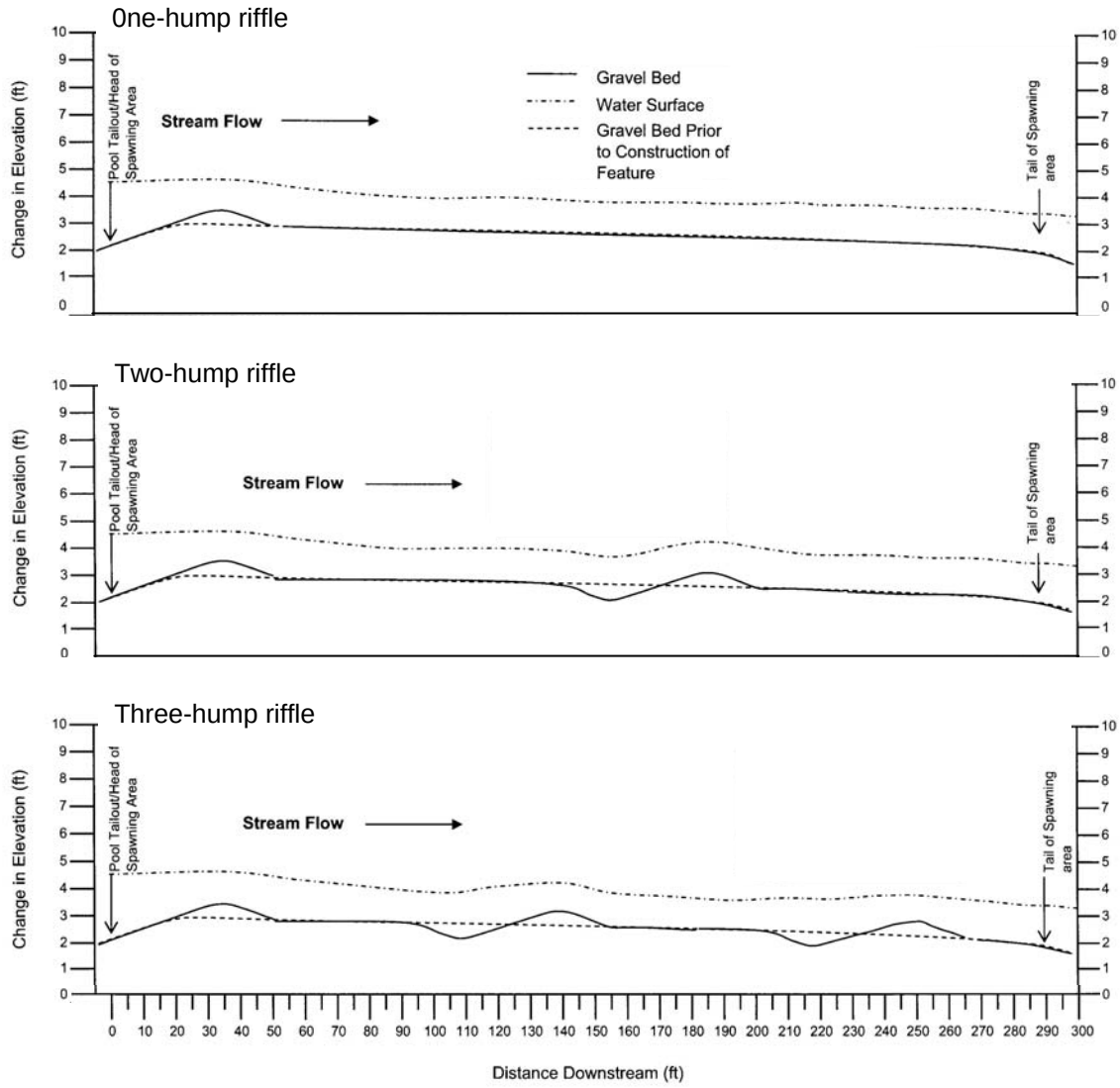


Fig. 2.2.2.5: Riffle surfaces structured by adding one, two, and three humps (copied from CDWR 2001 and slightly modified).

2.2.3 Artificial spawning channels

Salmon spawning beds have been created in side channels below a dam since the 1960ies and 1970ies (Kondolf and Matthews 1993). These channels may exist naturally or be constructed particularly for this purpose (e.g., across a point bar on the Trinity River, or as a built channel in Tehama Colusa Fish Facility). The advantage of these hatchery-like spawning beds is that flows can either be regulated or have velocities sufficiently low such that bed scour does not occur. An influx of fine sediment into the spawning channel must be prevented to ensure gravel properties suitable for spawning. Potential problems may be insufficient water supply, high water temperature, adverse hydraulic conditions, aquatic weeds, and disease.

2.2.4 Complex spawning area design based on hydraulic and sediment transport modeling (SHIRA)

Shaping of the gravel augmentation area based on personal experience can provide satisfactory results in some cases. However, experimentation with different designs can be an expensive trial and error approach. By contrast, using detailed hydraulic and sediment transport modeling approach allows one to computationally compare different gravel augmentation designs. The design with the best hydraulic suitability, least erodibility, and the minimum amount of added gravel can then be selected for implementation. Pre-implementation modeling is particularly important if the gravel augmentation area is to provide spawning habitat over a wide range of flow conditions.

An example of a detailed modeling approach to gravel augmentation (Salmon Habitat Integrated Restoration Approach, SHIRA) is provided by Wheaton and Pasternack (2002) and Pasternack et al. (2004) who restored a 140 m long reach of the 30 m wide Mokelumne River below Camanche Dam in California where spawning habitat was severely degraded to a narrow, over-deepened and immobile bed with established vegetation. A digital elevation model (DEM) was created based on a detailed survey of the reach in which existing relief was surveyed with high density, while flat areas received less density. A commercially available 2-D hydraulic model was then applied to the DEM (see also Section 4.4.3.2).

After the modeled flow hydraulics (flow depth and mean depth-averaged flow velocity) were adjusted to fit the measured ones in several cross-sections, flow hydraulics were modeled for four different scenarios of spawning areas. The scenarios differed by the volumes of gravel added to the bed and the shaped bed features: 1) a braid (mid-channel bar and riffle-pool-riffle sequences with downwelling flow in the two lateral channels); 2) alternate bars (small lateral bars with riffle-pool-riffle sequence); 3) alternate bars and a braid combined; and 4) a flat riffle with 10 isolated, large boulders (Fig. 2.2.4 a). Flow velocity vectors, depth, and a global habitat suitability index were computed for about 750 points within the reach for each of the four stream-bed scenarios (Fig. 2.2.4 b). Similarly, the susceptibility for gravel erosion was assessed for each design by evaluating the ratio of the modeled shear velocity to a critical shear velocity (assuming τ^*_{crit} = 0.045) at near bankfull flows.

The four gravel augmentation scenarios were compared and ranked by their percent area with suitable spawning habitat, the size of individual spawning areas, the total area of spawning habitat created per volume of gravel used, and the percent bed area susceptible to erosion at various flows. The flat riffle with boulders yielded good marks for a specified flow, while the braided design yielded acceptable marks for a wide range of flows. The suitability of a particular design for optimal spawning habitat is probably site specific, such that different designs may be differently suitable at different sites.

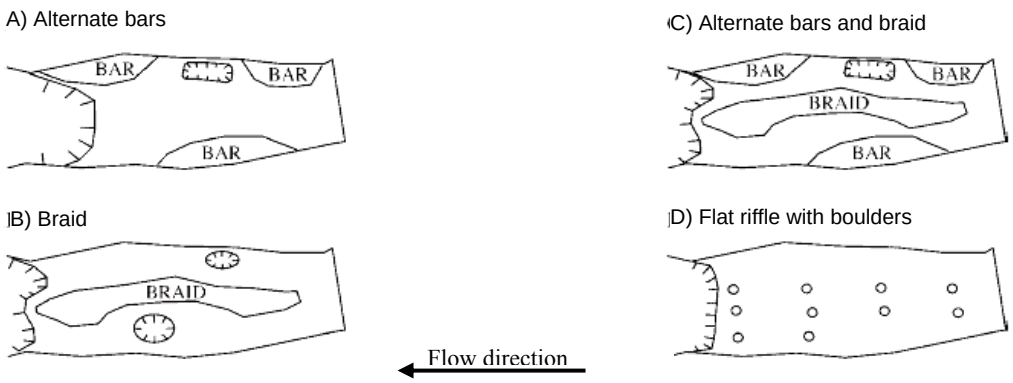


Fig. 2.2.4 a: Schematic illustrations of the four alternative gravel placement scenarios. Hatched areas are pools while circles in (D) are boulders (copied from Pasternack et al. 2004 and slightly altered).

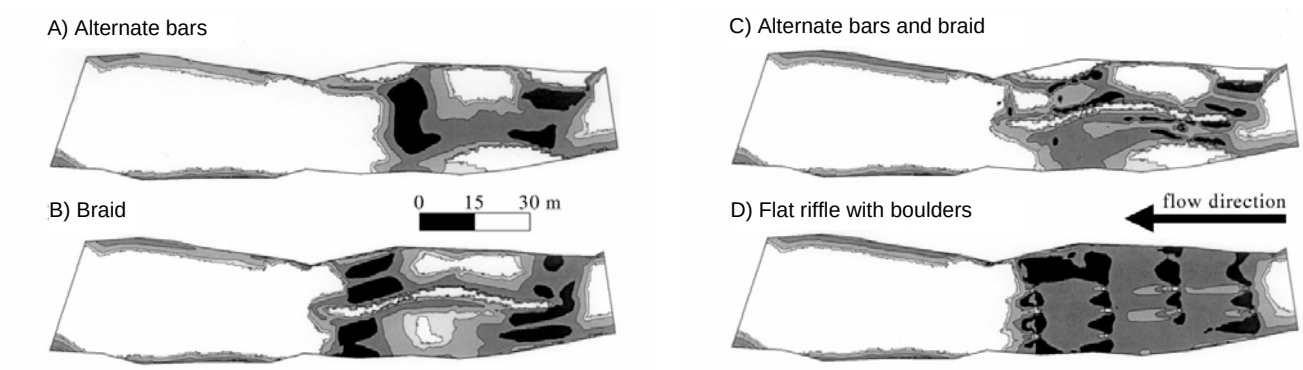


Fig. 2.2.4 b: Comparison of global habitat suitability index (GHSI) values among the four alternative gravel placement scenarios. White = 0 (dry areas and deep pools), light gray ≤ (very poor quality), medium gray = 0.1-0.4 (low quality), dark gray = 0.4-0.7 (medium quality), and black = 0.7-1 (high quality) (copied from Pasternack et al. 2004).

2.2.5 Spot fixing, filling of ponds, pools and scour holes, and bar shaping

Riffle augmentation cannot unfold its full potential for increasing the salmon population if the surrounding environment is counterproductive to the formation and maintenance of spawning habitat and hostile to juvenile fish. Scour pools, in-stream gravel pits, and ponds annexed by the stream are not only gravel sinks that reduce the upstream gravel supply, but the relatively warm and stagnant pond waters harbor potential predators to juvenile salmon (AFRP 1998). These areas need to be filled or permanently separated from the stream (Fig. 2.2.5 a). Fixing these areas is particularly important when gravel augmentation extends over a multi-reach or a long river segment and needs to provide a continued appropriately-sized and functioning stream channel to ensure unimpeded sediment conveyance through the ameliorated and gravel-augmented stream system. The

buried portion of fill material does not need to be spawning gravel (which is costly), but an appropriately thick surface layer must be of spawning-size.

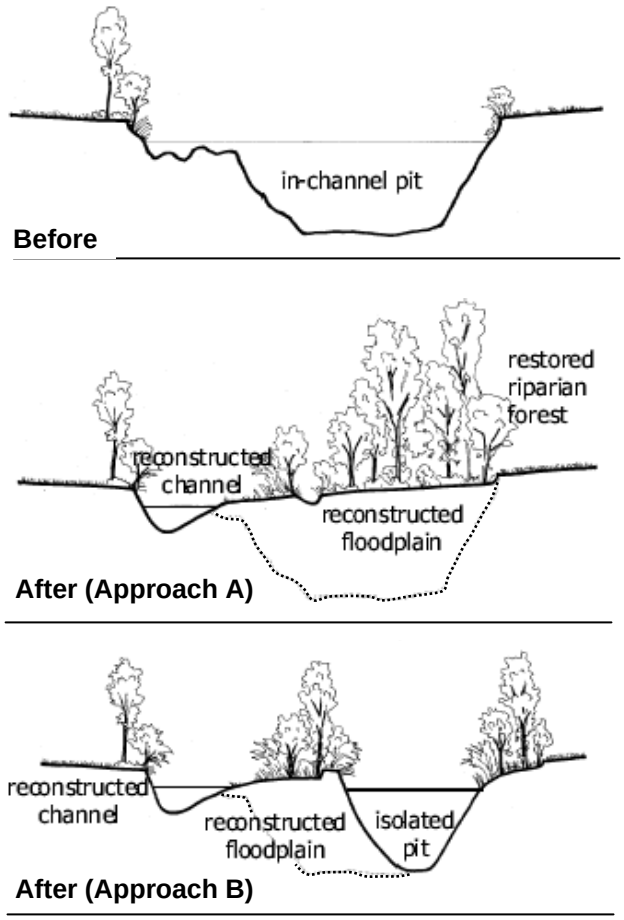


Fig. 2.2.5 a: Two alternative approaches to restore reaches with in-channel pits: A) Complete filling and integration into floodplain surface (large fill volume). B) Isolating the pit from the stream (less fill volume required) (Copied from Stillwater Sciences (2002) and slightly modified).

Gravel may also be supplied to individual stream features such as point bars and pool tails that are particularly starved of gravel (Figs 2.2.2.3a and 2.2.5b). Local gravel additions here create not only spawning habitat but a geomorphologically functioning alluvial stream feature that permits an exchange between scoured and deposited gravel during a highflow. As the location is no longer a gravel sink, the local sediment balance is restored and downstream conveyance is maintained. McBain and Trush (2003b) call this approach "Gravel contouring to mimic alluvial features". If gravel contouring is applied mainly laterally to a stream, such as on a point bar, stream-bed disturbance can be kept low if a long-necked back-hoe can be used for gravel placement.

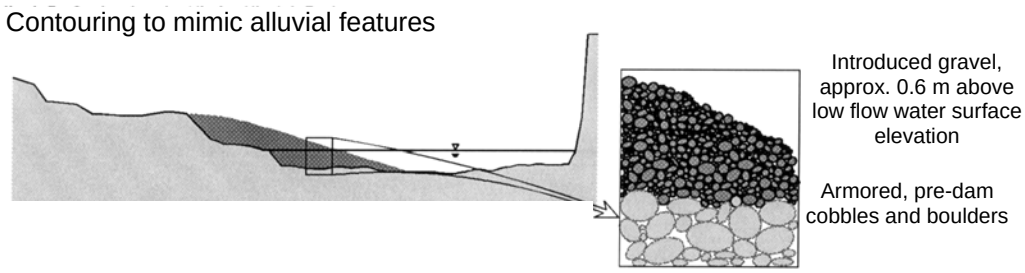


Fig.: 2.2.5: Gravel placement on a depositional alluvial feature to prevent it from being a gravel sink and to restore its geomorphological functioning (copied from McBain and Trush 2003b, slightly altered).

2.2.6 Passive gravel augmentation (indirect gravel placement)

A common and easily manageable form of spawning gravel improvement is passive gravel augmentation. It is based on the idea that if spawning-sized gravel is supplied at some logistically convenient place that is also hydraulically suited for gravel entrainment and transport, the gravel will be naturally dispersed and deposited on downstream riffles, point bars and pool tails to enhance spawning habitat there. Locations for indirect placement may be based on convenient access to the stream (road close to stream bank or a bridge), high entrainment probability, proximity to the gravel sources, or on "convenient circumstances" such as wing dam operation. Passive gravel augmentation extends from the reach scale to (eventually) a river-segment wide scale.

2.2.6.1 Dumping at place of convenience and/or entrainment

Gravel may be added to a stream by dumping it from a truck down the bank laterally onto the stream bank or into a stream (Figs. 2.2.6.1 a and b). The advantages of dumping are easy logistics and generally low cost. Access is available and no vegetation has to be removed. The permitting process is easy and there is no need for heavy equipment in the stream which is not only costly but detrimental to interstitial habitat. Transportation costs can remain low if the dumping location is close to the gravel source. The dumping can occur any time of the year, and this eliminates the need for stockpiling gravel that has become available from some source at a specific time.

Disadvantages of indirect gravel placement are the dependency on a highflow for entrainment which may delay gravel distribution because gravel-moving highflows are rare in a post-dam flow regime. Thus, dumping should seek a stream location where entrainment occurs at relatively low flows (e.g., at narrows). If entrainment occurs at highflows only, gravel will not be available to improve downstream spawning habitat until after the next (couple of) highflow(s), which might not be before several years if the dumping site is relatively far way from the riffles to be augmented. To monitor the downstream gravel displacement velocities through subsequent highflows and assess the

suitability of a site for indirect gravel placement, some of the gravel particles can be outfitted with radio transmitters (Spawning Gravel 2003).

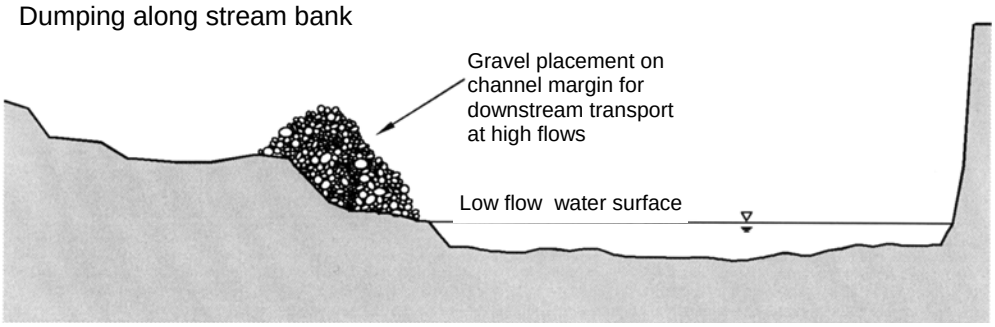


Fig. 2.2.6.1: Depositing spawning-size gravel along the bank for entrainment at highflows and natural deposition in locations that form spawning habitat given sufficient gravel supply (redrawn from McBain and Trush (2003b) and slightly modified).

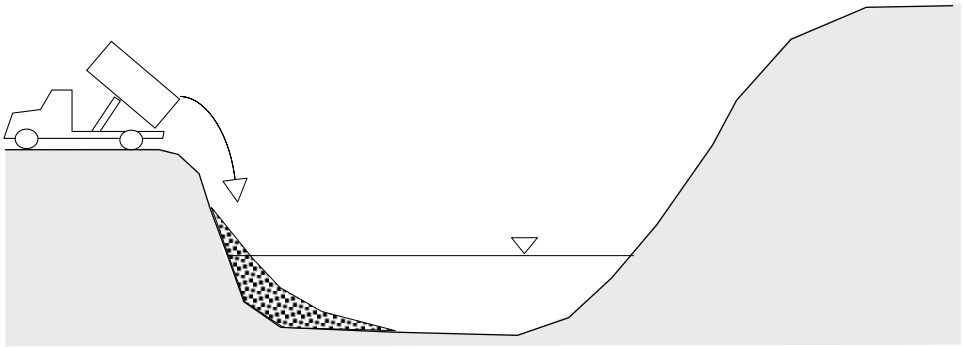


Fig. 2.2.6.1 b: Dumping of spawning-size gravel into the stream for entrainment at highflows and natural deposition in locations that form spawning habitat given sufficient gravel supply (redrawn from McBain and Trush (2003a)).

The success of passive gravel augmentation depends on undisturbed downstream gravel conveyance to ensure that the added gravel does not disappear in a gravel sink but is available for deposition at a location suitable for forming spawning habitat. As only a fraction of the added gravel will be deposited at sites where flow hydraulics are suitable for spawning habitat, indirect placement of gravel appears to involve relatively large annual quantities of several thousands or tens of thousand tons per site and dump and may necessitate repeated dumps over a number of years (Spawning Gravel 2003)[2].

[2] *e.g., Clear Creek below Wiskeytown Dam near Redding (CA) where between 6,000 and 32,000 tons were dumped annually between 2002 and 2003, and unknown quantities since 1996. Another example is the Upper Sacramento River where 15,000 and 8,000 tons were placed in 2002 and 2003. See also Table 7 in Section 5.2 for volumes of spawning gravel introduced into California streams.*

2.2.6.2 Spawning gravel supplied by wing dams

An opportunistic approach to indirect gravel placement is the attempt to improve spawning habitat on wing dam-supplied gravel (Merced Irrigation District and Natural Resource Scientists, Inc., 2003). Wing dams are artificial gravel dams that are annually built to funnel stream flow into irrigation ditches branching off the main stream. Wing dams extend about 3/4 across the stream and are several feet high (Fig. 2.2.6.2). The dams raise the upstream water surface elevation and enable gravity flow into riparian irrigation ditches. Wing dams are usually washed out during winter and spring highflows (events approximately larger than 6 times the summer low flow). The washed out material typically forms a fan-like deposit immediately downstream of the eroded wing dam, and results obtained from radio tagged cobbles and painted gravel tracer studies indicate that transport distances are generally short. Thus, wing dam material are likely to be slow to benefit reaches downstream reaches further away. On the other hand, spawning has been observed on wing dam deposits directly.

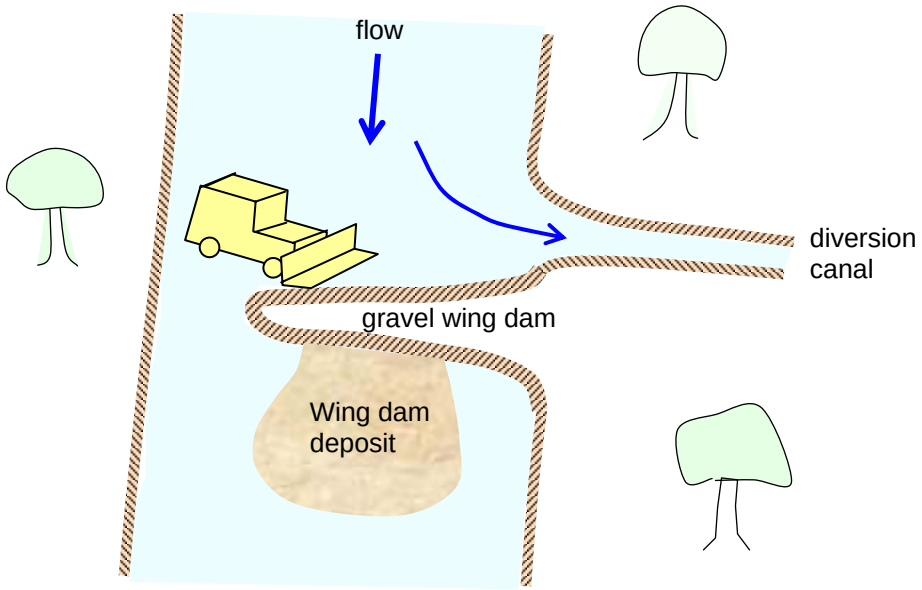


Fig.: 2.2.6.2: Sketch of a wing dam and its downstream deposit (wing dam and downstream deposit do not occur simultaneously).

Before the beginning of the irrigation season, wing dams are annually re-built in late spring. They are usually pushed together on top of the washed-out remains of last years wing dam using heavy equipment and any material close at hand, be that the streambed material or material from the floodplain which may be contaminated with fines. It was suggested by the Natural Resource Scientists (2001) to provide operators with spawning gravel sized material to build wing dams, such that during wing dam erosion, spawning-sized gravel is supplied to the stream and helps forming spawning habitat on rehabilitated riffles downstream of an eroded wing dam. Supplying off-stream spawning gravel to

build wing dams also reduces or eliminates the need for heavy equipment on the streambed. Opponents of wing dam operations point out the environmentally detrimental effects of wing dam operation in general as it takes up additional water, misguides fish, and disturbs the bed. They argue that the practice should therefore be eliminated altogether instead of being considered an opportunistic way to augment gravel supply.

2.3 Multi-reach river restoration effort

A stream may be so disturbed in its form and geomorphological functioning (incised, with stabilized banks, isolated from a floodplain, with gravel pits as gravel sinks and predator habitat), that local gravel augmentation alone would not have a long-lasting effect, nor would it achieve a geomorphologically functioning gravel-bed stream. Added gravel would quickly erode in a narrow and confined reach with no possibility for bank and floodplain deposits. Supplied gravel would also vanish in deep spots (gravel sinks) without creating spawning habitat.

Thus, before spawning habitat can be successfully restored and attain a long-lasting effect, channel restoration needs to re-shape the misfit channel in order to facilitate geomorphological functionality. This requires creating a design channel that is appropriately sized and shaped (i.e., includes point bars, riffles and pool tails if these were pre-dam channel features), such that the post-dam flow regime and the given stream gradient facilitate annual mobility of the coarse portion of artificially supplied spawning-sized gravel. The deposits formed by gravel augmentation and maintained by post-restoration bedload transport processes will then provide long-lasting spawning habitat.

Stream restoration usually spans several neighboring reaches that have similar problems and are part of one project or project group with common organization, aims and coordination. However, measures to be taken for stream restoration in any specific project reach depend on the problems that cause poor salmon spawning habitat in the first place. Multi-reach methods of shaping a new channel bed may require:

- Expanding the bed of a narrow and incised channel,
- Carving a new, off-stream design channel into gravel deposits, and
- Narrowing an overly wide bed with gravel fill.

These methods are supplemented by local measures such as riffle augmentation, accentuating existing fluvial forms, filling of ponds and gravel sinks and episodic passive gravel replenishment (Section 2.2). Since channel restoration is expensive, restoration efforts to attain geomorphological functioning are usually restricted to reaches that are badly impaired but where salmon historically used to spawn. Some stream reaches may be left unrestored as long as they do not act as gravel sinks or predator habitat. The general steps involved in stream restoration for spawning habitat improvement are briefly summarized below.

Text box 1: General steps involved in stream restoration for spawning habitat improvement

Bankfull flow is computed (usually as the 1.5-year recurrence interval flow) from the frequency distribution of the post-dam flows for which the new channel is to be designed. Information on channel plan form (e.g., meander wavelength, sinuosity) and channel geometry (width, depth) is obtained from regional curves of hydraulic geometry relations for the post-dam bankfull flow or by comparison with functioning neighboring streams. A channel bed of the appropriate size, shape, planform, gradient, and bed material composition is designed and a series of cross-sections are computed from the design. Using hydraulic modeling (e.g., HEC RAS), the cross-sectional size and shape are then fine-tuned such that the post-dam bankfull flow fills the designed channel to the morphologically characteristic bankfull stage. The critical flow for incipient motion of the coarse portion of the bed material (approximately the D_{84}), and if necessary, transport rates for the finer gravel portions, are then computed using a hydraulic model and bedload transport modeling (e.g., EASI-model (Stillwater Sciences 2001b)). The aim is to design a channel in which flows just below bankfull start mobilizing the coarse gravel portion. If the post-dam flow regime, stream gradient and bed material size require a meandering channel shape, then space needs to be allowed along the channel banks to facilitate lateral channel shifting which is a natural feature of meandering streams. Once an approved design has been implemented, cross-sectional shapes and bedload transport rates need to be monitored to ensure that the new design behaves as expected.

2.3.1 Expanding the bed of a narrow and incised channel

While dam closure that cuts off the upstream gravel supply and post-dam highflows that deplete the remaining gravel beds are the primary reasons for gravel scarcity and poor spawning habitat, there are often subsequent stream processes that exacerbate the problem of low spawning gravel availability. Post-dam flows that may be further diminished by flow diversions rarely flood the pre-dam floodplain. This leads to vegetation encroachment with mature trees and shrubs on the floodplain and the stream banks, stabilizing the gravel in both. Gravel can neither be recruited by overbank flow nor by lateral channel migration. The result is a narrow channel with high shear stress and a paved, immobile bed. Artificial stream constraints by berms and levees or dysfunctionally high floodplain elevations further exacerbate the problem.

Gravel augmentation as a measure by itself would not be very effective in such reaches, because the high shear stress would quickly erode the added gravel. Thus, before gravel augmentation measures can have a long-lasting effect, stream restoration must restore the geomorphological stream functions. This may involve removal of some riparian vegetation and expanding the channel bed to attain an appropriate shape and size of the cross-section (Figs. 2.3.1 a and b). The gravel deposit into which the stream is expanded either has a size distribution suitable to become spawning gravel, or spawning gravel needs to be supplied to the bed.

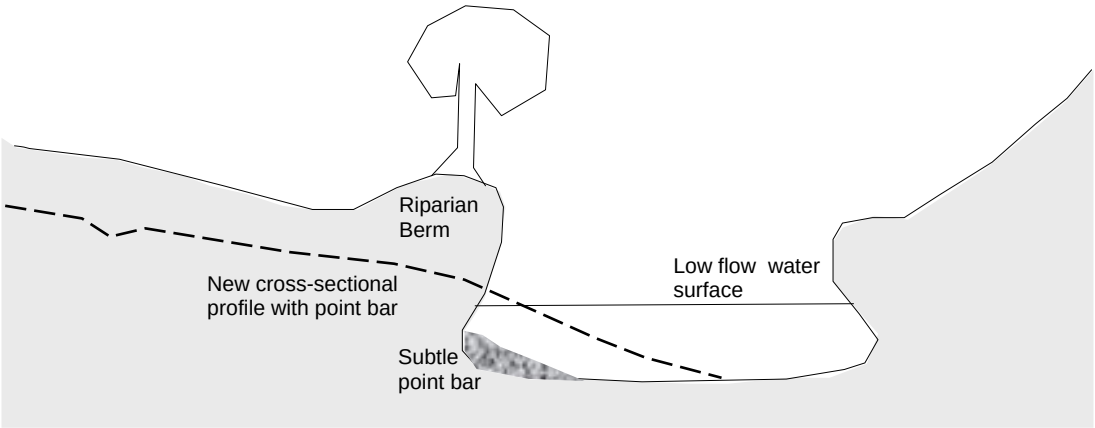


Fig. 2.3.1a: Expanding a channel to attain an appropriate shape and size for geomorphological functioning into the constricted bed (Trinity River, CA) (redrawn from McBain and Trush 2003a).

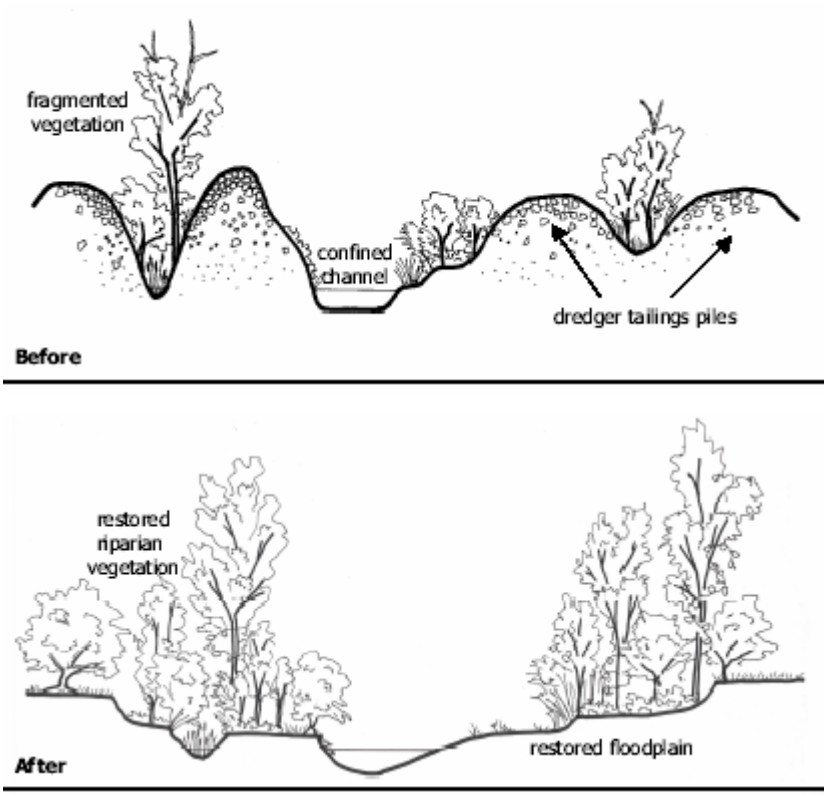


Fig. 2.3.1 b: Setting an appropriately sized channel and floodplain into misfit, overly narrow channel without a functioning floodplain (Dredger Tailings Reach on the Merced River) (copied and slightly modified from Stillwater Sciences 2002).

A problem arising with reshaping and resizing the channel is that its full benefits will develop over time only. The reshaped channel may lack mature riparian vegetation that provides large woody debris to form refuge habitat. In the absence of a natural wood

supply, refuge habitat in the vicinity of spawning habitat may need to be created artificially by placing boulders and large woody debris. In addition, streams need to be designed with structural diversity such that both spawning habitat and refuge habitat are created immediately (Carl Mesick, Pers. Comm. Jan. 2004).

2.3.2 Carving a design channel into gravel deposits

Very wide reaches and those in which the stream annexed near-stream mining pits may be geomorphologically dysfunctional with little sediment movement. A completely new meandering channel with a new course that is independent of the old misfit channel may need to be designed. If the new channel is excavated into a floodplain gravel deposit, the new bed may have bed material suitable for spawning. If not, the channel bed needs to be lined with spawning sized gravel (Section 2.3.4). An example of this approach is the Robinson Reach of the Merced River (CDWR 2001, 2002a) and The Two-Mile Bar in the Stanislaus River (AFRP 2000).

2.3.3 Narrowing an overly wide bed with gravel fill

A depleted gravel supply may cause an overly wide stream in which the shear stress of the post-dam 1.5-year recurrence interval flow does not suffice to mobilize the coarse portion of the bed material distribution. Stream restoration in this situation might add large amounts of gravel to fill the extra space in the misfit cross-sections. The anticipated result is increased shear stress in the diminished stream size and annual mobility of the coarse portion of the bed material. Ideally, all of the fill gravel would be of spawning size, such that if the stream migrates laterally, the bed remains within a gravel deposit of appropriate particle size for spawning (Section 2.3.4). If large volumes of fill material are needed, any kind of available fill material may have to be used. Spawning-sized gravel is just applied to the top of the reshaped bed (see below).

2.3.4 Channel lining with spawning gravel

If a completely new channel is designed into a gravel deposit that is too coarse for spawning purposes, the channel is deliberately excavated too large such that a layer of spawning gravel up to about one meter thick (Fig. 2.3.4) can be added on top. The thick layer of spawning gravel permits approximately annual transport of the coarse gravel fraction of the bed and lateral channel shifting which is a normal activity for a functional gravel-bed stream (CDWR 2001). A bottom layer of large cobbles placed under the layer of spawning gravel prevents excessive local scour and degradation.

Note that the gravel volume required when shaping alluvial features in spawning gravel is very large and adds up when gravel augmentation extends over stream reaches several km long, even if spawning-sized gravel is “only” applied as a meter-thick layer. However, the reshaped stream-bed surface is, if all went well, immediately fully functioning, both geomorphologically and for spawning habitat, although reestablishment of benthic invertebrate community may take longer.

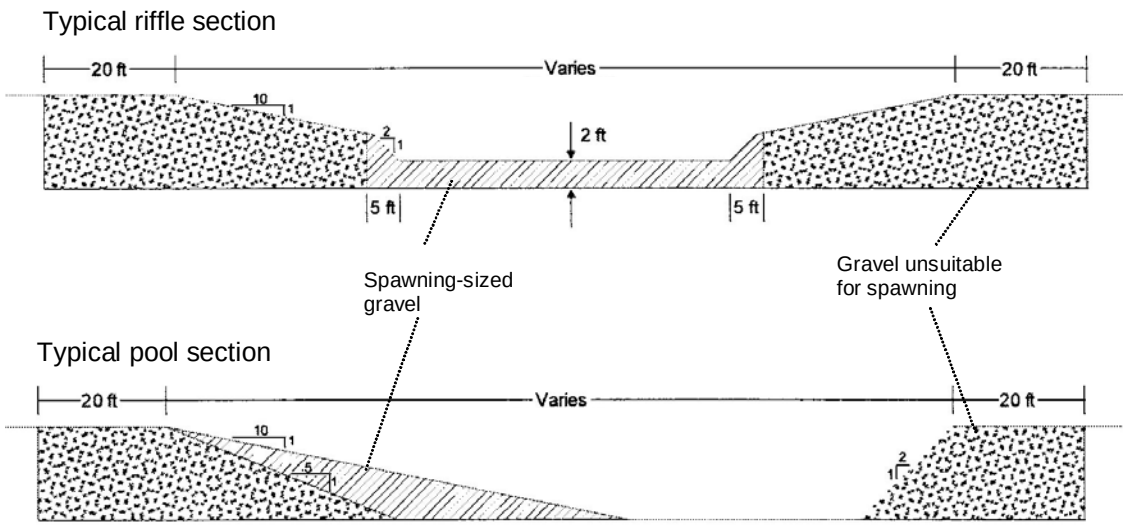


Fig. 2.3.4: Thick layer of spawning-sized gravel in overly-large cut channel to shape a designed, geomorphologically functioning channel in spawning gravel (copied from CDWR 2001 and slightly altered).

2.4 River segment-wide Gravel Augmentation and Management Plan

The river segment-wide Gravel Augmentation and Management Plan is the most recent approach to gravel augmentation. It attempts to overarch and consider all aspects affecting the geomorphological and biological functioning of a stream and the life stages of salmon in gravel-bed rivers. This ambitious approach is still in the planning and early implementation phase as it is currently (as of 2003) applied to a few rivers in California:

- Clear Creek (*The Lower Clear Creek Floodway Rehabilitation Project* by McBain and Trush et al. 2000).
- the Merced River (*The Merced River Corridor Restoration Plan,* by Stillwater Sciences (2001 a and b, 2002),
- the Trinity River (*Trinity River Flow Evaluation Study* and *Preliminary Draft Coarse Sediment Management Plan)*, by USFWS/HVT (1999) and McBain and Trush (2003a), and
- the Tuolumne River (*Coarse Sediment Management Plan for the Lower Tuolumne River* by McBain and Trush 2003 b and 2004a[3]).

A few consulting companies with extensive experience in fluvial geomorphology, riparian ecology, and fisheries biology are involved in these projects (including Stillwater Sciences in Berkeley, CA, McBain & Trush in Arcata, CA, and Graham Matthews in Weaverville, CA). These companies either provide scientific background for projects

[3] *A revised version of the report "*Coarse Sediment Management Plan for the Lower Tuolumne River" *was released by McBain and Trush in July 2004. Much of the manuscript for the present study (Bunte 2004) had been completed by that time and is based on the 2003 version unless where specifically noted.*

managed by government agencies or they manage the projects themselves. The terminology "*Gravel Augmentation and Management Plan*" was inspired from "*The Coarse Sediment Management Plan for the Lower Tuolumne River*" by McBain and Trush (2003b) and is adopted for the present study (Bunte 2004) to distinguish it from the spatially smaller multi-reach river restoration approach[4].

Similar to the multi-reach stream restoration approach, a river segment-wide gravel augmentation and management plan is based on the underlying idea that highly regulated streams need to be restored such that the post-dam flow regime and the given stream gradient facilitate annual or biennial mobility of the artificially supplied spawning-sized gravel. Once a geomorphologically functioning stream channel is established with equilibrium conditions between gravel supply and gravel transport, the resulting alternate bar morphology[5] will not only provide spawning habitat but habitat for many riverine salmon life stages. To achieve these aims, i.e., not only to improve the spawning success but establish favorable conditions for all salmon life in the stream, the coarse sediment management plan employs some of the same measures used in the local approach to gravel augmentation (Section 2.2) and in the multi-reach stream restoration approach (Section 2.3). However, the *Gravel Augmentation and Management Plan* then goes a few steps further and may include:

- A two-step approach with short-term stream restoration and long-term episodic passive gravel replenishment to balance the long-term coarse sediment budget;
- Extension of the spatial project scale to a stream segment of many tens of km (downstream gravel conveyance);
- Establishment of a seasonally variable flow regime that mimics pre-dam conditions and may receive additional flows in times of biological or geomorphological need;
- Reduction of supply of fines (or other substances harmful to fauna and flora) from the watershed;
- Purchase of riparian land to provide space for natural stream bank and floodplain development, and
- Project support through involvement of public and stakeholders.

2.4.1 Two-step approach: short-term active transfusion and long-term passive replenishment

A coarse sediment management plan consists of two temporal stages: 1) A short-term gravel supply that is used for stream restoration and gravel augmentation to build spawning habitat on riffles and to restore the stream to a geomorphologically and biologically functioning shape. 2) Long-term gravel augmentation supplied to upstream

[4] *This naming is not to infer that the "Merced River Corridor Restoration Plan" and "The Trinity River Restoration Plan" are in any way less advanced than "The Coarse Sediment Management Plan for the Lower Tuolumne River".*

[5] *The interaction between a particular flow regime, stream slope, particle-size distribution, and sediment supply forms a stream. Alternate bars are the resultant stream morphology is this particular case. Other channel forms result for different flow regimes stream gradient, particle size distribution and sediment supply.*

reaches that is meant to maintain the functioning of the restored stream and to compensate for the lack of natural upstream gravel supply.

2.4.1.1 Short-term transfusion

Short-term gravel augmentation in the context of a Gravel Augmentation and Management Plan is the first or restoration phase. It is to replenish the instream gravel storage, re-supply alluvial features, and create salmonid spawning habitat (McBain and Trush 2004). The word short-term in this context is not an absolute measure of time, but used to contrast long-term. Restoring a channel by short-term transfusion is a process that will likely take many decades to accomplish. The volume of gravel needed during this initial and active reshaping of the bed may be very large and the costs very high. In order to persevere, the newly created mobile bed of spawning-sized gravels needs to receive artificial long-term gravel supply.

2.4.1.2 Long-term gravel augmentation

In order to maintain an active stream bed with local scour and fill in the long run and to achieve a balanced coarse sediment budget over an appropriate reach length, gravel eroded off a riffle at high flow must be replaced by a deposition of gravel supplied from upstream during the falling limb of the highflow. The scarce post-dam upstream gravel supply is too low to balance the scour with deposition in the restored channel and needs to be supplemented by repeated episodic or periodic gravel augmentation.

The deliberate fining of the gravel bed achieved during the short-term gravel transfusion increases the post-restoration transport rates, such that long-term augmentation rates are higher than pre-restoration transport rates and may increase over time as larger areas of the stream are covered with spawning sized gravel erodible at near bankfull flow.
The required maintenance volume to be artificially supplied to the stream depends on the gravel supply from tributaries and on the amount of gravel generated in the new stream channel. If the design channel features lateral migration within a floodplain comprising spawning-sized gravels, then the amount of gravel to be supplied for long-term maintenance is less than if lateral channel migration is not part of the plan. In this case, annual supply may be similar to the long-term mean annual rate of downstream bedload transport estimated from bedload sampling or bedload modeling in the post-restoration channel (Section 4.3.4.2).

Passive augmentation approaches that place the gravel at some logistically convenient upstream “dump” location that is hydraulically suitable for gravel entrainment and transportation (Section 2.2.6) and that are considerably cheaper than direct applications of gravel into the stream can be selected for this task. From the augmentation site, the gravel will be transported downstream and take part in the cycle of scour and deposition. Prerequisite for the success of passive gravel augmentation is the undisturbed downstream sediment conveyance (Section 2.4.2) such that sediment supplied to and entrained from some upstream reach will benefit consecutive reaches downstream over time.

If the post-dam flow regime includes annual high flows and the channel bed is not too disturbed and without gravel sinks, a functioning channel may be attained and maintained simply by feeding appropriate amounts of spawning-sized gravel to the stream using passive augmentation (Section 2.2.6). Spawning habitat will develop on the natural deposits formed from the artificially supplied gravel. In this case, the short-term transfusion can be omitted. This saves costs, but given the relatively low mean annual travel distance for gravel (probably in the order of a few 100 m; Bunte and McDonald 1999)), it may take years to achieve the aim.

2.4.2 Downstream gravel conveyance

Scour, transport and subsequent deposition utilize the added gravel, but, except for attrition, the gravel is not used up. Once gravel sinks are filled, the added gravel migrates downstream, replenishing and maintaining spawning sites there. The longer the stretch through which the added gravel travels while creating spawning habitat on the way, the more "mileage" one gets from a specified volume of added spawning gravel. Optimizing the usefulness of added spawning gravel and thus the cost/benefit ratio is an important aspect of gravel augmentation, given the high cost of preparing and placing gravel for use in spawning habitat improvement (source identification, sieving, washing, storing, hauling, channel design and construction, gravel placement) and the large volumes of gravel needed. Establish a continued gravel conveyance over a many km long stretch of stream is therefore a prominent aim of a river-segment wide gravel augmentation and management plan.

One must consider, though, that once the gravel has completed its useful journey as spawning gravel, it may arrive at a stream location where the gradient is too low for further downstream travel, even when considering that attrition has decreased the gravel particle size. Ideally, the final deposition should occur in an area suitable to deal with the effects of this material.

2.4.3 Other measures

To optimize the beneficial effects of the added spawning gravel, gravel augmentation is often accompanied by other measures. These are briefly discussed below:

2.4.3.1 Establishment of a post-dam seasonably variable flow regime

Post-dam flow regimes reflect consumer need for electricity generation as well as flows used for agricultural and municipal water supply. The resulting seasonal hydrograph may therefore be quite different from the natural one. However, the geomorphological and biological functioning of a stream depends on a natural, seasonally variable hydrograph that includes an annual highflow season and enough water to ensure salmon life in the different riverine life stages (McBain and Trush 2000a). Because channel restoration can downsize and shape a stream to be geomorphological and biological functioning with

reduced water flow, it is easier to deal with a hydrograph in which all flows are about equally reduced than with an unvaried hydrograph or a hydrograph that has high and low flows at times of the year that do not agree with the needs of salmon in their different life stages. It is therefore important for the success of a Gravel Augmentation and Management Plan to negotiate a seasonally variable runoff regime with the reservoir operators that mimics a natural flow regime and provides favorable flow conditions (using e.g., PHABSIM or Habitat Suitability Curves) for all life stages of fish and benthic invertebrates.

2.4.3.2 Clean water supply: reduction of fines and other harmful substances

Clean water supply is vital to the success of gravel augmentation measures. The biological value of spawning gravel is reduced when fine sediment intrudes and clogs interstitial spaces which blocks intragravel flow. Gravel augmentation makes little sense in reaches downstream from locations where fine sediment supply occurs. It is therefore an important aim within a Gravel Augmentation and Management Plan to reduce the input of fines to a stream segment in which spawning habitat is created by gravel augmentation. This may be done by implementing erosion control measures in the watershed, by building sediment retention basins in the sediment delivering tributary, or by dredging accumulations of fines from deep pools.

The need for clean water likewise applies to other substances carried with the water flow that may be harmful to fauna and flora. For example, arsenic may leach from former gold mining sites and irrigation return flow may be contaminated; return flows from water treatment or power plants may be too warm. It is important for the success of spawning gravel augmentation to maintain water flows that are uncontaminated and have the right temperature regime over the year to agree with the fluvial ecosystem needs.

2.4.3.3 Purchase of riparian land

One problem for streams that could bear salmon spawning and salmon life is lateral confinement of the stream (Section 2.3.1). A geomorphologically functioning stream with an alternate bar or pool-riffle morphology will migrate laterally. This causes problems if the land up to the banks has a designated agricultural or infrastructure use. To provide space for the natural stream bank and floodplain development, a seam of land is needed along the stream banks free of plowed fields or roads. Purchase of streamside land by the agency responsible for spawning and fish habitat restoration and setting it aside for this use is therefore another aim of a Gravel Augmentation and Management Plan.

2.4.3.4 Project support through involvement of public and stakeholders.

Stream restoration and gravel augmentation for salmon spawning habitat improvement is likely to meet general public approval, but it may not meet the approval of those who see

their daily activities or their property curtailed by the proposed salmon habitat improvement measures.

Stakeholders (e.g., owners or authorized users of streamside land), public interest groups and the interested public need to be invited to stakeholder group meetings that give detailed information about the aims, construction plans and results anticipated in the Gravel Augmentation and Management Plan. Their concerns need to be heard and addressed, and they should be involved in the project whenever and wherever possible. The informed public or stakeholders who feel they have some say in the matter are much more likely to support the project and agree to changes in their activities or properties.

3. Adaptive Management in gravel augmentation studies

Some gravel augmentation projects can have a clear-cut approach: If the likelihood of erosion is very low, and the water quantity and quality is fine, spawning habitat may be created by simply placing spawning-sized gravel in a layer thick enough for spawning and with flow depths and velocities favored by spawning fish. In many cases, however, gravel augmentation is a difficult matter, because a series of things that went wrong with the stream after dam closure and destroyed the spawning habitat. Simply adding spawning gravel will most likely not provide a long-lasting beneficial effect, but send the gravel to follow the same fate as its natural predecessor. One needs to understand how water and sediment supply was altered by the dam and how this caused disturbances in the geomorphological and biological functioning of the stream before one can find a solution that will mitigate and restore the geomorphological and biological functioning of the stream under the given circumstances. Expertise in the understanding of fluvial and salmon-related processes alone is not enough to fix impaired spawning habitat, because the general knowledge about fluvial and salmon-related processes is not well enough advanced to accurately quantify processes and clearly see all relevant cause-and-response links. This means even experts have to rely to some degree on a trial-and-error approach in gravel augmentation. But doing so in a skillful and cautious way hopefully allows one to intervene in the restoration process should the results turn out undesirable.

In order to optimize the project benefits and to minimize the damage that might result if something went wrong during the gravel augmentation project, one needs detailed background knowledge of the natural processes involved, well thought-out project steps, good project oversight, and immediate as well as long-term monitoring of the obtained effects. The underlying model concepts about physical and biological processes in the stream, the steps taken until project implementation, and particularly the project results, must be repeatedly scrutinized with the aim to catch and correct potential errors early. The more adverse the stream conditions, the more complicated, far reaching, sophisticated and involved a gravel augmentation project is likely to be, and the less unsure one can be about the project outcome, the more scrutiny is required in all steps along the way. Project approaches to uncharted territory (and very much in the field of gravel transport is uncharted[6]) require pre- and post-project scrutiny which is provided by an Adaptive Management approach.

Adaptive management is a project strategy adopted when scientific understanding of the processes involved is incomplete. The project is then treated as a scientific experiment that employs clearly defined goals, measurable objectives, testable hypotheses and measurable results. Each project step gathers information that is then used to develop the

[6] *For example, gravel transport processes are still poorly understood and the difficulty associated with field measurements of gravel transport in non-wadeable streams makes it very difficult to verify modeled results. Similarly, habitat requirements of salmon in different life stages, and the natural fluctuation of salmon populations in different life stages, are not fully understood which makes it difficult to attribute a change in salmon population to a management effect in a direct and straightforward manner.*

next or modify an earlier project step (Halbert and Lee 1991). This approach allows the project implementers to revise former as well as future decisions that may not have had sufficient scientific basis. Applied to complex gravel augmentation projects, Adaptive Management prescribes a sequence of stages (Text Box 2).

The degree to which an Adaptive Management approach is followed within gravel augmentation projects increases with the spatial and temporal scale of the project, the project budget, and the degree of complexity, and with that, the degree of uncertainty. For quality assurance and quality control, funding agencies generally request that Adaptive Management be followed as a project strategy.

Text Box 2: Stages in projects following Adaptive Management

Assessment of problem (1)
↓
Establish objective (2)
↓
Establish models and assumptions (3)
↓
Design (4b)
↓
Implementation (4c)
↓
Monitoring (5)
↓
Analysis (6)
↓
Re-evaluation and adjustment (7).

The numbered[7] project stages in Text Box 2 are often not simply sequential, but may have to be followed in a circular fashion. In many cases, the circle is reinitiated from the monitoring stage (5) after which project results are evaluated to make changes in a second project round or a similar future project (Fig. 3a). However, a geomorphologically and biologically challenging gravel augmentation project may be so complex and feature so many unknowns that much needs to be learned at each project stage. Information obtained at any stage in the project, and particularly by monitoring of post-restoration geomorphological and gravel conditions as well as the spawning success, is immediately used to improve and readjust the project plan at whichever stage it may become necessary. This flexible and circular approach allows the project implementers to gain immediate benefit from the most recent learning and revise course wherever and whenever necessary.

[7] *For ease of comparison, the same numbering of project stages was applied to Text box 2, and Figs. 3a - d).*

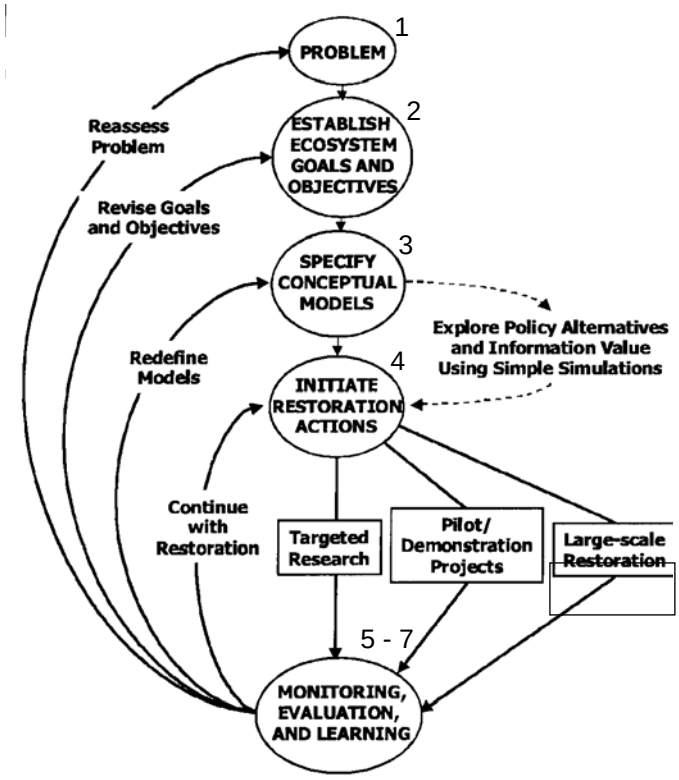
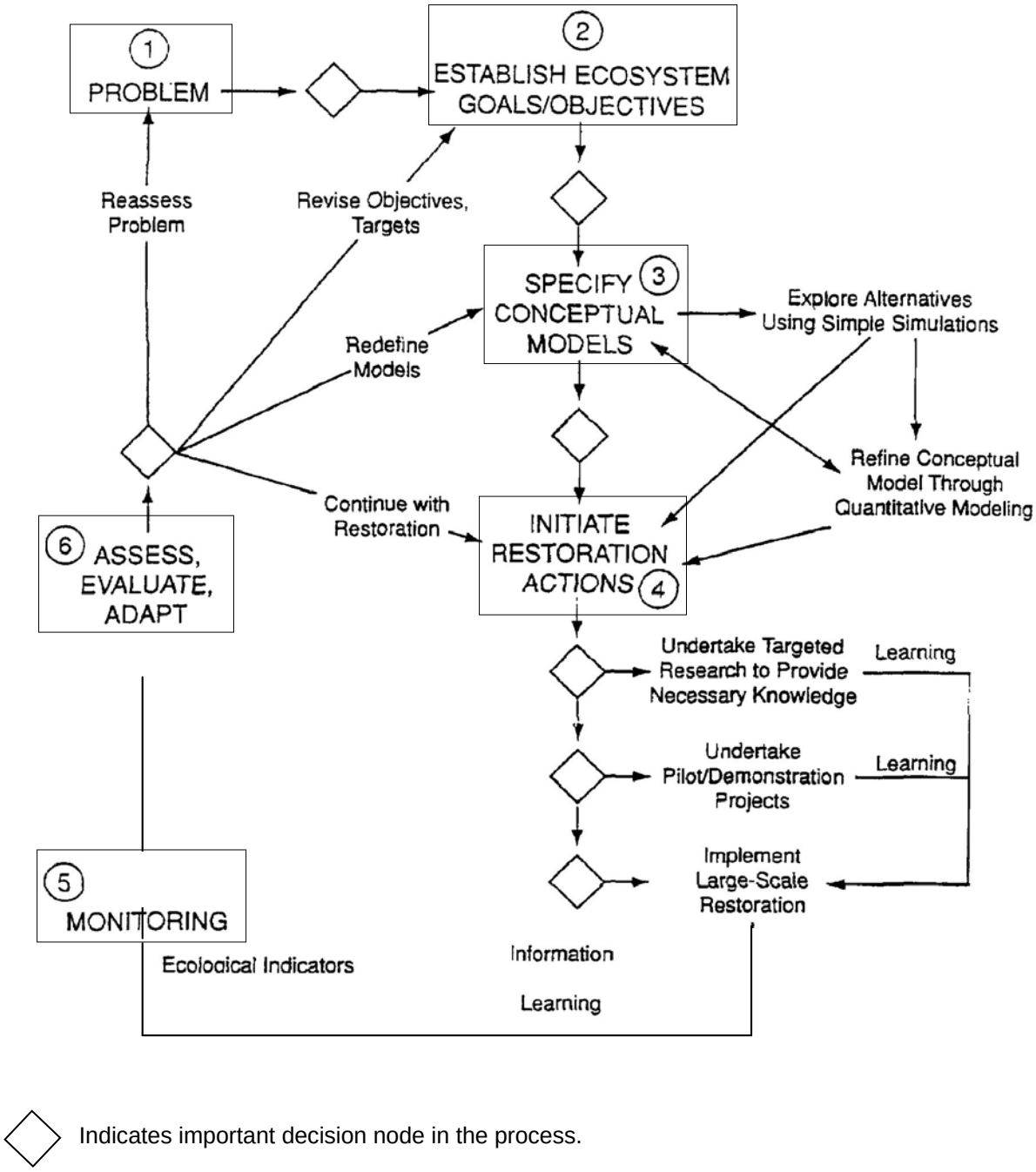


Fig. 3a: The adaptive management process. Source: Strategic Plan Core Team 1998. (Copied from: CDWR (2003); the numbering refers to stages in adaptive management and was added to the diagram).

The 5-stage adaptive management process in Fig. 3a is quite general and should be extended and adjusted to fit the specific project circumstances and needs. Examples of adaptive management plans used for a gravel augmentation project are shown in Figs. 3b to 3d. All three plans have added project steps around the implementation stage (4). In Fig. 3b, the proposed plan receives support from target research that is then applied locally in a pilot project before being applied to the restoration of a large river reach. Stage 5 that lumped monitoring, evaluation, and learning in Fig. 3a was split in two and obtained an additional 6th stage with assessment, evaluation and adaptation. Emphasis is put on the development of the conceptual model in this plan as side loops are added in which conceptual models are revised and refined through simple simulations and quantitative modeling.

The adaptive management plan in Fig. 3c has a channel-restoration stage added between the stages 3 and 4 in which a channel design is prepared, revised and finalized before the 4th stage of initiating the restoration, indicating that this project puts a strong focus on the design development. A new stage 4b indicates that the design implementation is likewise a major project stage.



Indicates important decision node in the process.

Fig. 3b: Organization of Adaptive Management and Monitoring. The CALFED Strategic Plan for Ecosystem Management (copied from McBain and Trush (2003 b) and slightly modified).

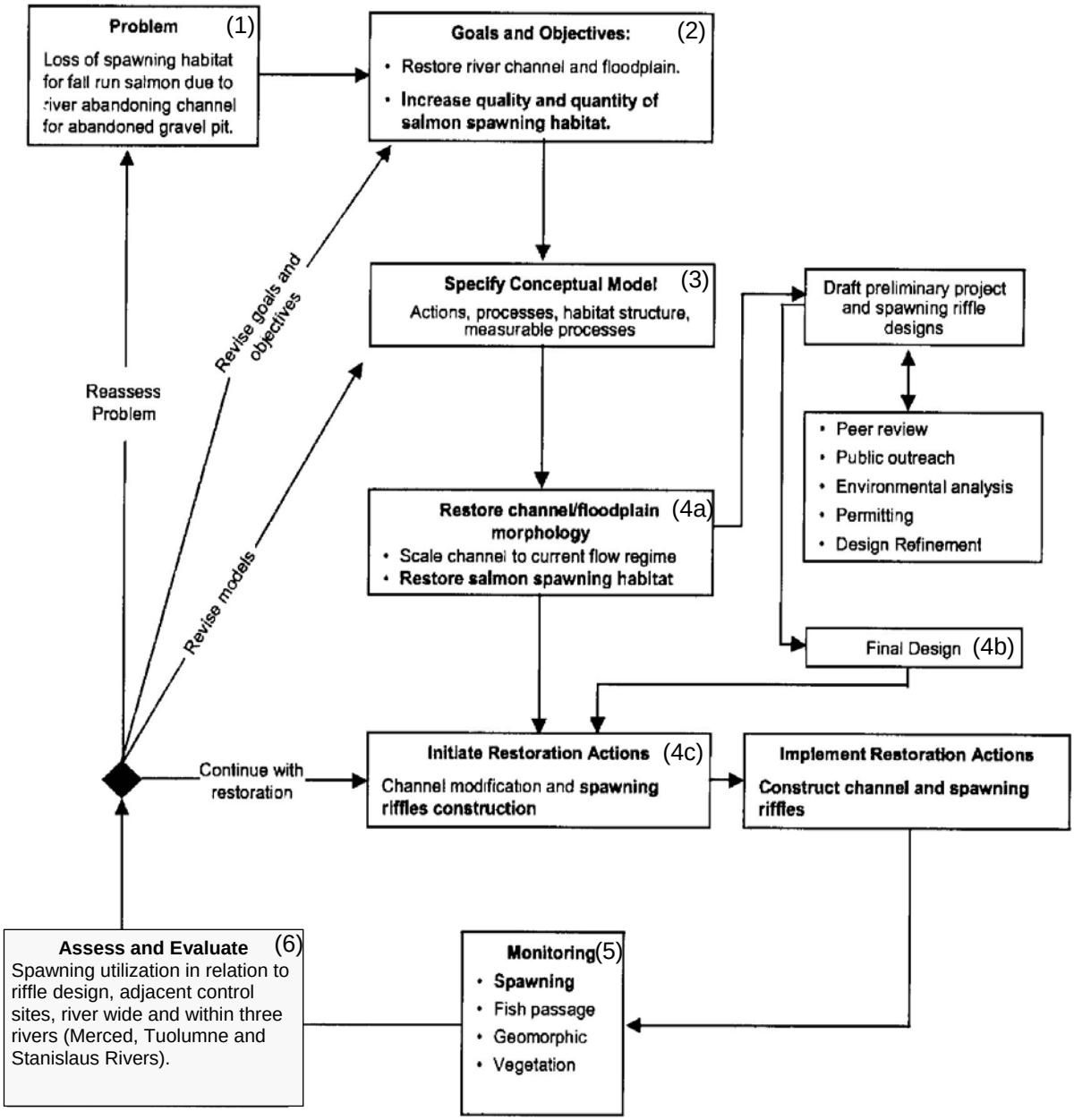


Fig. 3c: Adaptive Management Plan for Merced River Spwning Habitat Enhancement Project (copied from CDWR (2003), slightly modified).

The adaptive management approach followed in the Spawning Habitat Integrated Rehabilitation Approach (SHIRA) (Pasternack et al. 2004) focuses particularly on the design development (4a) and the adjustment of the design whereas the development of goals and conceptual models did not require particular emphasis in this project (Fig. 3d).

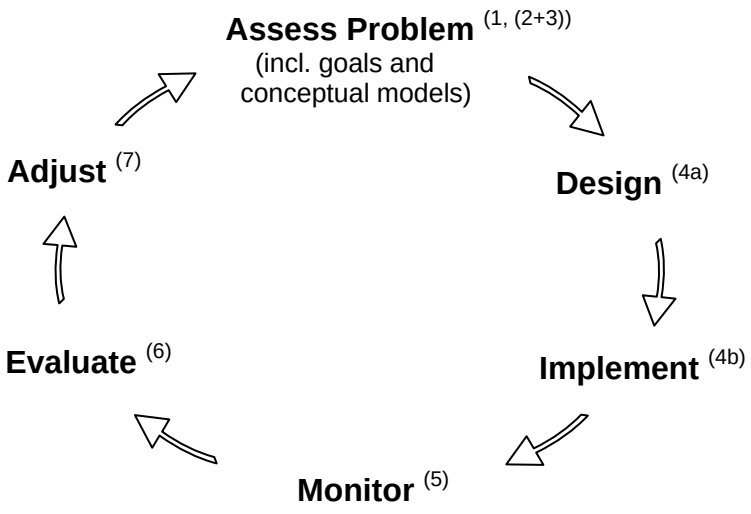


Fig. 3d: Adaptive Management within the Spawning Habitat Integrated Rehabilitation Approach (SHIRA) (redrawn from the G. Pasternack website (http://shira.lawr.ucdavies.edu) and slightly modified.

4. Project steps and tools

4.1 Straightforward, geomorphologically unchallenging gravel augmentation

Gravel augmentation studies can be small in temporal and spatial scale, of narrow scope, and in a geomorphologically unchallenging setting. This means that the flow regime is known and has a low probability of flood events that would cause substantial gravel movement and scour, and upstream gravel supply is stable and low or absent. Gravel augmentation in such a setting may be a straightforward matter of supplying a specifiable amount of spawning-sized gravel to a known area to accommodate a specified number of spawners. Project tasks in a geomorphologically unchallenging gravel augmentation project might be to:

- Verify that suitable spawning habitat is the factor limiting salmon populations. This would be the case if all other factors potentially limiting various stages of riverine salmon life are unproblematic (e.g., water quality, temperature, and flows are acceptable; low predation of juveniles, etc.)

- Obtain information on the critical flow above which bed particles start to move. This can be done either via tracer gravel experiments (Section 4.3.3.1) or through the computation of the dimensionless shear stress for a range of flows (Section 4.3.3.1). The computed value must be lower than an assumed critical value, a suggestion of which may be obtained from the literature.

- Verify that the probability of floods that move substantial amounts of gravel is very low;

- Verify that the flow regime suffices to occasionally entrain and slightly move the added gravel to maintain clean interstitial spaces;

- Obtain information on the upstream gravel supply or verify that it is cut off and consider it in the amount of spawning gravel to be supplied to the stream and whether that gravel needs to be re-supplied over time;

- Define the extent of the spawning rehabilitation area, either from the number of spawners to be accommodated or from the available area suitable to become spawning habitat;

- Compute the necessary gravel quality and quantity needed to augment the target area; Consider placement of gravel to achieve an undulated surface with humps and depressions in order to mimic a pool-riffle morphology with downwelling flow at the upstream side of each hump.

- Compute flow depth and velocities to be expected after the gravel has been supplied and ensure it is acceptable to spawning salmon (e.g., habitat suitability curves, PHABSIM);

- Ensure stream access is possible if gravel is to be placed using heavy equipment; weigh damage to benthic invertebrate and riparian vegetation versus benefits gained by augmented spawning gravel.

- Consider budgetary constraints.

- Estimate how long the beneficial effect of enhanced spawning habitat will last; will scour or clogging of interstitial space cause the augmented spawning gravel to deteriorate? Does the expected longevity justify the expense?

- Monitor success of the gravel augmentation and its beneficial effects (e.g., by measuring intragravel dissolved oxygen, intragravel flow rates, increase in the number of redds, number of hatchlings and fry emerged).

In contrast to relatively simple and straightforward projects (Section 4.1), gravel augmentation may be very complex, geomorphologically challenging, with a high degree of uncertainty regarding the volume of gravel needed and whether the created spawning habitat will have any long-lasting beneficial effect. Tasks in involved in this setting are described in Section 4.2 – 4.5.

4.2 Highly complex and geomorphologically challenging gravel augmentation

The problem necessitating gravel augmentation below dams is likely to be related to changes in water and sediment supply after dam closure. Project managers need to fully understand the concept that changes in water and sediment supply will cause changes in the shape and size of the stream, its bedmaterial size-distribution and the stream gradient, before problems in a post-dam stream situation can be identified. A brief overview of channel change following changes in water and sediment supply is provided below.

4.2.1 Channel change in response to altered water and sediment supply

Dams usually decrease the water and sediment supply to downstream reaches, but the extent of these reductions may vary widely between dams or for a given dam over time and with distance downstream from the dam. Changes in the magnitude and frequency of sand- and gravel-moving flows and in the upstream sediment supply lead to changes in the channel size and shape as well as in the bedmaterial size downstream of the dam. (This concept of channel response to changes in water and sediment supply will be picked up in the discussion of conceptual models in Section 4.2.7.1. See tiers two and three of the five-tiered model of physical and ecological linkages in an alluvial river-floodplain system in Fig. 4.2.7.1a). Specific interactions of flows and sediment transport cause specific channel configurations and bed material particle sizes: a large reduction in

high flows and small reduction in sediment supply will cause the channel to respond in a different way than a small reduction in highflows and a large reduction in sediment. It is not easy to predict the geomorphic outcome of a certain change in water and sediment supply for a specific case. An overview of the possible outcomes is provided in Table 1. Almost all of the outcomes have the potential to decrease or destroy salmon spawning habitat. Note that these effects are likely to increase with time since dam closure and decrease with distance below the dam. Channel responses are also not necessarily linear in space or time. A channel response observed close to the dam may switch into its opposite further away from the dam.

Table 1: Downstream response in channel shape to changes in (flood) flows and sediment supply according to Schumm (1969, 1971) and Hook (1997).

Change in flow and sed.	Response in channel shape	Description	Potential effect on spawning habitat
Q^-, Q_b°	S^+, D_{50}^-, d^-, w^-	Decrease of cross-sectional area due to aggradation and narrowing.	Gravel fining, Decrease in area;
Q^-, Q_b^-	S^*, D_{50}^*, d^*, w^-	Parallel decrease in flow and bedload is likely to causes channel narrowing, but may cause otherwise unpredictable channel response.	Decrease in area;
Q^{--}, Q_b^{--}	S^+, D_{50}^+, d^-, w^-	Strongly reduced flow and bedload supply cause bed scour below the dam, channel shrinkage and pavement formation.	Gravel immobility, Decrease in area;
Q°, Q_b^{--}	S^+, D_{50}^+, d^+, w^-	Low flows reduced or increased, supply of coarse bedload largely reduced, and high flows of pre-diversion magnitude causes strong armoring and the formation of deep pools.	Gravel immobility, Decrease in area;
Q°, Q_b^+	S^-, D_{50}^-, d^-, w^+	Sediment release into the system causes aggradation	Gravel fining, increase in area;

Q = highflow magnitude and/or duration, Q_b = bedload discharge, S = stream gradient, D_{50} = median bed-material particle size, d = mean depth of flow, w = stream width, $^+$ = increase in, $^{++}$ = strong increase in, $^-$ = decrease in, $^{--}$ = strong decrease in, $^\circ$ = no change, * = variable direction of change, ≈ = proportionality.

4.2.2 Necessity of understanding the underlying problem

A problem statement saying "loss of spawning habitat" may be true, but is not very helpful for correcting the problem, which would be best solved if the process that caused the loss of spawning habitat was remedied. Removal of an economically viable dam can rarely be suggested as a feasible solution. Instead, remedial actions will typically have to focus on tackling the adverse effects in the post-dam water-sediment interaction. If the post-dam water-sediment interaction can be analyzed and understood in a proposed gravel augmentation project, one has a chance to determine how the water-sediment

interaction should be influenced to obtain a post-dam channel that provides spawning and other habitat for salmon in riverine life stages. Different strategies can then be followed to address the problem. If the project envisions a long-term habitat improvement goal that extends over many miles of stream, with the underlying concept that a geomorphologically functional stream in which spawning-sized gravel annually moves without depletion and automatically provides biological functioning in its wake, then stream restoration to obtain a geomorphologically and biologically functioning stream becomes the goal. By contrast, it may be debatable whether in a long-term project approach is the most beneficial strategy to improve a biologically urgent problem in a specific case.

4.2.3 Long-term or short-term solutions?

Establishment of full geomorphological and biological functioning through restoration of a disturbed stream is a well thought out, but long-term solution to improving spawning success and the salmon population in general. Projects proposing reach-wide restoration and river-segment wide gravel management are still in the planning phase and full geomorphological and biological functioning may not necessarily be reached immediately after gravel has been augmented. The establishment of mature riparian vegetation and the large woody debris they provide to the stream is a particular long-term process. As a short-term interim solution, it may be necessary to respond to fish needs quickly by creating artificial spawning habitat in reaches of low entrainment probabilities and by creating diverse salmonid habitats with large woody debris and other structures nearby (Section 4.1). Those mechanically placed spawning gravels immediately provide favorable spawning conditions in terms of intragravel flow and dissolved oxygen, and the gravel tends to be readily accepted by spawners irrespective of the geomorphological unit at which the gravel was placed (Carl Mesick Consultants 2002 b). However, although quick and effective, gravel augmentation projects that are not tied into the geomorphological functioning of the stream may not have a long-lasting effect. If placed with erosion resistance in mind, the spawning gravel may not experience enough mobility, while the gravel may be scoured away if not placed in erosion protected location. Both long-term and short-term approaches are needed and should perhaps be used in combination with each other.

4.2.4 Steps and tools in complex and geomorphologically based gravel augmentation projects

Complex and geomorphologically challenging gravel augmentation projects follow an Adaptive Management Plan (Section 3) that comprises a sequence of project stages (Text box 2, Figs. 3a-d). To fulfill the project stage requirements, one needs to carry out a variety of specific tasks at different project stages. The tasks, or their importance within a gravel augmentation project, vary depending on the specific project settings, focus, and problems. This study uses the examples of two management plans from complex gravel augmentation studies to explain the tasks involved in complex and geomorphologically challenging gravel augmentation projects:

1. The river-segment-wide Gravel Augmentation and Coarse Sediment Management project at the Tuolumne River (McBain and Trush (2003b), focusing on long-term geomorphic and biological functioning (Table 2).

2. The reach-scale gravel augmentation project at the Mokulumne River (Pasternack et al. 2004; Wheaton et al. (2004 a, b), focusing on creating optimal spawning habitat at the local scale (Table 3).

Both management plans have commonalities as well as differences. For example, specific tasks are performed at different times in the project, some tasks are solved by measurements in one project and by modeling in the other, and the importance and amount of discussion provided to specified topics is different. Thus, there is no one-to-one match between the presence of tasks or their timing within the project. A further difference is that the plan for creating optimal spawning habitat at the local scale has already been successfully applied, while the plan for the river segment-wide Gravel augmentation and Coarse Sediment Management Plan describes planed project activities. Based on these two different management plans, this study selected series of (mainly geomorphological) topics to be discussed in more detail.

4.2.5 Identifying the problem through assessment and comparison of pre-project and pre-dam conditions

The first steps in a gravel augmentation project are an assessment of the current and past conditions of flow, amounts and timing of sediment transport, the stream morphology and bedmaterial sizes as well as the size and dynamics of fish populations. These conditions are then compared to pre-dam conditions (assuming spawning habitat was ample and undisturbed then) or to desired post-dam conditions (which may be crafted after a comparable but undisturbed neighboring stream). Some information on current and past stream conditions may be available from earlier and unrelated projects or from routine monitoring carried out by government agencies. Familiarization with the past research and monitoring activities at a gravel augmentation reach as well as scouting and gathering this information is an important step at the beginning of a gravel augmentation project. Other information has to be actively measured. A variety of field tools and computational analyses can be used for these tasks. Many of the tools, described here in general and relatively simple terms, require expertise in fluvial geomorphology, sediment transport, hydrological analyses and fisheries biology. Someone unfamiliar with these fields of knowledge should not attempt to use their tools without expert help.

Table 2: Sequence of specific tasks and stages of adaptive management required for river-wide gravel management and augmentation project

Specific task requiring field work, data analysis or modeling	Adaptive Management Stage
A. Assess conditions a. First set of field surveys. b. Analyze pre- and post-dam water supply. c. Analyze pre- and post-dam sediment supply. d. Compare maps and aerial photograph from pre-dam and post-dam times. e. Gather any kind of information that could be relevant or helpful.	***1) Identify the problem:*** *does lack of gravel quantity and/or quality necessitate gravel augmentation.*
	2) Establish goals and measurable objectives *for gravel augmentation project.*
	3) Establish a conceptual model *regarding interaction of flow, gravel transport and deposition, and fish spawning habitat.*
B. Identify what needs to be computed or modeled for a gravel augmentation project.	
C. Field investigations to quantify input parameter for geomorphological computing and modeling and establish pre-project conditions. a. Topographic survey, incl. cross-sections. b. Geomorphological survey. b. Pebble counts, tracer experiments, and scour cores to determine bed mobility and scour depths. c. Measure bedload transport rates.. d. Stream survey to determine quantity and quality of spawning gravel. Compare to pre-dam conditions.	
D. Gather information relevant to salmon spawning and population dynamics.	
E. Compute and/or model to solve specific questions for gravel augmentation. a. Determine sites and prioritize them. b. Design channel based on hydraulic and sediment transport modeling. c. Compute gravel amounts and sizes. d. Determine methods of placement and devise augmentation schemes (e.g., initial, large volume transfusion and long-term, low volume passive augmentation for maintenance). f. Consider gravel sources and costs.	
	4) Design and implement planned actions.
	5) Monitor project effects *through geomorphological and salmon related field surveys.*
	6) Analyze, evaluate and make adjustments wherever necessary

Table 3: Sequence of phases and tasks performed in different project modes within the Salmon Habitat Integrated Rehabilitation Approach (SHIRA) at the Mokulumne River. Bold entries with numbers in parentheses refer to stages in Adaptive Management (from Wheaton et al. 2004 and slightly modified).

Phase	**Project modes**			
	Data Collection	**Conceptualization**	**Modeling**	**Scientific Exploration**
1: Preliminary Planning	Baseline data collection; Historical flow analysis; Compile historical annual redd surveys and HSC; Historical geomorphic analysis;			
	Historical context summarized Recognize basin context (watershed assessment)			
		Define Problem (1) **Develop conceptual model (2)** **State Objectives (3)** Select monitoring indicators and select timeline; Recognize how project fits into basin management plan; Feedback from stakeholders		
	Identify project constraints (e.g., budget, access, construction, timing, gravel availability)			
		Select specific project site		
2: Pre-project	Topographic survey for DEM generation and habitat mapping; Bedmaterial characterization; Collect flow validation data		Build and run hydrodynamic, habitat suitability and sediment entrainment models; Validate and refine models	
3: Design		Formulate designs	Model, test, evaluate and rank designs	
4: Final design		**Select final design (4)** and prepare construction documents		
5: Construction	Communicate key goals and design elements to contractor (including: construction access, gravel particle-size distribution, handling and cleanliness, construction staging areas, identification of sensitive areas and potential hazards); Stake construction area to delineate boundaries, fill elevations, etc.			
	Observe construction (4b) for clarification, modification and reality check			
6: Project Assessment	Topographic survey and habitat mapping; Bed material characterization; Collect flow validation data	Prepare first post-project appraisal	Run hydrodynamic, habitat suitability and sediment entrainment models; Validate and refine models	
7: Long term Monitoring and Adaptive Manage-Ment	**Long term monitoring (5)** of pre-defined indicators and track morphological change and habitat utilization.			
	Adaptive Management (Assess and evaluate) (6)			
				Publish data as part of an information inventory

4.2.5.1 Field maps, aerial photographs, balloon photos and historical documents

Spatial information from field investigations (including geomorphological units, different habitat features, redds, etc.) are best recorded, analyzed, and presented in maps. Field maps can be prepared from recent aerial photographs in a scale of 1:24,000 that are enlarged to a workable scale of 1:6,000 or 1:1,200 and laminated for field use. High resolution maps with a scale of approximately 1:20 can be obtained by rectifying and aligning overlapping photographs taken with a digital remote-control camera attached to a tethered helium balloon held at a height of about 10 m. Impressive composite "balloon photos" are provided by McBain and Trush (2003 c). Field observations can be drawn directly onto maps for digitization and spatial analyses in the lab (e.g., computing and summing areas of particular characteristics, such as riffles or salmon habitat. See Section 4.3.1 for topographic surveys). Information on pre-dam stream conditions obtained from early aerial and landscape photographs or drawings, old maps and newspaper reports on stream events may help to better understand the current stream condition.

4.2.5.2 Pre-dam and post-dam hydrographs

Obtaining and analyzing flow records for pre-dam and post-dam times is an important part of a gravel augmentation project (Kondolf 1995b). If flow records are not available from locations near the project, records from neighboring streams will have to be used as a substitute and appropriate adjustments may have to be made. If a local stream gauge is not available, the project should immediately start automatic stream gauging as well as discharge measurements and establish a stage-discharge rating curve. An approximate long-term record for the project site can be computed by comparing measured flows to those from a suitable established long-term gauging station. Searcy's (1959) method for flow duration extension is based on a comparison of flow duration percentiles, while Emmett's methods (pers. comm., 1995) is based on a comparison of mean monthly flows.

A hydrograph component analysis of pre-dam and post-dam flows (e.g., Kondolf and Matthews 1993; McBain and Trush 2004b) is used to determine changes in the post-dam timing of highflows, decrease in base flows and peak flows, and changes in the flow frequency distribution between the pre-dam and post-dam flow regime. These changes should be analyzed with respect to effects on post-dam gravel bedload transport characteristics (Sections 4.3.4 and 4.4.4) and be compared to pre-dam conditions and the effects on salmon needs. Post-dam highflows not only need to be large enough to move gravel annually, but flows during the entire year need to be appropriate to support salmon in all life stages. A visual example of these different needs is provided in the richly illustrated brochure by McBain and Trush (2000a).

4.2.5.3 Pre-dam and post-dam geomorphic features and sediment supply

Visual analysis of stream features

A visual inspection of the stream features (such as channel shape and size, bedmaterial size, closeness of riparian vegetation to the stream bank) may provide insight into the current state of sediment supply in relation to transport capacity, i.e., the amount of

gravel transportable under the current flow regime. A lack of upstream sediment supply may show as scoured bar surfaces that are at a low elevation above the bed. The channel bed is likely coarse with little fine gravel, perhaps even mossy and with little or no signs of current movement. Bedrock may be exposed and riparian vegetation may be scoured. Fine sediment may have accumulated in stillwater zones. A comparison of aerial photographs taken at different times before and after dam closure with most recent field mappings may show a decrease in the number and size of riffles and bars, while pool areas may be increased. A lack in post-dam gravel mobility may also be indicated by vegetation that established close to the banks and is of similar age as the dam.

Cross-sections surveys and analyses

Cross-sections surveys are useful for analyzing the stream shape and also serve as input parameters for hydrodynamic modeling and bedload transport computations. Comparison to cross-sections surveyed for some other, earlier project at that stream can provide an insight into change over time. Lateral erosion following a lack of upstream supply may have resulted in overly wide cross-sections, while downcutting may have caused cross-sections that are narrow in comparison to undammed and unimpaired neighboring streams. An indication of a post-dam bankfull stage, with vegetation-free gravel deposits that are annually or biennially flooded and mobilized, and a knickpoint to the higher elevation, less frequently flooded floodplain, may not be visible in the stream bed because no channel-forming gravel material is annually or biennially transported.

Surface particle-size distribution (pebble counts)

The surface particle-size distribution in gravel and cobble bed streams can be determined from pebble counts. Particles identified from a pre-selected pattern (usually parallel transects or a reach-spanning grid) are picked up from the stream bed and passed through a template (or gravelometer) to measure the particle-size class. Measured values are recorded, preferentially in series from bank to bank and for each transect individually (Bunte and Abt 2001a and b). A frequency distribution and the percent cumulative frequency are computed from which percentile sizes D_x (for which x% of the distribution are smaller) are determined. The number of particles to be sampled increases with the range of particle sizes encountered on the stream bed. Collection of about 100 particles is often considered sufficient for information on the D_{50} to D_{84} particle sizes in relatively well-sorted (or narrowly graded) deposits. Collection of about 400 particles usually ensures that percentiles between the D_{25} and D_{95} can be determined with sufficient accuracy in moderate to poorly sorted deposits (Rice and Church 1996).

A comparison of the bedmaterial size below the dam with pebble count results from reaches above the dam may demonstrate post-dam bed coarsening. However, only upstream and downstream reaches with similar gradients and uninfluenced by direct hillslope sediment contribution should be compared to eliminate the effects local stream competence and lateral sediment input.

Pre- and post-dam mean annual gravel load

Several options exist to estimate the pre-dam mean annual gravel supply and compare it to the post-dam gravel transport. None of the options provides a superb result, all have their weaknesses, thus several approaches should be used together to obtain a range of values. See Section 4.3.4.1 for a more detailed description of these methods.

The average growth rate of the delta at the upstream end of the reservoir provides an estimate of the pre-dam mean annual gravel supply. The volume difference between two surveys made about 20 years apart is computed and divided by the number of years between the surveys.

Annual sediment load can also be computed from field measurements of bedload transport (Section 4.3.4.1) upstream and downstream of the dam. A rating curve that relates bedload transport rates to the instantaneous rate of flow at the time of sampling is then applied to a long-term flow record to obtain annual sediment load for individual years.

4.2.5.4 Additional effects from anthropogenic instream and watershed disturbances

Besides the dam, there may be other anthropogenic or natural influences that could have affected the stream condition and the geomorphological and biological functioning of the stream. These may result from instream disturbances such as deposits left over from gold or gravel mining and confinement of the stream by riprap along the banks. Downstream disturbances unrelated to the upstream dam (such as lowering or raising the erosional base due to instream gravel mining (Kondolf and Matthews 1993; Kondolf 1997) or either taking out or constructing a dam/weir downstream) migrate upstream and cause incision or aggradation in reaches affected by the upstream dam.

The post-dam flow release patterns may have changed over time, and the stream may have received or lost water to other uses besides the dam. The water quality may be changing as water of different temperature is released, or water is becoming more contaminated by pollution or fine sediment. Tributary water and sediment supply may be changing due to management activities (e.g., logging) or natural disturbances (e.g., fires) in the watershed. The geomorphological and biological effects of a recent large flood may still be predominant or the stream may be in a phase of pronounced change from the flood disturbance. The possibility of multiple, perhaps even counteracting influences increases with the geographical extent of the project. All of these influences need to be considered, their extent quantified and their role in the post-dam water-sediment interaction be determined before one can formulate the problem and set up goals for mitigation. Not considering the larger picture of how various instream and watershed effects influence a stream reach may lead to a wrong choice in the means for addressing the problem. For example, gravel augmentation may not be the most important action to increase spawning habitat if a sand wave is passing a spawning site or predicted to arrive. Flushing flows may be in order instead (Section 4.3.6.2).

4.2.5.5 Does lack of spawning gravel quantity and/or quality necessitate gravel augmentation?

Based on an assessment of current and past conditions of the stream (i.e., channel shape, bed material, riparian vegetation, post- and pre-dam hydrographs, pre-dam mean annual sediment supply, change in the number and size of sediment storage areas along the stream) one can start to identify the geomorphological and biological functions that have been impaired. A number of different questions could be formulated in the problem statement: Which parts of the fluvial and biological ecosystem are disturbed? Why is the disturbance detrimental to spawning habitat? Is spawning limited due to a scarcity in suitable gravel deposits or to their poor quality? What other factors limit spawning? Will juveniles survive? (See Sections 4.3.5 and 4.3.6 for more information on assessing quantity and quality of spawning habitat).

4.2.6 Establishing goals and objectives for a gravel augmentation project

Establishing goals and objectives is the second stage in an adaptive management approach. Here, the changes that ought to happen in the stream in order to mitigate the spawning problem are formulated, and an action plan is devised describing measures that can reasonably be done to mitigate the problem. Initially, goals can only be general, but need to be refined and concretized as more information is gathered when the stage "goals and objectives" is revised before the onset of the design phase. Measurable goals and objectives need to be set as a basis for discussion with technical personnel or stakeholders and for pre-project phase evaluation before project implementation.

4.2.6.1 Goals depend on the project settings

Precise project goals depend on the project setting and stream projects. The problem statement might find, for example, that flows are reduced by the dam but still exceed the transport capacity for gravel during moderate flood events. The excess transport capacity erodes the gravel that receives no upstream supply and causes spawning gravel scarcity. As added spawning gravel would not remain in place for a long time given these flows, the primary goal might be to manage reservoir operation to reduce flood peaks and thus bed scour. The secondary goal might then be to add spawning gravel at locations least prone to erosion.

In another setting, the problem statement might find that so much water is withdrawn from the stream system that the gravel in the stream bed never moves and that fine sediment supplied by tributaries below the dam makes the gravel unsuitable for spawning. In this case, the goal could be to reduce the size of the active streambed, such that the force of the flow in the downsized channel would be adequate to restore annual gravel mobility. Another goal would be to obtain an annual highflow release from the dam that ensures gravel mobility. A third goal would be to curb the tributary sediment supply through watershed restoration, pool dredging and/or sediment retention basins. Creation of spawning habitat would follow almost automatically once annual gravel mobility is restored and fines are reduced. However, if there is no upstream gravel

supply, the fourth goal would be episodic gravel supplementation to maintain the equilibrium between sediment transport and sediment supply. Setting goals requires a thorough understanding of the geomorphological and biological processes and interactions of different factors in the specific project setting. This understanding can be complemented or deepened by formulating conceptual models that describe the functioning of the stream system (Section 4.2.7). A goal in short-term gravel augmentation projects may be the quick creation of large spawning areas wherever feasible in the stream to provide urgently needed spawning habitat (Carl Mesick Consultants 2002b). By contrast, goals of a gravel augmentation project may also be the well-thought out placement of spawning gravel to achieve an optimal solution between the quality and quantity of spawning habitat, erosion resistance with moderate gravel movement during flood events and the least gravel use (Pasternack et al. 2004; Wheaton et al. 2004 a and b).

4.2.6.2 Setting measurable project goals and objectives

Measurable project goals constitute quantifiable changes in physical or biological properties over space and/or time. In pre-project discussions, they facilitate an evaluation of whether the planned changes in properties are feasible. In post-project evaluations, quantifiable properties facilitate an evaluation of whether the project implementation has resulted in a beneficial change of stream properties (Kondolf and Micheli 1995). Measurable goals may not be specifiable to a fixed value; instead, a fixed range of acceptable values may need to be set. Measurable goals in geomorphological channel properties could be whether the channel is filled to the bankfull stage by bankfull discharge and whether a preset number and size of pools and riffles have been established. Measurable goals in spawning gravel properties could include whether a preset particle-size distribution, intragravel flow rate, and dissolved oxygen content has been attained (See Section 6.1.4.3 for a listing of parameters to be monitored). Measurable project goals that are based on a pre-project evaluation and an up-to-date science background facilitate a meaningful post-project appraisal from which something can be learned for future projects. In the absence of measurable goals, there is nothing against which to compare the project outcome (Kondolf 1995b) and little to learn.

4.2.7 Establishing a conceptual model

A conceptual model should describe how the system with all (or most) of its relevant components and interactions ideally would work. The conceptual model established for a specified stream project is based on general expertise in the fields of fluvial geomorphology, sediment transport and salmon biology and through an assessment of the flow, sediment, and salmon conditions in the project reach. It may incorporate other conceptual models that are generally known and accepted in these fields and that are suitable to describe parts of the geomorphological and biological system.

The conceptual model is based on information gained in the initial problem statement and the goal formulation. However, the act of formulating the conceptual model may help to redefine it and allow one to see the problem in a different way, which may then lead to a

different approach to fixing the problem and to a revised project goal. The sequence of problem statement, goal setting, and establishing a conceptual model may thus have go through several iterations, each time with a little more understanding (Fig. 4.2.7) until coherence is reached between the three stages. Goal setting and establishing conceptual models may become so interwoven that the actual order of the stage (goals first or conceptual models first) is of little importance and might be interchangeable.

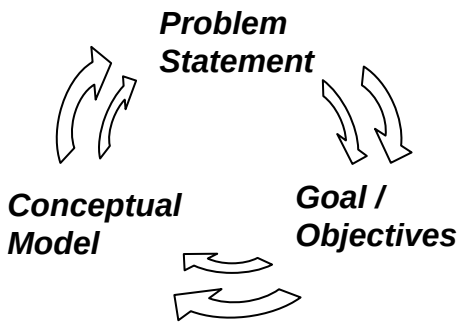


Fig. 4.2.7: Circular sequence of problem statements, setting goals and objectives, and formulating conceptual models.

Conceptual models concerning the water-sediment interaction vary for different stream types, e.g., alluvial rivers and bedrock rivers. For gravel augmentation projects in alluvial gravel-bed rivers, McBain and Trush (2003 a and b) use a conceptual model that is based on two major components:

1. Interrelation between fluvial processes and salmonid habitat, and
2. Attributes of a geomorphologically functioning stream.

4.2.7.1 Interaction between fluvial processes, sediment supply, transport and conveyance, and salmonid habitat

The five-tiered alluvial ecosystem

An alluvial river system can be depicted as five-tiered hierarchical system. Watershed inputs (e.g., flow regime water and sediment supply) on the top tier affect the interactions between flowing water and sediment supply (fluvial geomorphic processes) (Fig. 4.2.7.1 a) on the next tier down. The measurable outcomes are channel and floodplain form, size, and gradient as well as water temperature and turbidity on the third tier (See also "Downstream response in channel shape to changes in (flood) flows and sediment supply", Table 1). The stream with its specific size, shape, bedmaterial and water flows provides aquatic and terrestrial habitat on tier two and the habitat conditions determine the biotic stream ecosystem on the first tier. Thus, sediment transport processes driven by water and sediment supply and their interactions create the geomorphic features of the channel, such as alternate bar sequences and floodplain surfaces. These geomorphic features are the critical linkage between fluvial processes and the native biota that use the river corridor.

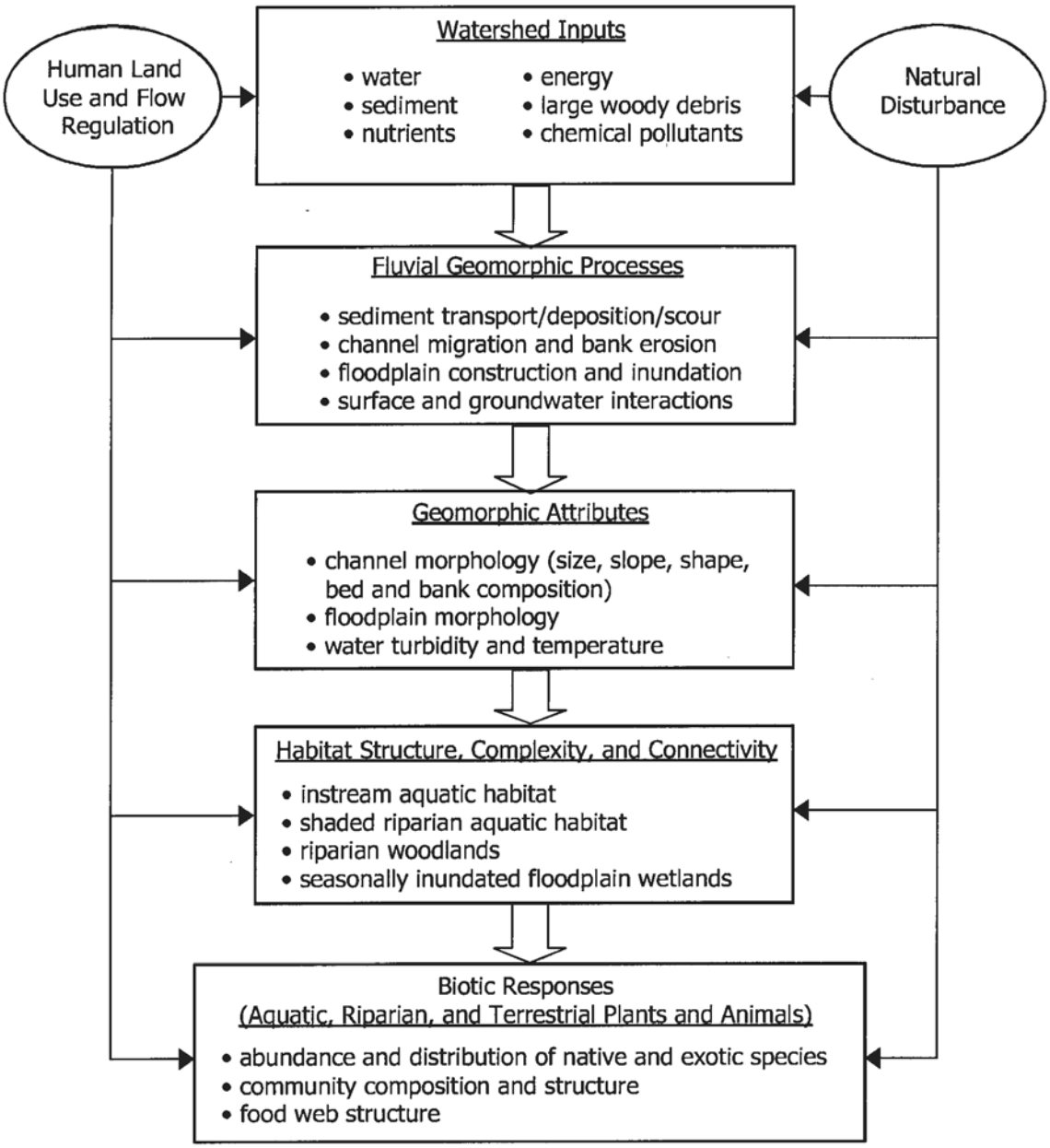


Fig. 4.2.7.1a: A tiered model of physical and ecological linkages in an alluvial river-floodplain system (copied from Stillwater Sciences 2002).

Gravel augmentation projects need to consider that changes to the input variables (e.g., water and sediment) on the top tier cascade down to lower tiers and affect spawning habitat as well as the biotic system. Human and natural changes can affect any level of the tiered system when cascading down through the system. An example of how the tiered model can be used to obtain a conceptual model of current processes and linkages is shown in Fig. 4.2.7.1b.

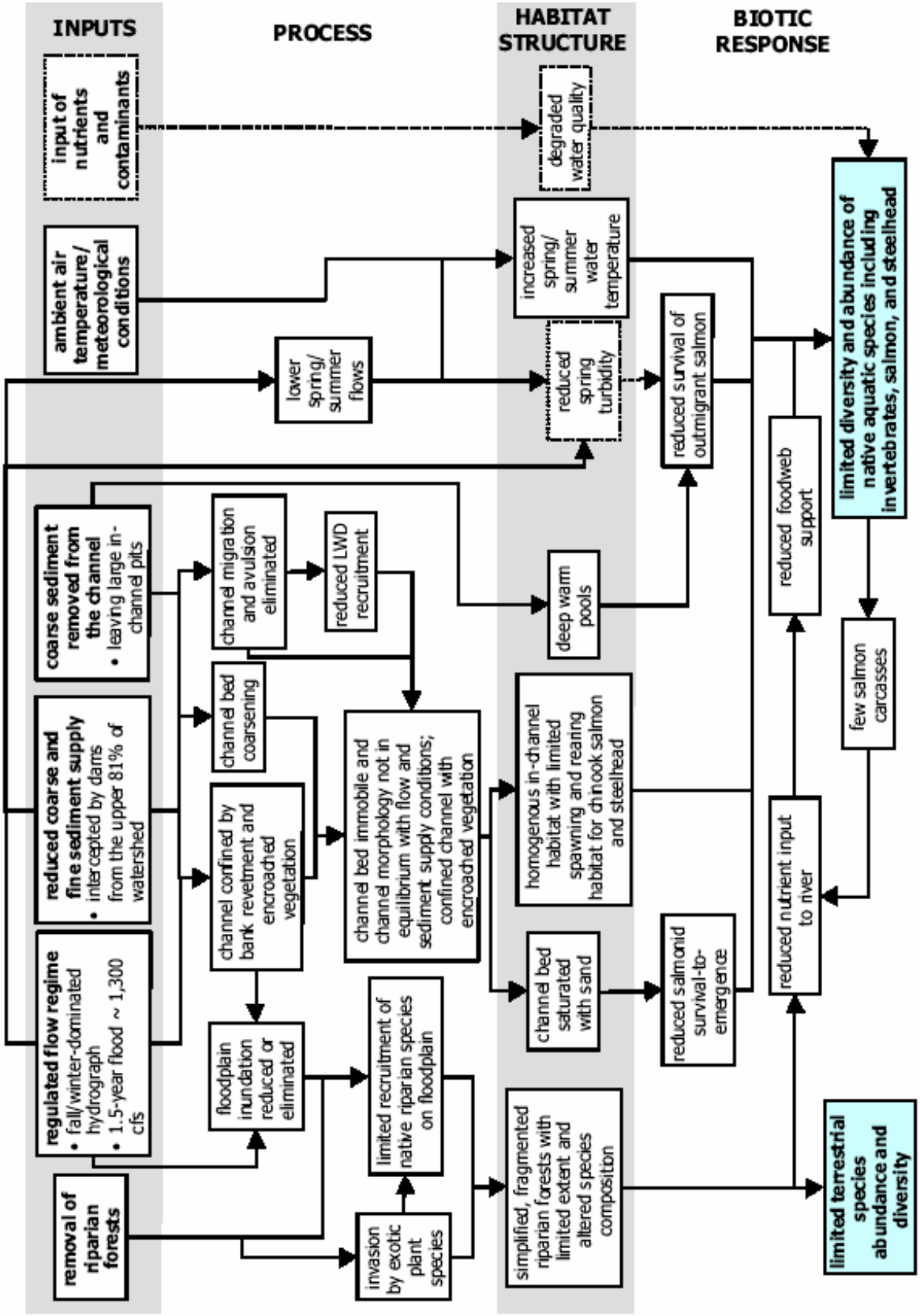


Fig. 4.2.7.1 b: Conceptual model of current processes and linkages. Example from the Dredger Tailings Reach of the Merced River, CA. (copied from Stillwater Sciences 2002).

Scour and fill versus aggradation and degradation

A conceptual model about gravel transport processes in alluvial streams is the scour-and-fill cycle. Scour-and-fill is a short-term process (intra-event), while aggradation and degradation typically are long-term processes spanning years and decades (except when caused by extreme events). When flow velocity and shear stress on the bed increase at high flows, particles erode off a streambed location and are replaced by newly arriving particles from upstream. Scour-and-fill occurs with a local exchange between out-going and in-coming particles. The process might experience short-term imbalances. As flow becomes stronger, particles continue to erode off, but newly arriving particles from upstream are passing by without being deposited or particles from upstream have not arrived yet and once they arrive they pass by. The location then experiences a net scour. As flow recedes, gravel arriving from an upstream scour location tends to deposit at the former scour site. As more particles are deposited than eroded off that location during the falling limb of flow, the scoured area receives a net deposit. The sediment balance at that site is being restored (see Section 4.3.3.2 for field measurements of scour and fill). Scour-and-fill processes form and maintain the channel morphology, prevent riparian encroachment into the active channel and maintain aquatic habitat, including clean spawning gravel for salmonids. Sediment moving through the system is stored in depositional areas at times of low flow.

Aggradation and degradation, by contrast, are typically long-term (years, decades) processes that indicate a disturbance in the relation between the actually transported and the supplied amount of sediment. If the long-term amount of sediment transported downstream is larger than the upstream sediment supply, the channel aggrades over time, while a continued supply that is less than the transport capacity degrades the bed. Aggradation and degradation change not only the physical appearance of the stream but also the results of the water and sediment interactions. Outcomes of aggradation or degradation may be desirable or not, depending on what is considered a desirable budgetary state of a particular stream. Channels that are in a "dynamic quasi-equilibrium" transport over the long run the same amount of sediment as is supplied from upstream (Leopold et al. 1964; Schumm 1977). The general morphology of the stream is maintained although scour-and-fill associated with the routing of material through the system produces local variations in the channel bed topography.

Bankfull flow, pool-riffle-bar units, gravel transport paths, and fish habitat

Another conceptual model employed for restoring alluvial gravel-bed rivers is that of bankfull flow and its importance for shaping and maintaining stream features in perennial streams with a rainfall or snowmelt flow regime[8]. Although the frequency of flows generally declines with their magnitude in natural flow regimes (disregarding the smallest flows which might occur infrequently, too), among the flows that have the capacity to shape and modify the channel, bankfull discharge occurs most frequently. With a return period of approximately once every 1.5 years, and the capability to shape the bed, bankfull is the most important discharge for scaling and forming the channel in its cross-

[8] *The role of bankfull flow is different for ephemeral or desert streams which should not necessarily scaled to bankfull flow (Kondolf et al. 2001).*

sectional shape (width, depth), plan form (meander characteristics), longitudinal form (gradient) and bedmaterial size. The 50-year flood certainly has more shaping capability, but occurs so rarely that more frequent but smaller highflows shape the channel most of the time. This means that the restored stream channel needs to be sized such that the channel is filled to the morphological "bankfull stage" at the post-dam 1.5 year recurrence flow.

Geomorphologically functioning streams with ample spawning habitat often have a riffle-pool (or alternate bar) morphology composed of two rows of longitudinally repeated pool-riffle-bar units that are laterally off-set to each other (Fig. 4.2.7.1 c). A pool-riffle-bar unit has the scour pool at its upstream end, followed by a pool tail and a riffle that ends in a downstream aggradational lobe, which is the lateral or point bar. The next pool-riffle-bar unit downstream starts with its pool on the opposite side of the lateral or point bar from the upstream unit. The major pathway of gravel bedload takes a meandering downstream course that does not follow the thalweg, i.e., the deepest part of the stream. Instead, it travels over the upstream end of the point bar (bar head) down into the pool tail and laterally over the riffle to the next bar head downstream (Bunte et al. 2004b) and follows a course similar to the one measured for the coarsest sand in a sand-bedded stream (Whiting and Dietrich 1993; Julien and Anthony 2002).

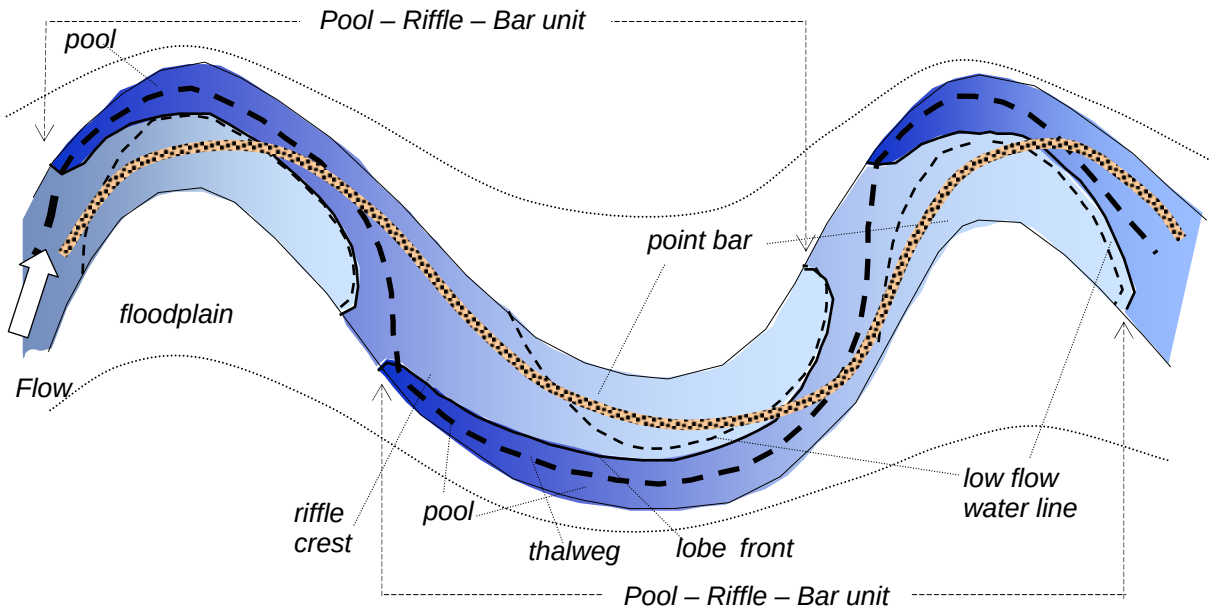


Fig. 4.2.7.1c: Pool-riffle-bar units in a meandering stream with alternate bar morphology. Banks are indicated for bankfull flow. The thin dashed line indicates banks that are exposed at low flow. Water depth is deepest in area with darkest shading, while areas of lightest shading are exposed during low flows. The thick dashed line indicates the thalweg, the thick stippled line indicates the major path of gravel transport. Copied from Bunte and Abt (2001) and slightly modified; original after Dietrich (1987), and Whiting and Dietrich (1993).

The pool-riffle-bar unit with its spatial distribution of flow depths and velocities that vary over the course of a highflow event, with its spatial patterns of bedmaterial sizes, and its gravel transport path provides a variety of different kinds of fish habitat. These are shown in their spatial configuration in Fig. 4.2.7.1d and summarized in Table 4.

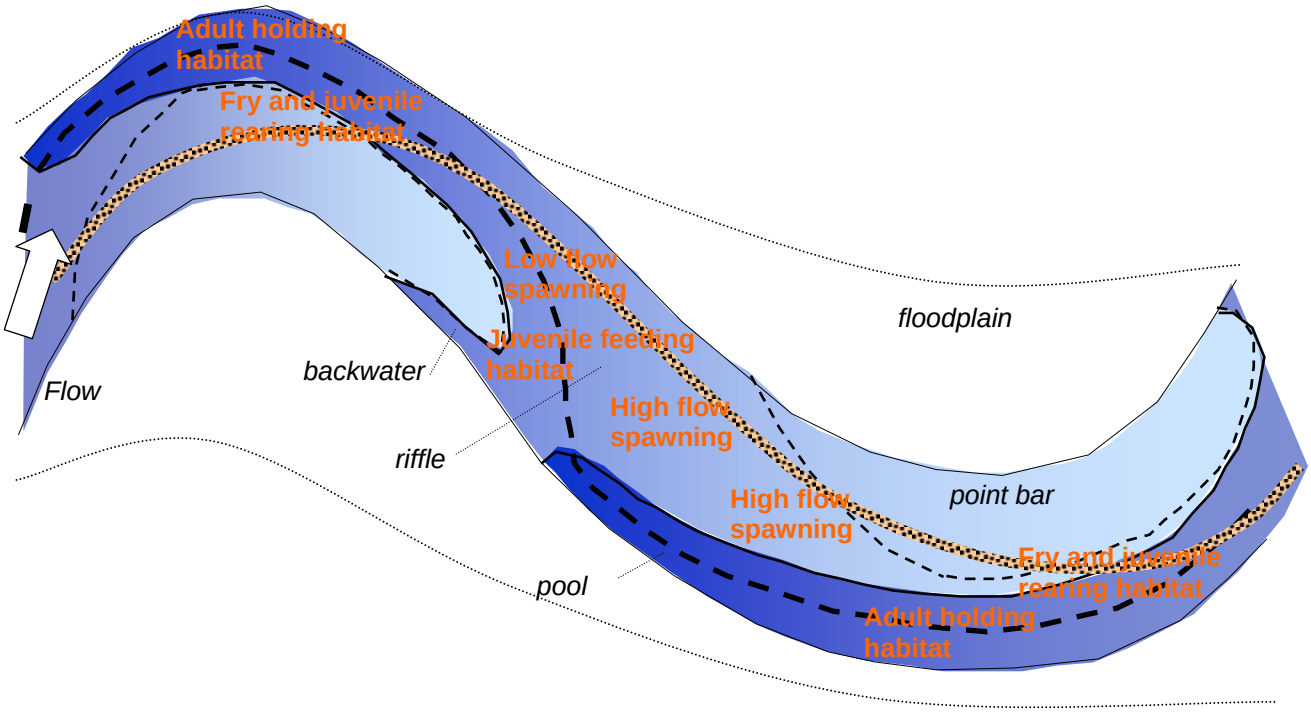


Fig. 4.2.7.1d: Idealized alternate bar sequence showing the locations of habitat features used by chinook salmon as defined by McBain and Trush (2003b) drawn into an enlarged copy of a pool-riffle-bar unit from Fig. 4.2.7.1 c.

During annual low flows, an alternate bar sequence provides adult holding areas in pools, preferred spawning substrates in pool tails, early-emergence habitat in slack water, and winter/summer juvenile rearing habitat in many locations. At higher flows, spawning habitat shifts downstream onto riffles and laterally to the submerged bar face. Fry and juvenile rearing habitat along the shallow margins of point bars migrates laterally onto the bar surface, and then onto the floodplain. Spawning habitat that extends from pool tails over riffles to the submerged bar face appears to coincide with the path of major gravel transport.

Habitat quality and quantity for all life stages

Within a salmon bearing stream, salmon use different stream locations that provide habitat for them during different life stages. Whether salmon vanish or thrive depends on the quality and quantity of all of those habitats. The quality of the habitat determines the p*roductivity* which is independent of population density. Spawning gravel quality, for instance, which might be characterized by variables such as particle-size distribution,

Table 4: Geomorphic units, general particle sizes, and salmonid habitat components in alluvial channel features (rewritten from McBain and Trush (2003a) with slight modifications)).

Geomorphic unit	General particle size	Habitat component
Pool (scour hole)	Boulder and large cobble	Adult holding, summer juvenile rearing
Pool tail	Coarse to fine gravel	**Low flow spawning**, egg incubation, juvenile feeding
Riffle	Small to large cobble	Juvenile feeding, juvenile overwintering, **higher flow spawning**
Point bar	Ranges from cobble and gravel near channel to small gravel and sand near floodplain transition.	**Higher flow spawning on thalweg side**; Fry and juvenile rearing along channel margin
Backwater	Fine gravel to sand	Winter and spring fry and juvenile rearing
Floodplain	Sand to silt	Fry and juvenile refugia during winter and spring floods
Side Channels	Gravel to cobbles	Adult **spawning**, fry and juvenile rearing

percent fines, embeddedness, permeability) determines how many of the eggs survive to emergence. Better gravel quality leads to higher productivity. *Capacity* refers to how much of a particular habitat is available in a stream. Increased gravel quantity means more habitat and leads to higher population capacity. As salmon need habitat of sufficient quality and quantity, salmon management needs to analyze whether habitat quality or quantity are limiting factors in a disturbed stream, and how each can be influenced through river management to increase habitat productivity and capacity for all riverine life stages. Considering quality and quantity of habitat for all life stages requires a broad perspective on the restoration and management approach. Focusing only on a single limiting factor may result in an increase in spawning activity, but not in an increase in the number of adult salmon.

4.2.7.2 Gravel augmentation in the context of a geomorphologically functioning stream

As salmon find habitat for their riverine life stages in a functioning alluvial gravel-bed stream, it follows that if the geomorphological functionality can restored in a stream disturbed by the effects of a dam, the resulting stream will again provide these habitats and become biologically functional. The geomorphological functioning of a stream can be described in ten attributes formulated by Trush et al. (2000) (Text Box 3). Fig. 4.2.7.2 shows a stream section in which the processes described in the attributes are indicated. Capital letters refer to locations and their processes.

Text Box 3: General Attributes of Alluvial River Ecosystems (Trush et al. 2000)

Attribute No. 1. Spatially complex channel morphology.
No single segment of channelbed provides habitat for all species, but the sum of channel segments provides high-quality habitat for native species. A wide range of structurally complex physical environments supports diverse and productive biological communities.

Attribute No. 2. Flows and water quality are predictably variable.
Inter-annual and seasonal flow regimes are broadly predictable, but specific flow magnitudes, timing, durations, and frequencies are unpredictable due to runoff patterns produced by storms and droughts. Seasonal water quality characteristics, especially water temperature, turbidity, and suspended sediment concentration, are similar to regional unregulated rivers and fluctuate seasonally. This temporal "predictable unpredictability" is the foundation for river ecosystem integrity.

Attribute No. 3. Frequently mobilized channelbed surface.
Channelbed framework particles of coarse alluvial surfaces are mobilized by the bankfull discharge, which on average occurs every 1-2 years.

Attribute No. 4. Periodic channelbed scour and fill.
Alternate bars are scoured deeper than their coarse surface layers by floods exceeding 3- to 5-year annual maximum flood recurrences. This scour is typically accompanied by re-deposition, such that net change in channelbed topography following a scouring flood usually is minimal.

Attribute No. 5. Balanced fine and coarse sediment budgets.
River reaches export fine and coarse sediment at rates approximately equal to sediment inputs. The amount and mode of sediment storage within a given river reach fluctuate, but also sustain channel morphology in dynamic quasi-equilibrium when averaged over many years. A balanced coarse sediment budget implies bedload continuity,' most particle sizes of the channelbed must be transported through the river reach.

Attribute No. 6. Periodic channel migration.
The channel migrates at variable rates and establishes meander wavelengths consistent with regional rivers having similar flow regimes, valley slopes, confinement, sediment supply, and sediment caliber.

Attribute No. 7. A functional floodplain.
On average, floodplains are inundated once annually by high flows equaling or exceeding bankfull stage. Lower terraces are inundated by less frequent floods, with their expected inundation frequencies dependent on norms exhibited by similar, but unregulated river channels. These floods also deposit finer sediment onto the floodplain and low terrace.

Attribute No. 8. Infrequent channel resetting floods.
Single large floods (e.g., exceeding 10-yr to 20-yr recurrences) cause channel avulsions, rejuvenation of mature riparian stands to early-successional stages, side channel formation and maintenance, and create off-channel wetlands (e.g., oxbows). Resetting floods are as critical for creating and maintaining channel complexity as lesser magnitude floods.

Attribute No. 9. Self-sustaining diverse riparian plant communities.
Natural woody riparian plant establishment and mortality, based on species life history strategies, culminate in early-and late-successional stand structures and species diversities (canopy and understory) characteristics of self-sustaining riparian communities common to regional unregulated river corridors.

Attribute No. 10. Naturally fluctuating groundwater table.
Inter-annual and seasonal groundwater fluctuations in floodplains, terraces, sloughs, and adjacent wetlands occur similarly to regional unregulated river corridors.

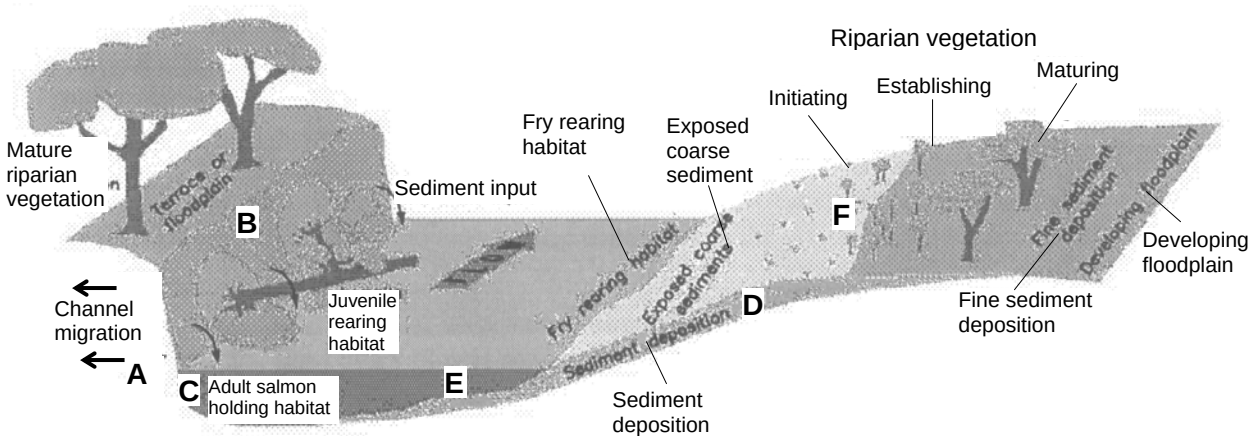


Fig. 4.2.7.2: Channel segment illustrating how active channel processes and varying flows form complex hydraulic and sedimentary stream conditions that provide habitat and areas for riparian vegetation to establish (copied from McBain and Trush 2003b, slightly modified).

To illustrate the interaction between stream geomorphology and fish biology, consider the following scenario: A channel with adequate space to migrate (*Attribute 6*) erodes the channel banks on the outside of the meander bend (A) during high flows (*Attribute 2*), and the steep eroded bank (B) encourages aged riparian trees to topple into the channel (*Attribute 9*). A deep pool (C) forms here, that provides structural complexity (*Attribute 1*) for good fish habitat. As bank erosion continues, the pool migrates downstream (*Attribute 6*) but maintains high-quality habitat. On the opposite bank (D), high flows (*Attribute 2*) scour and redeposit coarse sediment (*Attributes 4 and 5*), forming a shallow bar on the inside of the meander bend (E) (*Attribute 1*) and providing clean spawning gravel. This area (E) also provides ideal slow-water rearing conditions for juvenile chinook salmon, as well as habitat for aquatic insects (fish food), amphibians and reptiles. Progressively higher up on the gravel surface (F), a dynamic interplay occurs between receding water levels during the spring snowmelt (*Attribute 2*) and the presence of riparian tree seeds (*Attribute 7*). These woody riparian trees are sporadically scoured out (*Attribute 8*), and those re-established high enough on the bank are toppled into the channel as the channel migrates across the valley (A) thereby providing large woody debris that forms refuge. Given this interplay between stream functions in alluvial streams and salmon habitat for different life stages, the restoration goal is to regain full geomorphological and biological functioning of the stream.

4.2.8 The project proposal

Gravel augmentation projects often need to apply and compete for funding by submitting a project proposal to a funding agency. Projects are generally expected to follow the steps outlined in adaptive management. Before submittal, a proposal of a gravel augmentation project should have completed the steps leading to problem statement, goal formulation and tying gravel augmentation into a conceptual model of geomorphological and biological functioning. Having arrived at this stage, a project indicates to a reviewer

that it has a solid base in science and broad background information, problem awareness, and realistically attainable and measurable goals. Measurements and computations that will be necessary to obtain insight into stream processes, biological processes and gravel augmentation requirements are formulated at this stages. A general outline of the approach or the design is presented and parameters for post-project monitoring and evaluation are established. A detailed budget which includes post-project monitoring needs to be prepared which, if funded, is the monetary basis (or constraint) within which the project must operate. Analysis of previous gravel augmentation proposals and their review comments help to avoid pitfalls[9]. Other suggestions of issues to be addressed in a proposal for a salmon habitat restoration project are provided by Kondolf (2000b).

4.2.9 A note on project documentation

Concepts, activities, and preliminary results need to be carefully documented throughout all project stages. Clear documentation is particularly important during the planning stage (Kondolf and Micheli 1995) when the project is still in a pliable phase in order to:

- Guide project implementation,
- Provide a detailed inventory of predicted environmental benefits,
- Communicate with stakeholders and post-project evaluators,
- Help smooth personnel change, and
- Facilitate revision of project plan.

4.3 Field investigations and computations

Formulating the problem, the goals, and the conceptual models should provide sufficient insight into the matter to identify unknown parameters and interactions for which (more) information is needed. An overview of those parameters or interactions, what exactly to measure and compute and the methods employed is provided in Table 5.

Information on unknown parameters and processes is generally obtained from direct measurements in the field and computations based on field-measured data. However, some parameters or interactions that ought to be known before gravel augmentation are so complex that only modeling can provide insights or estimates (Section 4.4). In this case, field measurements have the aim to provide input parameters for modeling.

[9] *Proposals can be viewed on the CalFed internet sites at (as of spring 2004): https//ecosystems.calfed.ca.gov/WRRC/CalFed/proposals/selection panel_report_static and at http://calwater.ca.gov/Programs/EcosystemRestoration/EcosystemFY2001AccesstoProposals.shtml#I3*

Table 5: Overview of parameters for which information may be required in gravel augmentation projects

	Unknown parameter or interaction	**What to measure and compute**	**Methods used**
Streambed Topography	Current cross-sectional shape for pre-project condition and its change over time;	x-y coordinates of cross-section at geomorphologically active locations, repeated over time	Topographical Survey
	Stream gradient	x-y coordinates of longitudinal profile	
Sediment supply	Status of sediment supply: is the stream aggrading or degrading?	Areal extent of stream-bed covered by different geomorphological units and facies units	Topographical survey; Mapping geomorphological units and facies units (=areas with same dominant particle-size), digitization, and spatial analysis
Bedload transport	Bed mobility, critical flow for gravel entrainment, pre-and post-project	Bed surface particle-size distribution	Pebble count
		Post-flood displacement distance of seeded D_{84}, D_{50} and D_{31} particles at different flows	Tracer study
	Depth of scour and re-deposition	Pre- and post flood x-y coordinates of top and bottom of scour core	Topographical survey of scour cores.
	Current bedload transport rates, annual load, amount of gravel to be supplied	Bedload transport rates during flood events, annual load	Bedload sampling, annual load computation
	Amount of gravel to be supplied	Stream-bed elevation before and after flood events, prior to which gravel was applied; scour depth	Topographic survey, topographic differencing; scour cores
Spawning gravel	Current quantity of spawning gravel	Area suitable for spawning based on appropriate flow depth, velocity, and bedmaterial size; redd counts.	Stream mapping, digitization and spatial analysis
	Quality of spawning gravel;	Particle-size distribution; intra-gravel flow, temp., turbitidy, dissolved oxygen	Unstratified bulk samples; Piezometer water samples, egg/alevin counts,
	Sources and sinks for fines	Amount of fines in pools and other deposits, veneer thickness, bulk density, total amount of fines per stream segment; tributary supply of fines	Visual assessment, stream mapping, digitization, spatial analysis; geomorphic analysis at confluence; bedload sampling
Modeling complex interactions	Stream-bed topography	x-y coordinates of stream bed within project reach	Topographic modeling, DEM
	Interaction of water depth, velocity, total flow volume, and surface gradient in pre- and post-project channel shape	Current flow hydraulics for model validation; Flow dynamics for specified flow and channel shape	Hydraulic modeling, 1-D or 2-D
	Critical flow for incipient motion	Ratio of actual flow to an assumed critical flow	Based on output of hydraulic model and critical flow eq.
	Sediment transport and channel change for specified flows in pre- and post-project channel	Current bedload transport rates for model validation; Transport rates for specified flow & channel shape	Bedload transport modeling, based on output of 1-D hydrl. model and bedload eq.

Fieldwork throughout the project

Gravel augmentation projects require fieldwork at various stages throughout the project. Preliminary field work to assess conditions and formulate goals is done during the pre-project assessment phase (Section 4.2.1). Field work is most intensive in the beginning of the main phase of a gravel augmentation project when detailed measurements and associated calculations are done to work out the specifics of gravel augmentation within a project. This may include stream surveys, discharge measurements, collecting bedmaterial and bedload samples, identifying locations requiring gravel augmentation or special attention, determining the spatial extent of the project, calculating gravel quantity and quality, selecting appropriate placement methods and setting up temporal schemes for gravel augmentation.

Field work and the associated calculations will be repeated in later project stages to document the immediate and mid-term geomorphological and biological responses to gravel augmentation as well as during the post-project monitoring and evaluation phases to document the long-term response (Sections 6 and 7). Well marked locations of field measurements that permit follow-up measurements, as well as clearly documented data storage are important for establishing a time series of measurement results that will be part of monitoring and post-project appraisal. In fact, parameters to be evaluated in a post-project appraisal should be determined early on in the project such that they will be monitored as baseline parameters throughout the project (Kondolf 1995b).

Successful field work

Field work is the foundation of a gravel augmentation project and needs to be given its appropriate attention and priority. However, fieldwork is often considered labor- and time-consuming and sometimes regarded as less "worthy" than office time. This is a mistake because a good data base is crucial for the project success. To make the most out of a field trip, it is important to be organized, plan ahead and bring all necessary gear to successfully complete all measurements. As it may take hours to get to the field site, as well as time at home and in the field for preparation, it may be a good idea to consolidate the field work into focused field campaigns. Sloppy or hasty field work, done with little planning, by inexperienced personnel, with inaccurately performed methods, and insufficient number of samples or measurements serve no purpose and must not be the answer to the potentially high costs of field work. Experience in the subject and familiarity with field methods, good planning, meticulousness and commitment are needed to make fieldwork a success. Descriptions of field measurements used in fluvial geomorphology are provided in Gordon et al. 1992; Harrelson et al. 1994; Edwards and Glysson 1999, Bunte and Abt 2001 a and b, Potyondy and Bunte 2001, 2002; Kondolf and Piégay, 2003; Bunte et al. 2004a.

Criteria for selection of project field sites

Sites at which measurements will be taken in the field include those identified in the pre-project surveys to be most in need of gravel augmentation. As the effects of gravel augmentation may extend downstream from the direct augmentation site, the ability to show a downstream effect is part of a project as well. A project should furthermore

include reference sites that are (for the foreseeable future) unaffected by gravel augmentation. Reference sites should probably include disturbed as well as geomorphologically functional site. Measurement results from reference sites indicate channel responses that may happen irrespective of gravel augmentation, for example due to particularly low or high flows, or particularly high or low tributary sediment supply. Including reference sites is important for the post-project appraisal to distinguish stream responses to gravel augmentation from those that occurred due to unrelated influences (Kondolf 1995b).

A note on measurement accuracy and consistency

Doing measurements as accurately as practically feasible is important, not only to obtain accurate input data for later analyses but also to establish a consistent temporal record in which changes are not due to measurement error or operator variability. Measurement protocols need to be established according to which operators are trained. This is particularly important for long-term projects and personnel change. The stream response may be small and perhaps in the same order of magnitude as the measurement error. Reducing the measurement error and knowing its magnitude are thus important.

4.3.1 Topographic surveys

Topographic surveys provide cross-sections, longitudinal profiles, and if necessary 3-D surveys covering a reach. Cross-sections at stream locations that are likely to show a geomorphic response following a change in sediment supply and that extend up onto the floodplain need to be established and surveyed periodically throughout the project to monitor change. To ensure that exactly the same location is resurveyed, cross-sections need to be permanently marked with rebar on both ends. The surveys that provide data for hydraulic and sediment transport modeling for estimating the effects of increased sediment supply due to gravel augmentation should be located at the geomorphologically most active and functioning sites. Cross-sections should also be established outside the project reach to indicate whether the channel is responding to change unrelated to the gravel augmentation project (e.g., to the changes in water and sediment supply due to the dam or watershed effects). In order to obtain the longest time record possible (a prerequisite for detecting trends as well as for post-project evaluations), measurements on cross-sections established in the pre-project phase and, if possible, on cross-sections from an unrelated previous project should be continued.

Stream gradient is an important parameter for the design of gravel augmentation sites because it influences flow depth and velocity and therefore the suitability for spawning habitat (as well as gravel mobility). It is also used as input for hydraulic and sediment transport modeling (Sections 4.4.3 and 4.4.4)

Detailed topographic surveys covering the entire reach or crucial stream sections may be required as an input parameter if the project develops digital elevation models (DEM) of the reach. The newly designed stream bed surface structure (i.e., the design contours) is then entered into the DEM to compute estimated gravel needs, or the degree of

aggradation or degradation between surveys during the project (CDWR 2002a). A DEM based on a topographic survey may also be used as basis for 2-D hydraulic and sediment transport modeling (CDWR 2002a; Pasternack et al. 2004; Wheaton et al. 2004 a and b) (Sections 2.2.4, 4.4.3.2 and 4.4.3.3).

4.3.2 Geomorphological survey

As stream form and bedmaterial size develop in response to stream gradient, flow and sediment supply, a survey of the stream geomorphology and the bedmaterial size is needed to indicate the status of sediment supply (see also Section 4.2.1). In low-gradient streams, a braided reach and/or alternate bars indicate ample sediment supply, whereas cobble and boulder pavements, bedrock outcrops, absence of bars and floodplains indicate supply limitation. These morphological and bedmaterial facies[10] features can be identified and mapped during repeated field visits and their areal extent and change over time can be analyzed by comparing mapping results. The cumulative areal extent of stream locations with depleted sediment supply can serve as an estimate of the total amount of gravel that needs to be supplied to the stream system to achieve a mobile gravel bed in which salmon are able to spawn. This aspect is explained in more detail below. A comparison of results from geomorphological and facies mapping over time can be used for monitoring the success of a gravel augmentation project.

4.3.2.1 Geomorphologically based estimate of initial gravel transfusion volume

Modeling of the gravel supply needed for spawning gravel augmentation over a river segment-wide augmentation project (10-100 km) is still scientifically challenging because the post-project stream dimensions and the bed particle-size distribution will both be reduced to facilitate approximately annual mobility of the coarse bedmaterial portion. McBain and Trush (2003b) suggested the following multi-step approach to determine the volume of gravel needed for the initial short-term transfusion:

1) **List and map onto aerial photographs all locations that show responses to depleted gravel supply; features mapped in the field may include:**
   - <u>riffles with</u>:
     - coarse and armored surfaces,
     - gradients too steep for spawning,
     - small size due to scour over time, and
     - sites where the riffle has been lost completely;
   - <u>point bars</u>, small or non-existent at the inside of meander bends;
   - <u>pool-tails</u> with overly steep riffle crests and substrate embedded with fines;
   - <u>lateral bars</u> with signs of erosion and depletion of sediment supply (e.g., small in size, low lying, coarse surface), and overwidening of the channel;
   - <u>banks eroded</u> at high flow and missing deposition on the inside of the bend, causing channel widening;
   - relicts of historic dredging (e.g., backwater features).

[10] *bedmaterial facies = streambed area covered by bedmaterial of similar composition, e.g., a cobble-gravel or a sand-gravel facies*

2) Digitize the areal extent of these sites and assign a depth to the required gravel augmentation

This can be done either through field reconnaissance visits or by assigning a new bed profile to surveyed cross-sections such that mobility at approximate annual intervals will occur. Multiply the digitized area of gravel depletion by the estimated depth of the added gravel and determine a gravel augmentation volume for each site.

4.3.2.2 Selection of sites for gravel augmentation

The geomorphological survey identifies sites that are depleted of gravel supply. Whether or not these sites receive direct gravel augmentation, or will have to wait until they can benefit from upstream gravel that reaches the site after a generally increased sediment budget depends on a number of factors. Sites may be grouped and prioritized based on the following criteria by McBain and Trush (2003b):

- Immediate benefit to salmon spawning habitat: May depend how quickly the augmented gravel will travel to the site if provided further upstream;
- Proximity to the dam: Upstream locations seem to have a higher density of spawners thus gravel augmentation would benefit more spawners. Secondly, gravel introduced upstream will also benefit other sites as the gravel travels downstream.
- High gain in spawning habitat: Assign a high rank if a little gravel augmentation greatly increases spawning habitat at a site.
- Improvement of bedload transport continuity: Assign a high priority if filling a single pool restores downstream gravel conveyance versus impedance by a sequence of pools.
- Site accessibility, logistics, landowner willingness and cost factor in;
- Value of the site for experimentation and learning.

Project sites are then scored, ranked according to their priority, and listed. Areas of high priority are to be targeted first. The ranked list is then discussed in a Technical Advisory Committee and changes in priority may be made due to a wider input of opinions. Individual tasks are then grouped into various project phases.

4.3.3 Bed mobility and scour depth

In a geomorphologically functioning stream, the bed is generally mobilized at annual or biennial intervals and experiences local scour and deposition. This action provides the kind of gravel deposit suitable for salmon spawning and rearing. Thus, information on the frequency of bed mobility at submerged bars, pool tails and riffles (where salmon are likely to spawn) is very important, both before the project (to assess conditions and set goals) as well as during the project when spawning habitat is to be created and maintained.

4.3.3.1 Critical flow for incipient motion

Information on the critical flow that mobilizes a preset particle size of the stream bed can be obtained from computations or field measurements. Both methods have their challenges: the computational method must select an accurate reference shear stress value at which mobility is supposed to start for the specific stream-bed conditions, while field investigations have to ensure representative tracer placement on the bed.

Computation of incipient motion

Critical flow for incipient motion is often computed from the dimensionless shear stress parameter τ^* (i.e., the Shields value) that is defined as:

$$\tau^* = \frac{\rho_f \cdot g \cdot d \cdot S}{(\rho_s - \rho_f) \cdot g \cdot D_{50}} = \frac{\rho_f}{\rho_s - \rho_f} \cdot \frac{d \cdot S}{D_{50}} = 0.606 \frac{d \cdot S}{D_{50}} \qquad (1)$$

where ρ_s and ρ_f are the sediment and water densities (that assume values of 2,650 and 1,000 kg/m^3, respectively for quartz particles and clear water and in this case may be combined to a constant value of 0.606), g is acceleration due to gravity (9.81 m/s^2), d is the cross-sectionally averaged flow depth (m), S is the stream gradient (m/m), and D_{50} is the surface gravel particle size (m) for which 50% of the distribution is smaller. A critical value is selected for τ^*_{crit} (see below) and Eq. (1) is solved for d to determine the critical flow depth at incipient motion. A relationship between cross-sectionally averaged flow depth and total flow is either established from direct measurements of discharge (standard USGS procedure) or from a hydraulic model (Section 4.4.3).

A value of τ^*_{crit} in the range of 0.02 – 0.05 is generally thought to represent flow conditions at incipient motion in gravel beds[11]. Generally, higher values are required for deposits with fewer fines, angular particles and a strong particle packing bond (e.g., imbrication, wedging, or algae cover). The appropriate Shields value for pre-restoration gravel is therefore higher (perhaps as high as 0.10) than the post-restoration value when spawning-size gravel which tends to have an open framework and loose packing covers the reach. CDWR (2002a) used a value of 0.02-0.025 for the D_{84} bed material size, and a value of 0.03-0.045 for the D_{50} particle size of artificially supplied spawning gravel[12]. Wilcock et al. (1996a) observed incipient motion in spawning gravels within the range of τ^*_{crit} of 0.031 to 0.035. By contrast, Montgomery et al. (1996) estimated that the removal of fines during redd construction coarsens and roughens the gravel surface both of which act together and require a higher critical shear stress for entrainment. Given this disparity, the reader should consult the most recent literature for the best estimate of dimensionless critical shear stress values for augmented spawning gravel.

---

[11] *Note that there is no absolute transport rate in terms of gravel mass/time and stream width or number of particles/time and stream bed area that defines the onset of motion in gravel-bed rivers. The transport rate in a specified particle size-class q_{bi} that occurs when a dimensionless parameter $W^* = f(q_{bi} / F_i \cdot d \cdot S)$ reaches 0.002 is used as the onset of motion in the Parker bedload equation (Parker 1990). F_i is the proportion of the $_i$th size fraction on the bed surface, d and S are mean flow depth and stream gradient.*

[12] *Large particles may actually require a lower critical shear stress than smaller particles because large surface particles protrude into flow which makes them more affected by the force of flow.*

Tracer experiments

Critical flow for incipient motion can be experimentally determined directly for each site and each geomorphological unit using tracer gravel. The first step is to determine the D_{84}, D_{50} and D_{31} sizes of the bed surface particle-size distribution from a pebble count (Section 4.2.5.3). The D_{84} provides an estimate of the size of framework gravel[13]. The D_{50} is the median gravel size and is often used as input for bedload transport and hydraulic modeling, and the D_{31} represents the finer gravel portion. Tracer particles are then prepared for these sizes (e.g., the D_{84}, D_{50} and D_{31}) from particles collected from the streambed and coated with bright colors. Spray paint is adequate for short duration experiments or when the expected wear and tear is not too large. Highway paint may be a more robust solution but does not have a large color selection. Tracer particles for each size class are placed along several cross-sections in the stream bed during low flows. To ensure that a tracer particle has the same mobility as naturally deposited particles in the neighborhood, tracers must be placed into an embedded position. That usually means that a particle of about the tracer size is picked off the stream bed and replaced by a tracer particle. In unwadable stream locations, divers are needed for this task. If tracer particles are allowed to just settle on the stream bottom without embedding them, they will come to rest on top of the bed in a highly exposed position where the mobility will be considerably higher than for embedded particles. Thus, mobility of tracers placed on top of the bed overpredict bed mobility. If hand-placing cannot achieve natural particle positions, one can wait for natural positioning of the tracers after a preliminary highflow and use those positions as starting points for the event to be measured.

For mobility experiments, the questions are: did the particle move and was the move substantial (perhaps more than a few feet)? In this case, the number of tracer particles per size class can be less per site than the number needed to evaluate travel distances. McBain and Trush (2003 b) suggested 10-20 particles per size class per site, placed a few feet apart from each other across the stream. Different colors can be used for tracers of different sizes, placed at different morphological units, at different parts of a cross-section or at different times. Numbers written on individual tracers facilitate further specifications about tracer characteristics or placement.

As the aim is to determine particle mobility over a range of highflows and establish site-specific bed-mobility information, the location of displaced tracers is surveyed and tracers are recovered and newly emplaced after each flood. Significant bed mobilization may be defined as the movement of 80% of the D_{84}-size tracers. Based on these results one can compute flow competence curves that relate the size of moved particles to the critical flow required for movement (Q_{crit}). Q_{crit} can then be expressed in terms of the return interval flow to provide information on how frequently mobility of specified particle sizes can be expected. In the post-project design channel, the D_{84} bed material surface size would ideally be mobilized every one or two years. Instead of Q_{crit}, one can also relate the flow at incipient motion to the cross-sectionally averaged flow depth from which one then can compute the dimensionless shear stress (τ^*), a parameter more generally applicable than Q_{crit} (Section 4.3.3.1).

---

[13] *Framework gravel describes the size of large gravel particles that touch each other in a deposit with less than 20-30% of fines.*

4.3.3.2 Scour experiments

An active scour-and-fill process is desirable in geomorphologically functioning pool-riffle streams and is assumed to provide good spawning habitat (Section 4.2.7.1). It therefore needs to be determined whether the water-sediment interaction during post-dam floods will actually cause sufficient scour-and-fill. The depth of bed scour and the height of redeposition that occurs during a highflow event can be measured from scour cores (Fig. 4.3.3.2). The method is outlined below.

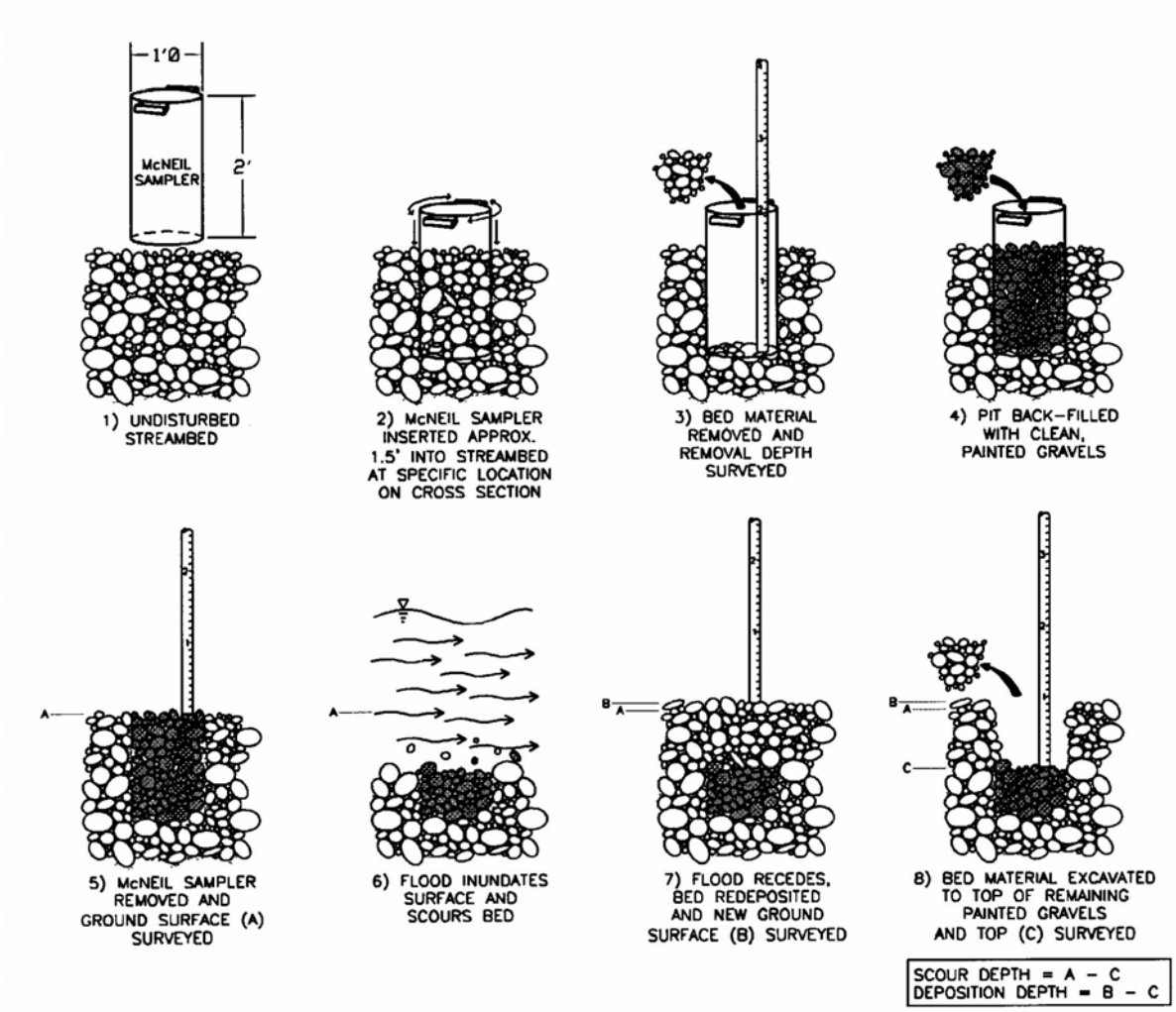


Fig. 4.3.3.2: Scour core installation and monitoring (copied from McBain and Trush 2003a).

A sturdy 2-foot long section of a 1-foot diameter pipe with handles welded on the top is driven into the bed on geomorphologically active locations such as submerged bars, pool tail and riffles. The core location is determined either as a point in the cross-section, by triangulation between two fixed points, or by surveying. The elevation of the pre-disturbed surface is also surveyed. Sediment from inside the core is removed and

replaced by brightly colored gravel (this may also be gravel of a different petrology, e.g., white quartzite in a bed of dark particles). The elevation of the bottom of the scour core and the top of the core are surveyed. During a flood event, the bed may scour and the painted particles inside the scour core are transported away. Deposition may occur during the falling limb of flow and cover the scour hole with a layer of unpainted bedmaterial. The scour hole is relocated after the flood event, and the thickness of both the deposited layer and the remaining scour core is measured. Typically, 2-3 scour cores are installed at a site where scour is measured. The vertical extent of the scour-and-fill process should be in the same range as the typical depth of redds.

4.3.4 Bedload transport

Gravel augmentation studies in geomorphologically challenging stream situations require information on bedload transport rates for a variety of purposes which include:

1) Computation of pre-dam gravel load (upstream from the dam);
2) Computation of post-dam gravel *load* at gravel augmentation sites;
3) Computation of post-dam gravel *loss* to the stream system (difference between pre-dam and post dam loads summed over the years);
4) Computation of annual *amount of gravel to be supplied* by gravel augmentation, and
5) Calibration of computed bedload transport rates and validation of modeled results.

Measurements and calculations of bedload transport will be discussed in Section 4.3.4.1, calculations of post-dam gravel loss and the amount of artificial gravel supply in Section 4.3.4.2. All of the analyses discussed below should be carried out for individual particle-size classes and summed for all sizes because amounts or transport behavior may differ between size classes. Spawning gravel augmentation has the potential to supply a specified particle-size spectrum to the stream specified to the geomorphological and biological needs.

4.3.4.1 Measurements and computations to determine annual load

Annual gravel load can be determined from measured or computed instantaneous bedload transport rates, from bedload measurements that span a season or a year, or from long-term accumulations of sediment (Table 6).

Direct measurements of bedload transport

Portable samplers that require no in-stream installation are most likely to be used for short-term sampling in gravel augmentation projects. Bedload traps with 0.3 m by 0.2 m openings (Bunte and Abt 2003; Bunte et al. 2004a; Bunte and Swingle 2004, in prep.) and large Helley-Smith-type samplers with openings of 0.152 by 0.152 m and larger (Dinehart 1992; Duisendstra 2001 a and b, Childers 1999; Ryan 2001) are suitable in size for gravel sampling. Accurate performance of bedload transport measurements requires using appropriate field techniques (Ryan and Troendle 1997) and is labor-, time-, and cost-intensive. Measurements in unwadable flow or during nightly storm events can be particularly challenging. Even though results obtained by different samplers may differ

strongly, measured bedload transport rates are still more likely to reflect true stream processes than uncalibrated rates computed from a bedload transport equation.

Table 6: Bedload information, computations and measurements needed in gravel augmentation projects.

Item to be known for gravel augmentation study	**Computations needed**	**Measurements/input data needed for computation**
Pre-dam long-term average annual load	• Sediment volume or mass stored in the delta; • Pre-dam bedload rating curve for computation of annual load.	• Survey of reservoir delta; • Bedload sampling upstream of dam.
Current annual load (either pre-project or post project during monitoring)	• Current bedload rating curve for computation of annual load; • Compute annual load based on surveys or establish rating curve for event loads versus event discharge volume or peakflow	• Bedload sampling at equilibrium transport site; • Survey and/or empty debris basin that catches either event loads or annual load
Calibration of bedload transport model to be used for prediction	Compare modeled and measured bedload rating curve and adjust model to fit measurements.	Take enough bedload samples at relatively low bedload transporting flows to establish a *reliable* bedload rating curve and measure flow hydraulics.
Prediction of post-project annual load and evaluation of different design alternatives	Model bedload transport rates based on hydraulics computed for cross-section in the reach, establish bedload rating curves and compute annual loads;	Channel and water surface surveys, bed surface particle size, flow duration curve
Predict long-term post-project annual loads	Model trends in annual loads based on monitored changes in channel shape and bedmaterial size.	Monitor channel shape, water surface and bed surface particle size which may change over time due to gravel augmentation.

The power function regression fitted to the relationship of instantaneous transport rates and discharge at the time of measurement yields the bedload transport rating curve. Data plotted for this relationship usually show a large scatter, typically about one order of magnitude or more. A large number of samples should therefore be collected over a large range of flows to establish a relationship between bedload transport rates and discharge (i.e., the bedload rating curve) with some accuracy.

Bedload equations and bedload transport modeling

The relationship between bedload transport rates and discharge can also be computed from sediment transport equations that are designed for gravel beds (e.g., Meyer-Peter and Müller 1948; Schoklitsch 1962, Bagnold 1980; Parker et al. 1982; Parker 1990a; Wilcock and Crowe 2003). The transport equation is then solved for different flows. As bedload equations typically quantify flow by cross-sectionally averaged flow depth d_m, a

relationship between d_m and the flow rate Q has to be established. This requires a series of discharge measurements at different flows (using standard USGS procedures). Alternatively, a hydraulic model may be used to establish this relationship (Section 4.4.3).

Different transport equations applied to the same stream location yield bedload transport rating curves that may vary by orders of magnitude (Gomez and Church 1989; Bravo-Espinosa et al. 2003). It may therefore be a good idea to use several equations to see the wide range of predictions. Even a specific transport equation may yield very different results depending on how variables used in the equations were quantified. The computed rating relationships need to be validated by comparison with measured transport rates and adjusted if necessary. After validation, bedload equations can be incorporated into hydraulic models to compute transport for different flows or different cross-sectional shapes (e.g., EASI model, Section 4.4.4.3). The application of bedload transport equations and bedload transport modeling should be reserved to experts in this field, not only to ensure that parameters have been quantified appropriately, but particularly to interpret and evaluate the model results.

Bedload discharge, annual and mean annual load

Bedload discharge is the amount of bedload transported over a specific time interval that may range from an event (hours to days), to a runoff season (weeks or months), to a year, to a multi-year average. Bedload discharge can either be computed from a measured or at least validated bedload transport rating curve that is applied to hydrographs of different length or obtained by collecting bedload over a long time. To account for the underprediction of transport rates from rating curves (e.g., Koch and Smillie 1986, Ferguson 1986, 1987; Hirsch et al. 1993), predicted loads need to be adjusted upward by multiplication with a bias correction factor that typically takes a value of 1.5 – 2.5 for rating curves obtained from measured instantaneous transport rates. Long-term collection and measurement of bedload can be done in sediment traps or debris basins that are sized to hold the sediment volume expected for one event, a season's, or a year's worth of sediment. Instream ponds (left over from instream gravel mining) that act as gravel sinks can be annually surveyed and likewise yield an estimate of annual gravel load. A rating curve for annual loads can be determined by relating annual load to the annual water discharge volume or the annual peak flow or the peak flow recurrence interval. While annual load is the amount of gravel actually moved, transport capacity is the amount of gravel that could be moved (i.e., for which the flows are high enough to facilitate transport), provided there was a large enough supply of upstream gravel or supply within the bed.

4.3.4.2 Pre-dam mean annual load

The accumulated multi-year sediment discharge can be estimated from the increase in the sediment volume of the delta in the upstream end of the reservoir over long time periods. Because the delta comprises particle sizes other than gravel, the proportion of gravel must be either estimated or computed from bores. The gravel fraction is typically assumed to

be 10-15% of the total sediment load comprising gravel, sand, silt and clay but this value is not fixed. If the delta comprises mostly sand and gravel and is situated in a reservoir further towards mountain headwaters the gravel portion is higher, reaching as much as 50% in a small headwater step-pool stream (Bunte and Swingle 2003).

Care needs to be taken when computing mean annual gravel loads as the sum of annual loads divided by the number of years or as the accumulated delta volume divided by the number of years between surveys. Annual loads may have an extremely skewed distribution in which the load of a single 20- or 50-year event makes up a disproportionately large fraction of the long-term total. The simple arithmetic mean of all data is unlikely to represent the sediment mass supplied by the mean annual flood but yields a higher value if extreme events are included. It is therefore advisable to compute mean annual loads including and excluding the contribution of extreme events and evaluate which value may be most suitable for the project purpose. Comparison of mean annual gravel supply per unit basin area with corresponding values from comparable neighboring streams (same geology, vegetation and watershed management) may help to increase confidence in the computed results.

For relatively small reservoirs, and in the absence of major tributaries into the reservoir, the pre-dam annual load (and thus the pre-dam annual sediment supply) can be estimated from measured bedload transport rates upstream of the reservoir.

4.3.4.2 Post-dam transport and amount of gravel to be supplied

Information on bedload transport rates and annual loads are used to estimate amounts of sediment transported by pre- and post-dam flows and to determine the appropriate amounts of spawning gravel to be supplied by augmentation. The post-dam reduction of water and sediment supply usually leads to a scarcity in gravel transport and gravel deposits, but it is not automatically obvious how much gravel will be needed for restoring geomorphological and biological functioning of the stream. Different approaches have been proposed to estimate the amount of gravel that needs to be supplied, depending on how the water and sediment supply was affected at some location downstream of the dam. These approaches are not generally tried and true methods, thus each project has to find their own best way to estimate gravel supply based on an analysis of the pre-dam water and sediment supply and how the dam affected the water and sediment supply thereafter. Examples for different combinations of the flow (Q) and bedload sediment supply (Q_b) situation below the dam are described below (see Table 1 for notations). It may be advisable to apply several different approaches and compare their numerical results to obtain a range of estimates which may then be further evaluated.

Q^-, Qb^+

If the dam mainly withholds flood flows and there is significant tributary sediment supply below the dam, the stream upstream of the reservoir can be assumed to represent the pre-dam conditions of stream reaches shortly below the dam site, and bedload rating curves measured upstream of the dam can be applied to a long-term sequence of post-dam

annual flows to obtain the post-dam annual load. This assumes, of course, a similar morphology of the stream above and below the dam.

Q^o, Qb^{--}

If the dam does not substantially reduce the number and frequency of gravel-transporting floods but collects all sediment from upstream, sediment supply that ought to be transported to some location below the dam can be estimated from the difference between the pre-dam mean annual gravel load and the current mean annual bedload discharge.

While annual gravel load obtained from this estimate may be acceptable as the amount of gravel to be supplied by augmentation if all gravel but no floods are withheld, this estimate is too high if the post-dam flood regime has fewer and less high floods than the pre-dam regime. By contrast, no amount of gravel addition will have a long lasting beneficial effect for spawning habitat improvement in streams in which even post-dam flows have a gravel transport capacity largely exceeds the pre-dam gravel supply (McBain and Trush 2004b).

Q^-, Qb^+

If the dam reduced both water and sediment supply, the amount of gravel to be added (i.e., the current sediment supply) might be estimated as the amount of gravel transported in high flow years below the dam. This estimate may still be on the high side if the dam drastically reduced the pre-dam flood regime and may have to be reduced to the long-term average of annual load in high-flow years.

Fining of post-restoration gravel surface increases long-term gravel augmentation needs

Creation of a bed finer than the pre-restoration bed surface particle-size is a declared goal of gravel augmentation with spawning-sized particles (Section 2.4.1.1). Transport rates in the finer, post-restoration bed will be considerably higher than in the armored and gravel-starved pre-restoration bed. Thus, pre-restoration transport rates cannot be used as estimates for post-restoration transport rates. It is also likely that gravel transport rates increase over time as more spawning-sized gravel is added to the streams, thereby (continuously) increasing the volume of gravel needed as long-term gravel supply.

Measure at locations with sufficient sediment supply:

In many locations below the dam, current post-dam transport rates are likely to be less than what could be transported by the post-dam flow regime because little or no sediment is supplied from the bedmaterial that is scoured to a non-erodible pavement, and little supply comes in from upstream. Measuring gravel loads here would provide values that are too low.

Instead, annual gravel load should be computed from measurements at sites that still receive enough gravel for geomorphological functioning with equilibrium conditions between sediment supply and transport capacity. Mean annual bedload discharge can

then be assumed to be the mean annual gravel supply. In aggrading reaches, the mean annual bedload supply exceeds the mean annual bedload discharge. In degrading reaches, mean annual bedload supply is less than the mean annual bedload discharge. Thus, aggrading and degrading sites should be avoided when attempting to establish post-dam transport rates and mean annual gravel supply.

The best site for bedload measurements would be a riffle in a relatively low gradient, alluvial reach some distance downstream from the dam but unaffected by major tributary inputs. If the rating curve established for this site is applied to the long-term flow release hydrograph below the dam, one could obtain a rough estimate of the amount of gravel that should be transported in post-dam times. This amount of gravel should be supplied annually just below the dam.

Use an experimental approach

The amount of gravel transportable by the current flow regime can also be determined experimentally. In this case, gravel is supplied to a reach and the newly created stream bed topography is surveyed before and after several flood events. Failing upstream supply, the post-flood surface is likely to be lower. The amount of sediment eroded off can be computed from topographic differencing. In situations with upstream supply, there is partial replacement of the scoured sediment volume. The topographic difference would not account for the sediment removed during the initial scour. The scour depth therefore needs to be measured using scour cores (Section 4.3.3.2) and be included in the computation of the total volume mobilized from the site.

Augmented gravel sizes to match stream competence

The above analyses aimed at restoring the gravel supply to meet the *amount* of gravel transportable by flows (i.e., the *capacity* of flow). Similar analyses may have to be done to establish the *largest particle sizes* transportable by flow (i.e., the transport *competence* of flow) in order to determine appropriate sizes for the coarse part of the augmented spawning gravel. The large particle sizes in the bed (approximately the D_{84}) should be transportable by annual or biennial highflows in a geomorphologically functional stream and, of course, meet the requirements that spawning fish have for gravel sizes (Sections 4.3.6.1).

4.3.5 Areal extent of post-dam spawning habitat

The conceptual model formulated in Section 4.2.7.1 describes how salmon habitat is linked to the interactions between flow, sediment transport, and stream morphology. Salmon spawning habitat can be further described by the productivity (how many fish result from a specified area) and capacity (how much habitat is available) that are related to quality and quantity of spawning gravel. To determine whether the quantity or the quality of gravel deposits limits the spawning success, productivity and capacity should to be assessed based on field measurements and computations.

4.3.5.1 Field surveys based on fish habitat criteria and redd counts

Areas suitable for spawning may be identified during field visits based on habitat criteria (flow depth, velocity, and bedmaterial size). They can then be mapped on large-scale aerial photographs (Section 4.2.5.1), digitized and summed. Spawning area surveys based on wading and visual identification are described in much detail in McBain and Trush (1999a) and McBain and Trush (2003c).

The location and percent area actually used for spawning can also be assessed by mapping and counting the number of redds (Carl Mesick Consultants 2001). Redds are more easily visible in stream reaches with high sediment supply where spawning is more ubiquitous than in sediment-starved reaches where spawning is limited to small patches. In streams too deep for wading, scuba divers or underwater video equipment can be employed. The U.S. Fish and Wildlife Service used a video system outfitted with two cameras mounted at angles of 45 and 90 degrees onto a weight lowered from a boat by a winch (USFWS 2003). Monitors on board let the operators see the stream bottom obliquely and vertically. The streambed is screened for redds in parallel transects. After locating a redd, bedmaterial size is measured using a calibrated grid that is mounted on the 90 degree camera monitor. Depth and flow velocity are measured at the site using a current meter. The redd location is recorded with a GPS system to ensure that no redd is measured twice.

The maximum redd count is the largest number of redds per riffle (or specified stream bed area) counted over the 10-15 week spawning period and represents the highest annual spawning density. The results of annually repeated redd surveys permit plotting the mean annual spawning area per consecutive riffle or stream reach and indicate the locations of highest spawning concentration and perhaps trends over time. A concentration of spawning in a smaller area than before may indicate a decrease the spawning success due to the superimposition of redds.

4.3.5.2 Analyses of aerial photographs

Spawning habitat delineation may also be based on large-scale aerial photographs (Section 4.2.5.1) taken at low flow. If a reach has a high sediment supply and a well-developed pool-riffle-bar morphology, riffle areas are assumed to equate with spawning habitat. This approach may overestimate spawning area if spawning is limited to a small part of the riffle, and field visits are necessary for verification. Field checking for localized spawning is particularly relevant in sediment-starved reaches. Examples of documentation of spawning areas the Spawning riffle Atlases for the Merced, Stanislaus and Tuolumne Rivers (AFRP 1999).

4.3.5.3 Historical extent of spawning habitat

For estimates of the historical spatial extent of spawning habitat in a stream, information is needed on the length of river used for spawning in pre-dam conditions and on pre-dam

stream morphology (e.g., from pre-dam aerial photographs). From the current field survey, a reach is selected that looks similar to the assumed pre-dam stream morphology. The current spawning density is then multiplied by the length of the reach with that morphology in pre-dam times. An analysis of (pre-dam) stream gradient could indicate whether the pre-dam stream had a variety of different morphologies. In this case, spawning density calculations will have to be done separately for each segment of a specified morphology. Pre-dam photographs of the stream, literature and personal accounts may help to supplement the historical estimate of spawning habitat area. Comparison between the historical and current spawning area shows the change over time. Results from this evaluation could be used to formulate problems and project goals, for monitoring, and for project evaluation.

4.3.5.4 General salmon related information

Besides information on quantity of spawning habitat as well as redd counts, projects should acquire the necessary body of knowledge on salmon populations and their temporal and spatial variability within a stream segment. Information on the number of fish passing a stream section can be obtained from rotary screw traps. Stock recruitment analyses may be important (Carl Mesick Consultants 2001). One should find out where within a stream reach or a stream segment salmon species find habitat in different life stages and the factors potentially limiting fluvial salmon survival (Kondolf 2000b). Expending effort for local increases of spawning habitat makes little sense if the stream provides poor habitat only for other salmon life stages.

4.3.6 Quality of spawning gravel

Before a gravel augmentation project starts, the quality of spawning gravel needs to be assessed to determine its role in limiting or supporting the spawning success. Spawning gravel quality is affected by several factors that can be measured in the field:

1. Size distribution of bedmaterial on spawning riffles;
2. Amount of fine sediment in spawning areas (as it impedes spawning success); and
3. Intragravel flows and dissolved oxygen content.

4.3.6.1 Size distribution of spawning gravel

Fish needs

The size distribution of spawning gravel deposits required or tolerated by salmonids covers a wide range and varies among species and among the size of spawning individuals within a species (Kondolf and Wolman 1993). As a general rule, salmon can spawn in gravel with a D_{50} particle size between 1 and 10% of the fish length (with an average of 4%). However, the coarse particles within the distribution should still be movable by the fish and not exceed 5 inches (127 mm) (Carl Mesick Consultants 2001). A high percentage of small gravel and finer particles in spawning gravel clogs interstitial spaces and is detrimental for embryo survival and fry emergence (Bjornn and Reiser

1991; Kondolf and Wolman 1993). To avoid this problem, fine particles are removed from gravel before it is added to the stream for spawning gravel augmentation. The size of the smallest particles in spawning gravel is, however, still debated. While there is agreement that very fine gravel smaller < 4 mm, and particularly sand and silt ("fines") clog interstitial spaces and should therefore be excluded from spawning gravel, there is disagreement whether spawning gravel should be screened at the typical 0.5 inch (12.7 mm) or at half that size. Recent observations have indicated higher salmon redd densities in gravel with a minimum particle size of 0.25 inch (6.4 mm) than in gravel with a minimum size of 0.375 inch (9.5 mm) (Carl Mesick Consultants 2001). An explanation for favoring the gravel with smaller particles is that salmon cannot move cobbles and coarse gravel to excavate the nest if the gravel mixture lacks medium and fine particles that "lubricate" the gravel mix and help mobilize the larger particles (Carl Mesick Consultants 2002b; Carl Mesick, pers. comm. Jan. 2004; McBain and Trush 2003 c). Using spawning gravel with a wider range of particle sizes (6.4 - 127 mm) may have the additional advantage that it attracts a larger variety of salmon species and perhaps even brings back spawners that have been absent for some time.

Stream needs

The gravel size to be used for spawning gravel augmentation needs to be in correspondence with the post-dam stream competence. Spawning gravel that is too fine is easily entrained and scoured away (Kondolf et al. 1996), while spawning gravel that is too coarse remains immobile (Kondolf et al. 2001) and may become clogged. Ideally, in geomorphologically functional streams, the coarse portion of the gravel (e.g., approximately the D_{84} particle size) should be annually or biennially mobile at bankfull flow (Trush et al. 2000). Particle larger than the D_{84} should remain mostly immobile to provide structure to geomorphological features such are riffles, pools and bars. The particle-size distribution used for gravel augmentation needs to be suitable for both, salmon and geomorphological needs.

Characteristic particle size parameters: D_{84}, D_{50} and the percent fines.

Kondolf (2000a) suggest comparing three individual particle-size parameters when analyzing the particle sizes of spawning gravel: the D_{84} and D_{50} particle sizes and the percent fines. He cautions against using a single-value index because it does not reflect the complexity of gravel particle-size distributions. The cut-off size between detrimental fines and larger sediment in spawning gravel depends on the fish species and the actual process by which fines negatively affect spawning (Reiser and Bradley1993; Rice 1995; Kondolf 2000). Fines smaller 1 mm decrease the intragravel flow and may harm incubation. Fines smaller than 3, 6 or 10 mm block the upward fry emergence. The timing of sampling is important, too. Redd construction removes fines, reducing the percent of fines smaller than 1 mm to an average 63% of the pre-redd content (Kondolf et al. 1993). However, fines supplied to the stream after redd construction easily infiltrate the relatively large interstitial spaces in the redd and are particularly detrimental in the weeks and months between egg development and fry emergence.

Collection of unstratified bulk sampling

The size of spawning gravel can be determined from unstratified (i.e., from the surface down to a specified depth) bulk samples of the bedmaterial. Under dry conditions, the material can be collected with a shovel. In submerged conditions, the sampling site needs to be shielded from flow by a stilling well to prevent the loss of fines (Schuett-Hames et al. 1996). A McNeil sampler is typically used for underwater sampling in wadeable conditions. These samplers come in different sizes and one with diameter large enough to enclose the largest particles should be selected. See Ramos (1996) for a comparison of sampling results from pipe and McNeil samplers with freeze cores and other samplers and Bunte and Abt (2001) for a general discussion of unstratified bulk sampling. For streambeds containing coarse gravel and cobbles, the plywood shield may be better suited than a McNeil sampler. The relatively large 0.6 by 0.6 m bed area sampled inside the plywood shield permits collection of a larger and more representative sample volume, and sampling can happen in a comfortable body position (Bunte and Abt 2001). Plywood shields are particularly useful if surface and subsurface particle-size distributions are to be evaluated separately. To obtain representative particle-size distributions, the weight of an individual sample should be 100 times the weight of the largest particles such that the largest particle comprises no more than 1% of the total sample weight (Church et al. 1987)[14]. Samples that weigh less than 100 times the weight of the D_{max} particle size risk that the largest particle comprises an overly large proportion of the total sample weight, thus overrepresenting its cumulative percent frequency. The number of samples collected per riffle depends on the spatial variability of the particle-size distributions (which would have to be established from repeated sampling). Pre- and post-project monitoring of the spawning gravel size-distribution is important for formulating problems, projects goals, and project evaluation.

It should also be considered that sampling depth affects the amount of fines: bulk samples collected to a shallow depth contain a large percentage of surface sediment that typically has less fine and more coarse particles than subsurface sediment. Samples that extend to a larger depth contain a smaller proportion of surface sediment and thus more fines. When assessing the percent fines it is also important to keep in mind that their percentage may change over time (Kondolf et al. 1993; Kondolf 2000a), due to the time when fine sediment was delivered to the stream, to bedload transport processes, and to the time it takes fine sediment to intrude into interstitial spaces.

Truncation of samples at some large particle size

The presence of a few large particles in relatively small bulk samples affects the numerical value of the computed percent fines. However, the presence of the few large particles does not really affect the fineness of the sediment for spawning (i.e., whether the amount of fines may result in clogging of interstitial spaces). Truncation of the sample at some large, commonly occurring particle size (perhaps the D_{84} particle size) before computing the percent fines is therefore advisable (Church et al. 1987). This measure makes has three advantages: 1) It permits collection of much smaller bulk samples (e.g.,

---

[14] *Plan on heavy samples: Given that a D_{max} particle of 127 mm weight about 6 kg, obtaining a sample of only 20-50 times the D_{max} particle mass amounts already to several hundred kg. Large samples become manageable when particles larger than 16 or 32 mm are processed in the field.*

if the D_{84} = 64 mm and particles this size weigh 0.8 kg, then an 80 kg sample becomes representative (see above)). 2) A comparison of the percent fines between samples from different locations or times becomes more meaningful. 3) It reduces the influence of the surface sediment which is coarser than the subsurface sediment. The largest particle sizes in the reach should nevertheless be noted because there is a limit to the particle size moveable by spawning salmon.

4.3.6.2 River-segment wide assessment of fines

If bedmaterial samples collected on spawning riffles indicate an undesirably high percentage of fines, an assessment of fines in the surface and near-surface bedmaterial may need to extend over a larger spatial scale such as an entire stream segment (possibly several km long) in order to identify sources and sinks for the fines. This information would help the decision whether removal of fines from the existing gravel bed in conjunction with gravel augmentation with would improve spawning success more than gravel augmentation alone. Questions to be addressed by an analysis of the percentage of fine sediment in spawning areas over a stream segment include:

- What is the spatial distribution of fine sediment and does it harm fish where it is?
- What are the sources of fine sediment?
- What is the seasonal timing of fine sediment delivery? And
- Would short-term removal of fines be beneficial and feasible in the long run?

Two general locations are targeted in the field analyses of fine sediment: a) Pools and other relatively deep or slowly-flowing areas where fines deposit preferentially (runs, glides, side channels, and backwater exposed at during low flows). b) Discrete fine sediment deposits that may be located in pool bottoms, in-stream wetland deposits, the top of gravel bars, sand bars and overbank deposits. All spatial information gathered during the field analysis should be carefully mapped in large scale field maps (Section 4.2.5.1).

For discrete deposits, the morphological unit is recorded and the percent of fines within or outside of the lowflow channel. The main 2-3 constituents of fines are visually assessed (e.g., Sand-Silt-Mud indicates that the majority of the deposit is sand, silt is present, too, as well as some mud) (Buffington and Montgomery 1999). The depth of the fines deposit, as well as the veneer thickness in pools, is estimated by probing with a graded rod. Bulk density is estimated via the compactness of the deposit which may range between 1.14 g/cm^3 for loose and 1.84 g/cm^3 for compact deposits. The total mass of fine sediment in pools or elsewhere can then be estimated from the mapped and digitized areal extent of the affected deposits multiplied by the deposit depth and bulk density. Tributary supply of fines can be estimated by a visual assessment of the confluence area (e.g., delta vs. downcutting). More information on the amount of fines can be obtained from direct measurements of the fines supply using a Helley-Smith bedload sampler (0.25 mm mesh bag) and a suspended sediment sampler.

Similar to the results from the spawning gravel quantity, results of mapping and quantifying the percent of fine sediment can be plotted over the river length. If surveys from different times are available, temporal trends in the spatial distribution may be detected, and these might show movements of waves of fine sediment through the reach.

Results of such analyses could also reveal whether deposits of fines occur specifically in a few pools downstream of tributaries or in near-stream gravel pits full of fine sediment deposited in a highflow event. The removal of pool fines due to localized sources of sediment supply may be worthwhile to prevent spawning areas just downstream of tributaries from being overloaded with fines. By contrast, if fines are a general problem, flow releases for the purpose of flushing fine sediment from the bed area may be useful to enhance and maintain the quality of spawning gravel. A large body of literature exists on "flushing flows" designed to cause some movement of the gravel bed to release and transport fines but not enough to cause widespread and strong gravel transport (e.g., Reiser et al. 1989; Wilcock et al. 1996b; Kondolf and Wilcock 1996; Wilcock 1998; Milhous 1998; Dalby et al 1999; Wu 2000). Reduction of tributary supply in fine sediment may necessitate watershed management to reduce sediment sources. Sediment retentions basins near the confluence prevent tributary fines from reaching the mainstem river, while dredging of pools and near-stream pits could help remove fines that are in the stream.

Considering the seasonal timing in the delivery of fine sediment is important as well. Fine sediment supplied at periods of low flow or during incubation periods is likely to have a more negative effect on spawning gravel than fine sediment supplied during the onset of a highflow when much of it is flushed through the system.

4.3.6.3 Gravel permeability and intragravel flows

The rate of intragravel flows which is important for egg development can be estimated from gravel permeability. However, standpipe measurements correlated poorly with the apparent intragavel velocity and are not a recommended measuring method (Carl Mesick Consultants 2002b). Not only does bed permeability locally change when the standpipe is driven into the streambed and hits a large rock that is then pushed aside, but pumping water and fines out of the standpipe also enhances a local flow path which causes an overly high permeability readings. By contrast, water temperature measurements inside artificial redds and at the water surface provided information on intragravel flow. Elevated and stable intragravel temperatures indicate that a redd receives higher rates of upwelling oxygen-poor groundwater than downwelling surface water. A decreased rate of downwelling surface water may be attributed to fine sediment intrusion which may occur after storm flows or gradually over time in silty riffles.

4.3.6.4 Effect of intragravel flow conditions on spawning success

The percent of egg survival to emergence - a declared measure of success in spawning gravel augmentation - is influenced by various parameters such as intragravel dissolved oxygen concentrations and water temperature, intragravel water suspended sediment

concentration and silty/clayey deposits, apparent flow velocity[15], permeability and the percentage of intragravel fine gravel and sand (Carl Mesick Consultants 2002b). Fine sediment intruding into the upper layers of the spawning gravel and forms a seal causing alevin entombment and blockage of fry emergence. This fine sediment may be deposited from flows carrying a high concentrations of fines or by redd superimposition when later-spawning females cover earlier redds with sediment as they dig their redds close to or on top of already existing redds. However, quantifiable relationships between amounts of fines and alevin entombment have not yet been established but would be desirable to predict the spawning success from intragravel conditions. Similarly, egg survival to emergence cannot yet be well predicted from habitat measurements, because the relative importance of a specific parameter within the interplay of several parameters is not well understood and because of feedback loops (e.g., healthier alevins due to higher general D.O. concentration may require less intragravel flow, whereas alevins with stunted growth may emerge but the fry may have low tolerance to stressors and low survival). Direct field measurements of habitat parameters together with the percent egg survival to emergence of eggs planted into artificial redds at various stream locations may help to better illuminate these relationships (Carl Mesick Consultants 2001, 2002b).

The intragravel fine sediment content changes over time depending on the fine sediment supply carried by storm flows. High suspended sediment concentration can leave a silty-clayey deposit in interstitial spaces, while fine gravel and sand can infiltrate into redds. This can be a particular problem in areas downstream from surface gravel mining that exposes easily entrainable fine subsurface sediment. By contrast, floods with little supply of fines may flush fines from near-surface interstitial spaces (see flushing flows, Section 4.3.6.2). The amount of fine sediment intrusion into gravel interstitial spaces can be estimated using Whitlock-Vibert boxes (Reiser 1995).

4.4 Modeling and design development

The interactions between flow hydraulics and bed topography and between water flow and sediment movement are complicated, and simple computations may not be able to show the dynamics of these interactions. Modeling can sometimes provide insights into cause-and-response relationships and show trends over time. This information is important for gravel augmentation projects.

4.4.1 Criteria for site selection

Hydraulic and sediment transport modeling is usually restricted to a few specified stream reaches. The spatial extent of the study determines the criteria according to which a reach for intensive modeling of gravel augmentation is selected.

In multi-reach river restoration projects, modeling may extend over several cross-sections within a reach or focus on individual reaches for which extensive resizing or reshaping is considered. In river-segment wide gravel management plans, sites for extensive

[15] *= horizontal vector of interstitial flow; measured using a standpipe and slower than the true or pore velocity (Carl Mesick Consultants 2001)*

modeling may be those that are geomorphologically functioning (to learn how the system should ideally function), or sites that are most in need of repair which are identified from geomorphological stream surveys (Section 4.3.2.2).

4.4.2 Topographic modeling

While surveying several cross-sections is sufficient to characterize the channel bed surface topography in some gravel augmentation projects, other projects require topographic modeling. The first step towards topographic modeling is a detailed reach-spanning topographic survey. Survey points are closely spaced where the topography is spatially variable and more widely spaced where the topography is relatively flat. A digital elevation model (DEM) can then be established by forming a grid or polygons from the surveyed points (Wheaton et al. 2004a and b). A DEM is not only used for topographic differencing that computes the volumetric difference between two surfaces and thus, for example, the amount of gravel needed for implementing a design plan or the amount of sediment deposited on or eroded off a spawning riffle (Section 4.3.4.2). It also be used as a basis for hydraulic and sediment transport modeling and developing gravel augmentation designs (Section 4.4.3.2).

4.4.3 Hydraulic modeling

Hydraulic models are used to compute the interaction among the parameters flow depth, flow velocity, total flow volume, channel shape, stream and water surface gradients and channel bottom roughness. One can compute how one parameter varies when one or several other parameters are changed, while the remaining parameters are held constant. Hydraulic models differ in the equations employed to describe these interactions and in the model dimensionality which may be 1-D, 2-D, and 3-D. The complexity of the model and the expertise required to run it increase sharply with the number of dimensions used. Hydraulic models, particularly 2- and 3-D models, need to be validated or calibrated against measured sets of flow hydraulics to ensure proper model functioning (Pasternack et al. 2004).

4.4.3.1 One-dimensional models (e.g., HEC-2, HEC RAS)

Hydraulic models for one-dimensional, gradually varied[16] steady[17] flow compute flow conditions within a cross-section as an average cross-sectional value. The basic input parameter for application in gravel augmentation projects is the cross-sectional shape (i.e., the survey data), the D_{50} particle size of the bed, discharge, and a roughness value for Manning's *n* that can be computed from discharge measurements or be estimated from values published in the literature (e.g., Chow's (1959) data in Yang (1996); Barnes 1967; Limerinos 1970; Jarrett 1985). Note that Manning's *n*-values for stream roughness may change with flow and over the stream width if floodplains (particularly vegetated ones) are inundated (e.g., Stillwater Sciences 2001 b; CDWR 2001).

[16] *changing gradually over space*
[17] *not changing over time*

1-D models compute the interaction between total flow (i.e., water discharge), mean flow depth and mean flow velocity for a specified cross-section and specified values of stream gradient, bottom roughness, and D_{50} particle size. Examples are the widely-used HEC-2 model and its successor HEC RAS both developed by the US Army Corps of Engineers. Both models can be easily obtained from the internet[18]. However, use without a solid background in stream hydraulics and modeling is not recommended.

Use as a testing tool

1-D hydraulic models are suited to evaluate the stage to which a specified flow will fill the cross-section, or the amount of flow that will pass through a cross-section at a specified fill level or stage and what the resulting mean depth and mean flow velocity will be. This information is useful for testing whether a design channel reach will be hydraulically functional at different flows (CDWR 2001; Stillwater Sciences 2001b). Ideally, the design channel should be filled to its morphological bankfull stage when discharge amounts to bankfull or the 1.5-year recurrence interval flow. Likewise, the 20- or 50-year flood should cover the floodplain but not areas beyond it. Modeling can also be used to compute flow depth and velocity at spawning flows to ensure that flow conditions in the newly designed gravel augmentation project are suitable for spawning. The model is applied to individual cross-sections, but results from consecutive cross-sections can be used to obtain information over a larger river reach. Multiple cross-sections can be generated from the design plan (which may be a digital elevation model DEM) using an AutoCad program.

Use as a design tool

1-D hydraulic models can also be used as a design tool in the initial project phase. The model cross-sectional shape may be modified until a shape is found that provides desirable outcomes in terms of flow depth, flow velocity and geomorphological fill level for different design flows (e.g., low flows, spawning flows, bankfull flows, and flood events). A 1-D model can likewise be used to compute the flow at which incipient motion will occur in a specified cross-section or how a cross-section should be designed such that incipient motion will occur at near-bankfull flow. The answer to both questions involves an estimated value of τ^*_{crit} (Section 4.3.3.1) that ideally is determined from tracer experiments in the field. Since for a specified flow, τ^*_{crit} is a function of cross-sectionally-averaged depth, stream gradient, and bed material particle size, the parameters width, depth and gradient can be modified to determine a channel shape in which the augmented spawning gravel becomes mobile at near-bankfull flows. Again, expertise is necessary to properly run the model and evaluate model results.

4.4.3.2 2-D hydraulic models

2-D hydraulic models also have as basic input parameters the stream bottom topography, channel bottom roughness, transverse eddy viscosity, total discharge and water surface

[18] *http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html*

topography. However, the model provides spatially detailed information on flow depth, mean flow velocity, and on the lateral direction of flow for preset increments within the cross-section and for consecutive cross-sections (Steffler and Blackburn 2002). 2-D models are particularly suitable for modeling flow depth and velocities that develop over a stream bed area shaped by augmented spawning gravel. By contrast, the complexity, difficulty, and expertise required for 3-D modeling makes them not well suited for application in spawning gravel augmentation projects (Pasternack et al. 2004).

Several 2-D hydraulic models are available. Gallagher (1999) tested and suggested using the River 2D modeling system (Steffler and Blackburn 2002) to assess the spatial variability of flow conditions. These results can then be used to evaluate whether the combination of flow depths and velocities are suitable to provide spawning and other salmon habitat. A similar use for the River 2D model was suggested to assess whether modeled post-restoration habitat conditions correlated positively with an increased number of redds and juveniles (AFRP – Annual Workplan 2000). A 2-D hydraulic model that has been extensively tested and used in gravel augmentation studies by Pasternack et al. (2004) and Wheaton et al. (2004 a and b) is FESWMS-2DH (Finite-element surface-water model for two-dimensional flow in the horizontal plane). The model was developed by the U.S. Geological Survey and is commercially available on the internet[19]. FESWMS-2DH is a modular set of computer programs that include an input data preparation program, a flow model, a simulation output analysis program, and a graphics conversion program. The flow model (FLOMOD) module simulates two-dimensional, depth-integrated, surface-water flows. Again, though easily available, it is not recommended that the model be used without a solid background in stream hydraulics and modeling.

A quasi 3-D extension of modeled results can be obtained when linking modeled results for consecutive cross-sections. This linking is important to evaluate the longitudinal effects of a proposed gravel augmentation. As an example, Fig. 4.4.3.2a shows a large gravel placement to enhance spawning habitat on a glide. While this measure successfully transformed the glide into a riffle with good spawning habitat potential, it also decreased the size of spawning area in the upstream riffle. The backwater effect from the voluminous downstream gravel augmentation (Scenario 1) elevated the water surface on the upstream riffle, rendering the flow depths there too deep for spawning. In Scenario 2, the elevation of the downstream spawning gravel placement is reduced to achieve an optimal solution between creating new spawning habitat on the former unproductive glide while maintaining the productive spawning habitat on the upstream riffle (Wheaton et al. 2004a).

Creating and testing different gravel augmentation designs (SHIRA)

High resolution 2-D hydraulic modeling is useful for investigating the response of flow hydraulics to a new stream-surface topography resulting from a proposed gravel augmentation at the local or reach scale. Wheaton and Pasternack (2002), Pasternack et al. (2004) and Wheaton et al. (2004 a and b) used a commercially available 2-D Model

[19] *http://water.usgs.gov/software/feswms.html*

"Finite Element Surface Water Modeling System" (FESWMS) designed for flows over relatively smooth beds. Application of this model to the design of one particular spawning reach at the Mokulumne River below Camanche Dam in the context of a Salmon Habitat Integrated Restoration approach (SHIRA) is shown in Section 2.2.4 (Pasternack et al. 2004), application to another reach is shown by Wheaton et al. (2004 a and b).

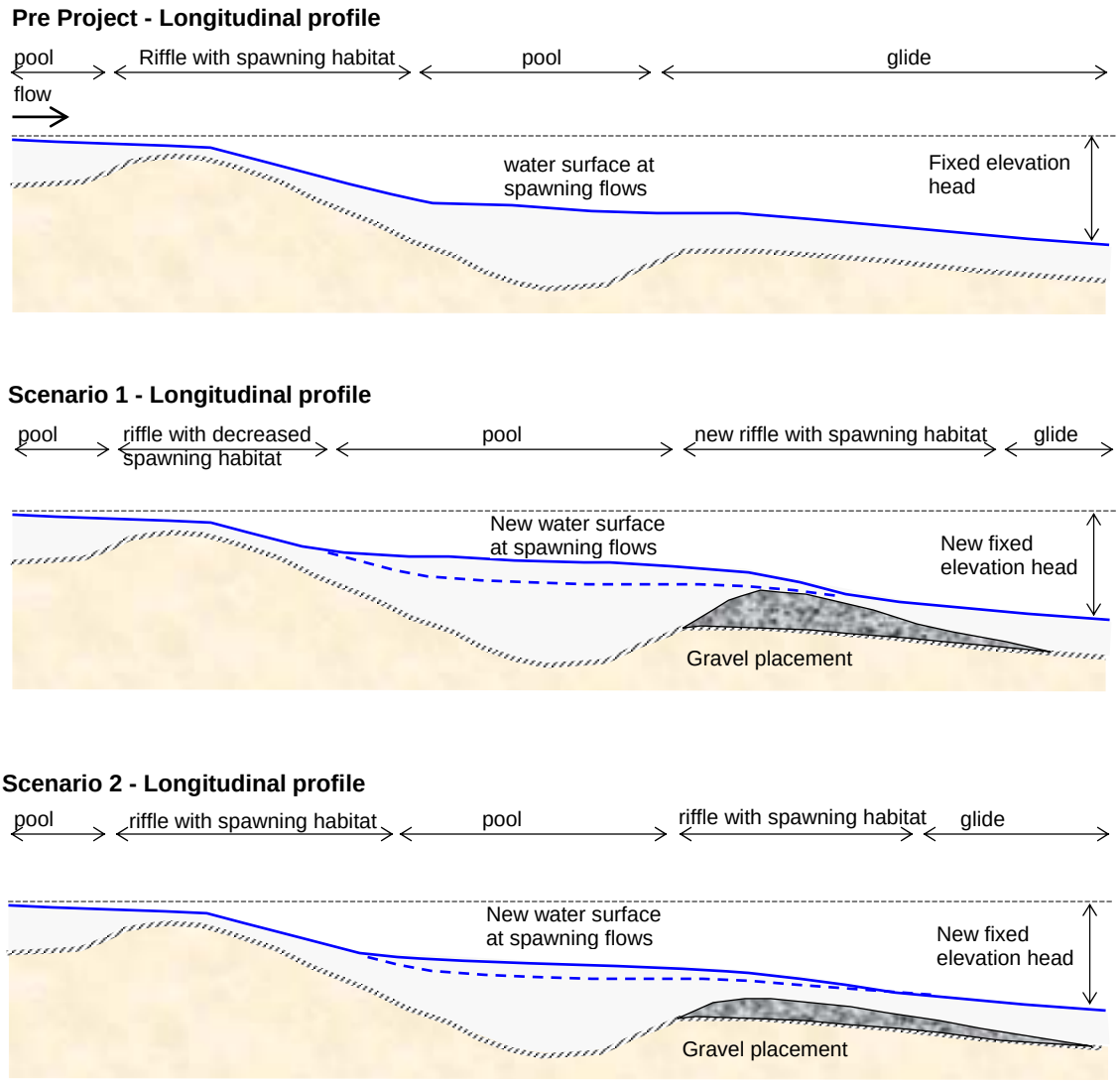


Fig. 4.4.3.2a: Effect of gravel placement on upstream water surface profile and longitudinal extent of spawning habitat (redrawn from Wheaton et al. 2004a).

Desirable attributes of a functional spawning reach are generally known, thus design objectives can be easily established and include (Wheaton et al. 2004b): (1) Enhancement of quality and/or quantity of spawning habitat with (2) geomorphologically sustainability,

and (3) intragravel conditions suited to attract spawning females and to increase alevin survival rates, (4) Development of habitat that is beneficial to spawning adults and juveniles, with (5) morphological diversity to enhance biological diversity. However, the design of the gravel augmentation project may also be influenced by a specific amount of gravel available to the project (6). This amount can be dictated either by the funds available for gravel purchase or from the deficit in gravel supply.

Design concepts for spawning habitat enhancement and sustainability are intended to fulfill the geomorphological, sedimentological, and biological functions listed above as well as practical considerations (e.g., must work with a fixed amount of gravel). Design development at this stage is mainly conceptual; it may involve drawing sketches or some preliminary modeling. A specific design that provides superb functioning on all levels will probably not take shape immediately. Instead, several competing designs may be developed each with a slightly different focus. Designs are likely to be different for each gravel augmentation project due to the specific post-dam stream disturbance and pre-project stream conditions. Once a few final design scenarios have been prepared, the depth of the gravel added for each scenario is entered into a DEM model (Fig. 4.4.3.2b). The resulting streambed topographies are then used for hydraulic modeling. Before a hydraulic model can be used for modeling the effects of gravel augmentation and for testing of various designs, it must be validated for the site. This means, adjustments need to be made in the model assumptions (e.g., bottom roughness, or equation used for velocities) until the model accurately reproduces values of flow depth, velocity, and water surface measured for specified flows during the pre-implementation period. Once this is achieved, flow hydraulics can be computed for the proposed gravel augmentation designs.

The combination of flow depths and velocities that are preferred by spawning salmon is obtained from locally established habitat suitability curves. As the 2-D model computes flow depth and velocity for each of its numerous grid points, a global habitat suitability index (GHSI, with the value of 0 for non-habitat and 1 for excellent habitat) can be computed for all grid points to show the spatial distribution as well as the overall percent streambed area with specified GHSI values (Fig. 4.4.3.2c).

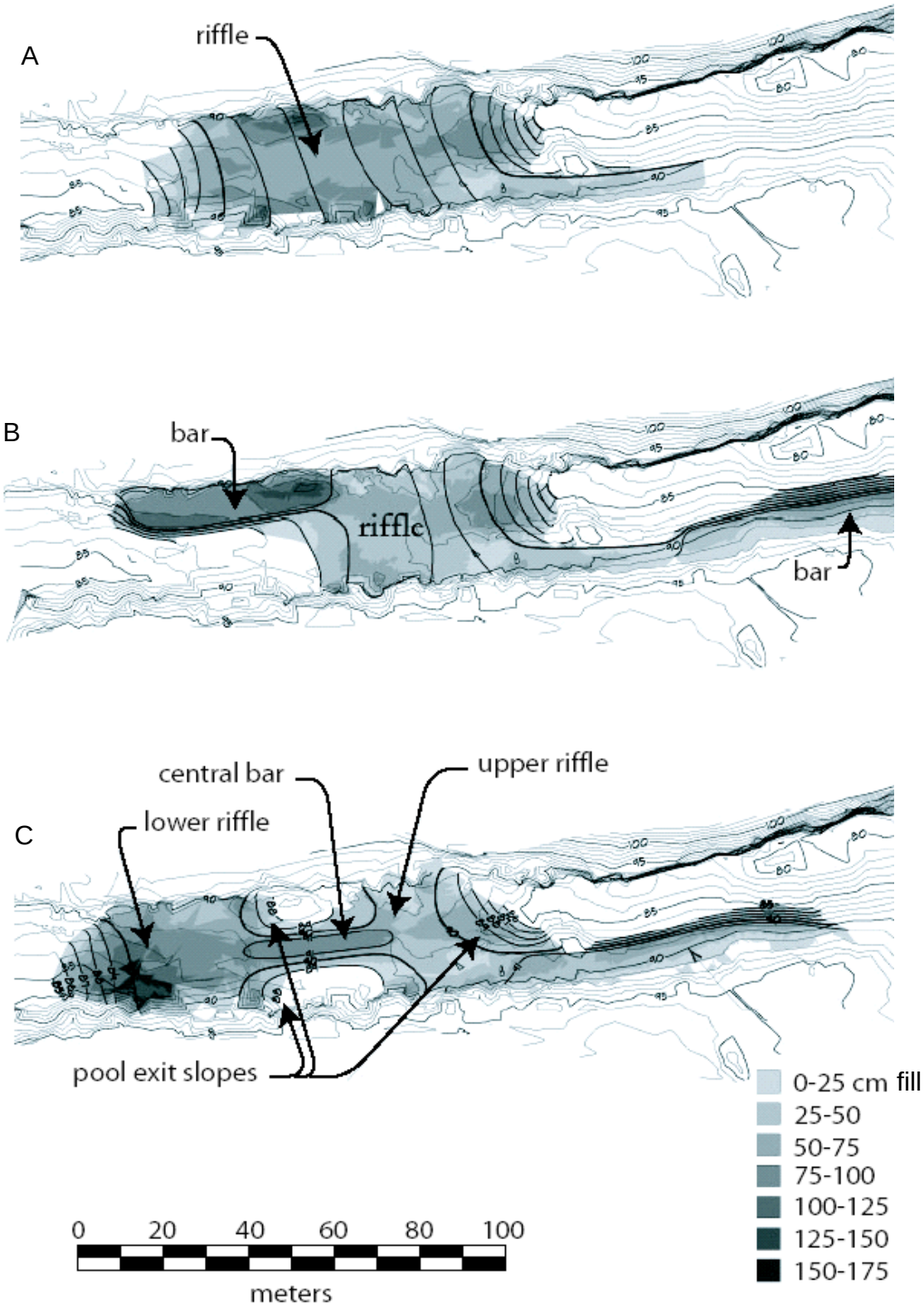


Fig. 4.4.3.2b: Topography and grading plans of selected gravel augmentation design scenarios at the Mokulumne River below Camanche Dam; Flat riffle (A), Constricted pool (B), and complex channel (C) (Copied from Wheaton et al. 2004b and slightly modified).

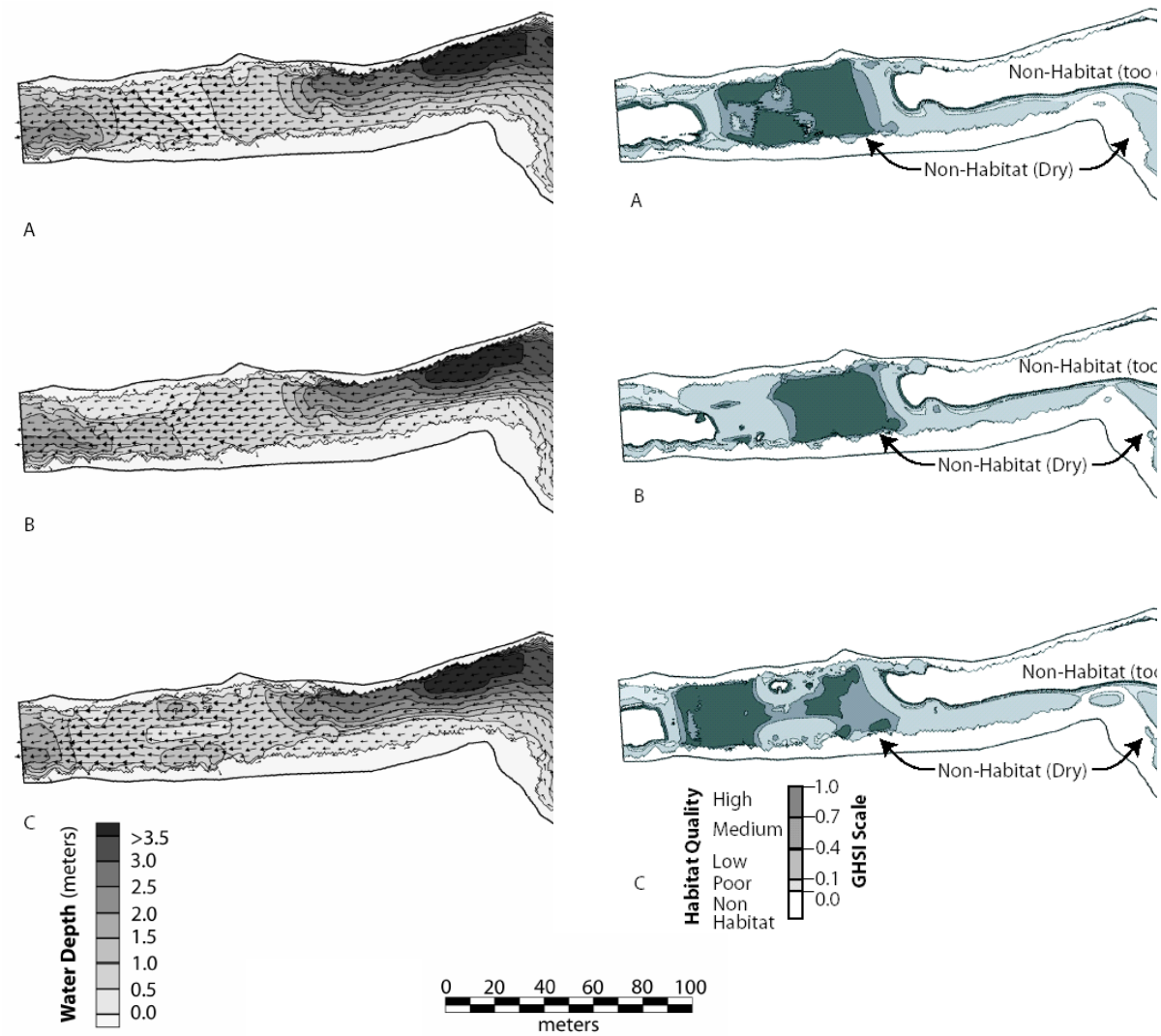


Fig. 4.4.3.2c: Flow depth, velocity (left) and global habitat suitability index (right) for selected gravel augmentation design scenarios at the Mokulumne River below Camanche Dam; Flat riffle (A), Constricted pool (B), and Complex channel (C); (Copied from Wheaton et al. (2004b) and slightly modified).

Modeling critical flow for incipient motion

If flow hydraulics are known for each grid point, and if bed material sizes are either spatially homogeneous or their spatial variability is known, likelihood of transport of the mean bedmaterial particle size can be estimated by comparing hydraulics computed for specified flows (e.g., spawning flows, bankfull flow ($Q_{1.5}$), or Q_5-, Q_{10}-, or Q_{20}-flood events) with the theoretically or experimentally established critical flow conditions for particle entrainment. It is conceivable to compute the dimensionless shear stress τ^* for each grid point and compare it to a predetermined critical value (See Section 4.3.3.1 for critical dimensionless shear stress computation). Pasternack et al. (2004) opted for a

slightly different approach and computed the depth-averaged flow velocity for incipient motion based on Einstein's log velocity equation combined with a critical value for dimensionless shear stress. The ratio of the computed value to a predetermined critical value was plotted for each grid point to show stream-bed areas most likely affected by erosion at spawning, bankfull, or flood flows. Bed scour due to wading fishermen, scour jets near local flow constrictions such as large woody debris, or the process of redd digging by the spawning female cannot be predicted by this kind of model.

Design evaluation

After testing, design results are evaluated with respect to the six criteria established above. The amount of habitat created (1) can be estimated from the GHSI values computed for the different designs. High values over a large percentage of streambed area and over a range of flows are preferable. Geomorphological sustainability (2) can be evaluated based on whether critical flow for bed scour will be exceeded during spawning flows. Suitable intragravel conditions (3) can be anticipated by the percent spawning area created in pool exit slopes. The proximity of spawning areas to pools, zones with flow separation, overhanging banks, etc. gives an indication of whether spawning adults and juveniles find refuge and shelter habitat in the proposed design (4). The variability in the post-project topography suggests the degree of morphological variability in the created design (5). Finally, the design must be gravel-efficient (6), an indication of which is either the total amount of gravel used or the area of spawning habitat created per volume of gravel applied. After the design scenarios are evaluated with respect to the six criteria, they are ranked to determine the highest-rated final design.

4.4.4 Gravel bedload transport modeling

4.4.4.1 A bedload equation coupled with a 1-D hydraulic model

Although a variety of sophisticated bedload transport models exist for sand, modeling gravel transport is still in its infancy. A conceptually easy approach to gravel transport modeling that has been applied to gravel augmentation projects is the coupling of a 1-D hydraulic model with either a measured bedload transport rating relationship in the form of $Q_b = f(Q)$ or a bedload transport equation (Section 4.3.4.1).

The main input parameters that need to be quantified in bedload transport equations usually include: cross-sectionally averaged flow depth and/or flow velocity, a stream bottom or water surface gradient, and bedmaterial size. A hydraulic model computes cross-sectionally averaged flow depth and/or flow velocity for specified boundary conditions (gradient, channel geometry, bedmaterial size and/or roughness). Thus, the model output of flow depth and/or velocity can be used as input for a bedload transport equation. Provided, the bedload equation rating curve has been validated by trustworthy field-based measurements, approximate bedload transport rates are computable over a range of flows.

Computation of annual loads and gravel augmentation needs

Computed instantaneous transport rates that are integrated over an annual hydrograph yield the annual load. Application to typical low- or highflow years in the post-dam flow regime estimates typical low- and highflow annual loads, while application to the long-term flow record provides the mean annual bedload discharge (Section 4.3.4.1). For a restored channel section or a reach that suggests equilibrium conditions between bedload transport rates and bedload supply, the computed mean long-term gravel load indicates the long-term mean annual gravel augmentation requirements.

General problems in bedload transport modeling

Ideally, bedload transport modeling should predict the geomorphologically functional channel shape that would transport a specified amount of annual gravel load of a specified median particle size for a specified flow regime. However, modeling gravel bedload is still problematic. Many processes in gravel transport and transport dynamics remain poorly understood. Different bedload equations may yield very different results, and these in turn may differ by orders of magnitude from measured transport rates. One often does not even know for sure that measured bedload transport rates are accurate and reflect the true transport values. Even less is known about how different channel geometries and longitudinal planforms affect bedload transport except for a rudimentary level. Thus, the same amount of flow may result in very different gravel transport estimates for different channel shapes. Bedload transport modeling should therefore be applied to simple, i.e., trapezoidal and straight channel reaches. Modeling should be done by experts only, because modeled results need to be interpreted judiciously, and modeled results should be considered as a first estimate only.

4.4.4.3 Stillwater Sciences' EASI-model based on the Parker bedload equation

A bedload transport model developed and used by Stillwater Sciences is the EASI model (Enhanced Acronym Series 1&2 with (User) Interface, Version 5.0). The model is based on the Parker (1990a) bedload transport equation and was originally developed by (Parker 1990b). Stillwater Sciences (2001a, b) and Cui (2004) modified it to apply to natural channels and entire stream reaches rather than to an individual cross-section and added several built-in bedload transport equations.

The EASI model computes bedload transport capacity and normalized dimensionless shear stress for a specified cross-sectional shape, channel gradient and bed material size-distribution and total flow. The normalized Shields stress is ratio of the mean cross-sectional dimensionless Shields value τ^* (Section 4.3.3.1) and the dimensionless reference Shields value of $\tau^*_{crit} = 0.0386$ that Parker (1990a) assumed for incipient motion. A ratio of 1 indicates incipient motion, and solving the dimensionless shear stress equation for depth yields the critical depth and discharge at which transport starts. Modeled transport rates assume unlimited sediment supply (i.e., transport is at it full capacity). Post-dam gravel starved stream are most likely supply-limited with transport rates less than the computed transport capacity. However, supply-limited transport rates cannot be computed directly using this model.

Variability in results and sensitivity to slight variations in model input parameters

When the EASI model was applied to compute critical flow and bedload transport rates for adjacent cross-sections, results were a mixed success. Transport rates for cross-sections just a few feet apart varied by a factor of three, while critical flow for incipient motion varied by a factor of 1.5. This variability cast doubt whether 1-D hydraulic models provide the appropriate input for bedload equations. Transport rates were generally two orders of magnitude lower than measured rates (McBain and Trush 2003b, Appendix. C), which argues for caution before using bedload transport models without validation. Modeled results were also highly sensitive to slight variations in model assumptions and input parameters. The computed long-tem gravel augmentation mass varied by a factor of about three depending on (1) whether flows above bankfull were assumed to spread over the floodplain versus being contained within the main channel; (2) when the water surface slope was changed by ±20% of its value; and (3) when the bedmaterial particle-size D_{50} was changed from 42 to 58 mm (the finest to the coarsest distributions within a reach).

Important information for gravel augmentation

The EASI model has also provided important insight for gravel augmentation projects. The model predicted, for example, that in transport rates within a restored reach would decrease in a downstream direction, alerting project managers that bed stabilization would be necessary in the upstream section while through-transport had to be ensured for the lower section (Stillwater Sciences 2001a, b). The model also indicated a high mobility of the added spawning gravel at highflows suggesting that episodic replenishment at the upstream end of the restored reach would be necessary to compensate for the lack of upstream gravel supply. However, introduced rates must be commensurate with the lower transport capacity in the downstream section and the gravel addition site must not interfere with current spawning locations[20].

Modeling channel designs that fulfill geomorphological and biological functionality

The EASI model can be used to determine reconstruction alternatives that fulfill stated objectives for geomorphological and biological stream restoration (Stillwater Sciences 2001b) such as: (1) Beginning floodplain inundation at bankfull flow, (2) bed mobility at bankfull flow, (3) appropriate bedmaterial particle-size distribution for spawning, (4) potential for lateral channel migration, and (5) timing and frequency of floodplain inundation supports establishment of native vegetation.

To achieve these objectives, the model is run repeatedly while input parameters are varied such that a solution is obtained by approaching the problem from different sides. For example, in a first approach, stream gradient and bedmaterial size may be held constant while modeling several scenarios with different values for top and bottom stream width, floodplain elevation and annual gravel loads. In a second approach, a

[20] *Carl Mesick cautioned that narrow and fast reaches between the mining-affected reaches are the only places in which salmon spawn. Supplying gravel here, particularly gravel that is too large for spawning, destroys the last of the remaining spawning habitat (Carl Mesick, email 1-26-2004).*

stream width is determined that fills the channel at bankfull flow and the floodplain elevation is then set at that level. With the channel slope held constant, bedmaterial size is varied to attain bed mobility at bankfull flow. Approaching a design problem from several sides permits the EASI model to balance channel capacity (i.e., floodplain inundation starting at bankfull flow) with bedload transport competence (amounts) and capacity (sizes), rather than designing a channel solely based on hydraulics and then determining whether the channel would also have the appropriate transport capacity and competence. The user should note, though, that unlike result obtained by hydraulic 2-D modeling (Section 4.4.3.2), outcomes from 1-D bedload transport modeling are not meant to be used as construction design for a specified site.

Long-term post-project conditions and channel responses are difficult to foresee

Even if transport rates and annual gravel supply could be modeled (with caveats) for a specified post-project channel shape, bedmaterial size, and bed mobility, modeling long-term post-restoration annual loads and gravel augmentation needs is problematic. Exact stream responses to the gravel augmentation are not predictable, and the long term response is affected by both gravel augmentation and pre-project effects.

4.4.5 Modeling downstream gravel movement as bedload waves

Gravel supplied locally to a channel that is annually or biennially mobile will eventually be eroded from the reach and travel downstream in the form of a bedload wave. Bedload waves move by translation (entire sediment body moves while keeping its topographical shape) and dispersion (the wave flattens while the peak remains stationary), usually employing both processes together. Progress has been made in modeling the downstream travel of bedload waves (Cui et al. 2003 a and b), and modeling the downstream travel of introduced spawning gravel in the form of bedload waves may become a future tool for gravel augmentation studies (Cui 2004). Easily available sediment routing models that have also been proposed for use in gravel augmentation projects are the Army Corps of Engineers' HEC-6[21] and the Bureau of Reclamation's GSTARS[22] models. Information on the amount and speed of downstream gravel movement would help to predict how long gravel supplied to a specified location will last, how much gravel needs to be supplemented, at what intervals and when un-augmented reaches further downstream would benefit from an upstream sediment supply.

4.5 Changes in the seasonal flow regime

A post-dam flow regime is mainly geared towards providing flows when water is needed for agriculture or municipal use, or for hydroelectric power generation. The resulting flow regimes do usually not match geomorphological requirements nor flow needs for salmon in different life stages. Unless post-dam flow regimes address these flow needs, spawning gravel augmentation will not yield its optimal results with respect to increasing the salmon population. A richly illustrated brochure by McBain and Trush (2000a)

[21] *http://www.bossintl.com/html/hec-6-features.html*
[22] *http://www.usbr.gov/pmts/sediment/gstars/3/*

provides visual descriptions of the timing of annual low and highflow seasons that support the needs of salmon in different life stages and help establish riparian vegetation that supports geomorphological functioning while minimizing the amount of water flows required to obtain these goals.

If changes in post-dam flow regimes are necessary, it would be helpful to negotiate these early in a project. Computations of the post-project annual gravel load and the amount of gravel to be added by gravel augmentation could be much more accurate if based on an actual rather than a hypothetical flow regime.

5. Project implementation

Implementation of a gravel augmentation project includes several steps:

- Final site selection for gravel addition(s) (unless the site was predetermined right from the start),
- Final computation of the gravel volume needed to achieve a specified channel design as well as the long-term gravel demand to be supplied episodically or regularly for maintaining a geomorphological and biologically functional channel,
- Preparation of final design plans, usually superimposed onto a large-scale topographic map from a pre-project survey.
- Determination of gravel source(s),
- Preparation of gravel to meet biological and geomorphological requirements,
- Contracting the construction work and supervising its progression. As modifications may be made during the implementation phase, the site should be re-surveyed immediately after the implementation to obtain a plan of the "as-built" topography.

Some of these steps are discussed below.

5.1 Sites for gravel augmentation and computation of gravel volumes

Different methods are used to determine sites for gravel augmentation and gravel volumes depending on the spatial project scale. In a river-segment wide gravel augmentation plan, gravel augmentation encompasses several sites that may be identified through a geomorphological survey as sites most in need of supplemental gravel to become geomorphologically functional (Sections 4.3.2.1 and 4.3.2.2). For a multi-reach project, gravel augmentation sites are within the reaches modeled and the gravel augmentation volume is typically determined from bedload transport modeling (Section 4.4.4).

5.1.1 Site selection in local scale projects

For projects focusing on a single reach or several individual reaches, site selection is an early project task. The most important factor is suitability for creation or enhancement of spawning habitat. Suitable locations are natural spawning riffles where existing habitat needs to be enlarged or improved (Carl Mesick Consultants 2002 a, b, c) or wide stream reaches where *large* spawning areas can be created and the likelihood of gravel lost to scour is low. Salmon appear to accept spawning habitat irregardless of the morphological unit within which the habitat was constructed (Carl Mesick Consultants 2001, 2002b). However, reaches downstream from recent surface gravel mining areas are not suitable, because they tend to receive large amounts of sand and fine gravel stemming from the subsurface exposed when the surface sediment was mined.

The range of flows expectable during the spawning season and their effect on spawning gravel needs to be considered. Spawning gravel should not be placed where redds are scoured at high flows or exposed to the air at low flows.

Proximity to a dam may also be a factor. The upstream water and sediment supply are known quantities and this location is also closest to pre-dam spawning areas further upstream and favored by spawners (Carl Mesick Consultants 2002 a, b, c). Restoration of spawning habitat immediately below the dam maximizes the length of stream in which spawning habitat may be restored. Locations just below the dam may also be most in need of restoration because post-dam gravel scour and deterioration of former spawning habitat were most severe here. Other factors for site selection may be stream access and proximity to gravel sources. Proximity to other environmental, riparian or stream studies can be desirable because it permits multiple projects to share data and to pursue comprehensive goals of environmental restoration.

5.1.2 Gravel amounts

Ideally, the amount of gravel used for spawning gravel augmentation is based on the need for geomorphological and biological functionality of the stream. This need may be estimated through:

- Assessment of post-restoration annual load (Section 4.3.4.1 and 4.3.4.2),
- Bedload transport modeling (Section 4.4.4.1 and 4.4.4.3),
- 2-D hydraulic modeling (Section 4.4.3.2), and
- Geomorphological survey and analysis of the “missing volume” (Section 4.3.2.1 and 4.3.2.2).
- Gravel resources and funds available to the project.

5.2 Gravel sources and preparation

Gravel augmentation projects, and particularly those that extend over large stream segments, require large volumes of gravel. The largest portion is used during the construction phase for building spawning riffles, lining the channel, as well as filling ponds and pits. Once this phase of short-term transfusion is completed, spawning gravel is episodically or periodically applied to replenish the scarce upstream gravel supply in order to maintain a geomorphologically and biologically functional channel.

5.2.1 Gravel costs

Gravel is a commercially used building material. Its market price has been quoted as \$25/ton or \$19/yd^3 (Kimball 2003) and \$33/ton or \$25/yd^3 (R2 Consultants 1994). As gravel costs can amount to several \$10,000 or \$100,000 per project, identifying economical gravel sources becomes important, particularly in large gravel augmentation projects.

An overview of gravel volumes and cost that accrued in various gravel augmentation projects is provided in Table 7 (Kondolf 2004) (see also Table A4 in Appendix A for gravel amounts used in newer projects). The average cost computed from Table 7 is about \$20/yd^3 (\$33 per ton) for placed gravel and within the range of \$15 - \$30/yd^3 suggested earlier by Kondolf and Matthews (1993) (method of placement not indicated). The costs may increase to \$50-100 per ton of gravel placed using off-stream methods (Kimball 2003; Section 2.2.2.1) and be as high as \$200/yd^3 for smaller projects that use less gravel, or if difficult access or long transportation is required (Kondolf and Matthews 1993).

Table 7: Gravel use and costs in augmentation projects below Central Valley dams, 1968- 2000 (includes Trinity) (from Kondolf 2004).

River (Regulating Dam)	Years	Number of Projects	Volume (yd^3)	Total Cost (\$)
Hat Creek (Crystal Lake)	1968-71	1	na	na
Trinity (Lewiston Dam)	1972-2000	12	36,407	347,765
Middle Creek	1998	1	185	3,835
Clear Creek (Whiskeytown)	1996-2000	7	23,704	500,000
Sacramento (Keswick)	1978-1999	13	268,396	3,905,000
Battle Creek	1993	1	513	Na
Payne's Creek	1986-1987	2	1,481	Na
Mill Ck (Clough Dam)	1988-1991	2	1,396	64,561
Feather (Oroville Res.)	1982-1987	2	5,045	Na
Hamilton Branch (Almanor)	2000	1	30	Na
Granite Creek	future	1	na	Na
Opapee Creek	future	1	na	Na
American (Nimbus)	1991-1999	2	5,445	530,000
Dry Creek	1999	1	up to 200	12,250
Mokelumne (Camanche)	1990-1999	8	14,545	299,575
Stanislaus (Goodwin)	1994-1999	6	33,107	1,420,240
Tuolumne (La Grange)	1993-1999	2	17,750	440,975
Merced (Crocker-Hoffman)	1986-1999	8	4,760	620,773
Helms Creek (Courtwright)	1985	1	7	12,000
Total: 19 Rivers		**82**	**412,970**	
\$8,156,974				

* List does not include large ongoing gravel augmentation projects after 2000.
1 yd^3 equals approximately 1.67 tons.

Securing gravel sources of appropriate quantity and quality is an important step for the project outcome. Budgetary or practical constraints, such that gravel of the right size and from the right stream is not locally available, may curtail a project's gravel use. A decision needs to be made to either apply less gravel or limit the spatial extent of the augmentation project. Information on gravel availability and costs should be obtained early in a project to plan the design accordingly.

5.2.2 Gravel sources and acquisition

Commercially purchased gravel from instream mining

Besides its high price, commercially purchased gravel brings with it the problem that it may be mined directly from the streambed or from annexed near-stream gravel pits. Thus, the purchased gravel contributes to the problem that gravel augmentation is supposed to ameliorate! Buying instream mined gravel to supplement a stream's gravel needs seems to be more than a waste of money.

Government owned gravel quarries

The problem of high gravel prices and the detrimental effect of instream mined gravel can sometimes be solved by government-owned quarries. In this case, a government agency (that typically financed the project in the first place) buys gravel deposits (such as dredger tailings) which will then be used for gravel augmentation purposes only (Turlock Irrigation District 2001; McBain and Trush 2003b).

Floodplain

Commercial gravel mining often targets the active floodplain which is dry during most flows but inundated during moderate floods such as the 5-year recurrence interval flood. This has detrimental effects not only for the geomorphological channel functioning due to the altered the cross-sectional shape, but also for spawning habitat because scraping off the armor layer exposes fine subsurface sediment that is entrained at moderate highflows (Kondolf and Matthews 1993; Trinity Associates 2000). To avoid detrimental effects on channel morphology and spawning habitat, gravel mining areas must by unreachable by the stream.

Mining tailings

Mining tailings, particularly dredger tailings piled next to the stream, may not only comprise huge amounts of gravel, but their removal is also necessary to restore a functioning floodplain (Stillwater Sciences 2002; McBain and Trush 2003c). However, using dredger tailings as spawning gravel is not unproblematic. Gravel that originates from mining tailing may be contaminated. Mining tailings deposited during gold mining could contain mercury that may negatively affect the environment and human uses (Clear Creek 2003). Gravel from dredger tailings is also relatively coarse and contain very little fine gravel in the 0.25 to 0.5 inch (6.4 – 12.7 mm) fraction. If used for gravel augmentation, the lack of fine gravel makes these gravels difficult to move during redd construction and apparently, spawning fish avoid sites augmented with dredger tailings (Carl Mesick, pers. comm., Jan. 2004).

Terraces - potential transportation problem

Part of the pre-dam floodplain may have become a terrace because post-dam flows are too small to inundate it. Gravel deposits no longer reached by the stream could serve as gravel sources for gravel augmentation projects. Pleistocene terraces are a potentially huge source for gravel but they may not be close to the present day stream or gravel augmentation site. Transportation by a slurry pipeline may be feasible due to the elevation difference between the terrace and the present-day stream (pers. comm. Peter

Wampler, March 2003, Oregon Sate University). However, transportation costs accrue if gravel needs to be transported over long distances. Noise and exhaust pollution may arise if the route goes through towns and hazard if the road goes through difficult or mountainous terrain.

Stream re-building

In the course of stream restoration, large amounts of gravel may become available if a new channel is cut through old river deposits. Similarly, building canals or other large stream construction works may provide excess gravel (Spawning Gravel 2003). These may be great gravel sources if the construction and augmentation sites are close to each other.

Gravel conveyance

Another option for gravel supply is gravel conveyance. Gravel supplied to upstream reaches will eventually erode and travel downstream and benefit gravel-starved reaches during its downstream travel. However, depending on the distance from an upstream augmentation site, the arrival of gravel may take years and decades[23]. The concept of downstream beneficiaries also requires unimpeded downstream gravel conveyance. Gravel sinks such as instream and annexed gravel pits and isolated large pools need to be filled and/or securely separated from the stream channel. However, gravel supply must not exceed the stream competence because pools in pool-riffle sequences are not to be filled.

Re-excavating and re-using gravel

Gravel conveyance comes to a natural halt at the gravel-sand transition zone where the stream competence is too low for further downstream transport of spawning-sized gravel. This is downstream of where salmon typically spawn. Large-scale aggradation in this reach due to upstream supply could be avoided by periodically removing the gravel from the channel. Subsequent upstream transportation by truck for another beneficial journey downstream may be feasible if upstream gravel costs are high.

Gravel from a different stream

Importing gravel from a neighboring stream is not recommended, even if it was logistically easier than obtaining gravel from the stream to be augmented. Salmon returning from the sea for spawning do not readily accept spawning gravel that was supplied from a different stream to their home stream. Carl Mesick Consultants (2002 a, b, c) observed a 41% higher redd density on spawning gravels mined from the floodplain of the parent stream compared to spawning gravel imported from a neighboring stream. Similar acceptance problems may arise for gravel from a (Pleistocene) terrace that may have a different petrologic composition than the current gravel in the stream. Salmon may also not accept gravel from dredger tailings if these have been contaminated with

---

[23] *Bunte and MacDonald (1999) estimated a mean annual travel distance for gravel in the order of 100 m for gravel-bed streams and of about 1000 m for sand-bedded streams. For mobile beds with spawning gravel, the value may be somewhere in between.*

mercury or other chemicals used in the gold washing process. Given enough time, however, gravel might "season" and adopt the right smell for salmon to accept it as spawning gravel over the course of several years (Carl Mesick Consultants 2002b).

Extracting gravel from the upstream delta

Large amounts of gravel may have accumulated in the delta of the upstream dam. These delta deposits decrease the useable reservoir capacity, particularly in small reservoirs. Two benefits could be obtained if part of this material was used for downstream gravel augmentation. However, gravel may comprise only 10 to 20% of the deposit and will have to be separated from the fines. Preparation and transportation costs will incur.

5.2.3 Preparation and placement of spawning gravel

Gravel used for augmenting spawning habitat usually has to be prepared to have appropriate biological and geomorphological properties (Section 4.3.6.1). It must be:

- well-rounded; angular gravel is unsuitable for spawning (Carl Mesick Consultant 1999, Wheaton and Pasternack 2002), because those particles pack tightly with little interstitial space,
- of the right size distribution for spawning fish. That means:
  - D_{50} particle size should be between 1 and 10 % of the fish length (Kondolf and Wolman 1993)), the D_{max} size should not exceed 5 in (127 mm) (Carl Mesick Consultants 2001);
  - contain fine to medium gravel (particles in the 0.25 - 0.5 inch (6.4 to 12.7 mm) size range) to increase the mobility of large particles and make the gravel better moveable by spawning fish (Carl Mesick Consultants 2002a and b);
  - without fines (very fine gravel smaller than approximately 6.3 mm, sand, silt and clay) that reduce intragravel flow, the dissolved oxygen contents and its uptake by eggs, stunt alevin growth and hinder fry emergence (Kondolf and Wolman 1993; Carl Mesick Consultants 1999),
- of the right size distribution such that part of the gravel becomes mobile at bankfull flows (McBain and Trush 2003 a and b; Stillwater Sciences 2002). However, a coarser gravel portion that remains stable at bankfull flow and becomes moveable only at the highest flood events is also needed to provide structure to alluvial features which in turn provide habitat for other salmon life stages as well as other aquatic biota.
- uncontaminated by mercury left over from the gold mining process, and
- preferably from the same stream as the stream in which the gravel augmentation is to occur, although imported gravel appears to be better accepted after a few years (Carl Mesick Consultants 1999; 2002 b). It was unclear, however, whether the delayed acceptance was due to the gravel adopting the "right" smell for the fish or whether an intrusion of fine sediment made the gravel more mobile by spawning fish and thus more attractive to spawners (Carl Mesick Consultants 1999; 2002 b).

Preparation of gravel to be suitable for spawning may include washing off fines, sieving, mixing, and particularly making sure that the augmented gravel does not contain toxins. Gravel with a size distribution that closely matches the needs of spawning gravel is cheaper to prepare. A staging area large enough to perform these tasks is needed.

Different methods can be used to mechanically place and distribute gravel in the stream. Heavy construction equipment is typically used, but it damages benthic invertebrates and requires accessibility into the stream. If tread impact is to be avoided, and/or the streambed is inaccessible to vehicles, various kinds of conveyor belts, slurries, high pressure pipes, helicopters, and cables lines are available (Section 2.2.2.1). Passive gravel augmentation might be a cheaper, but less predictable alternative. Various methods of passive gravel placement are described in Section 2.2.6.1.

6. Monitoring and evaluating project effects

Monitoring in gravel augmentation studies means repeatedly measuring and recording geomorphological and biological parameters over time to show their temporal development. Monitoring is an important part of adaptive management. It provides the basis for analyzing and evaluating the outcomes of a current project, which in turn provides a chance for learning from experience and for making adjustments if necessary.

Generally, the longer the monitoring period and the more dense the data, the better the time line, and the more can be learned from its analysis. To achieve a long time line, monitoring parameters need to be selected early in a project and measured from then on. If starting at the pre-project stage and continuing for many years after the design has been implemented, project monitoring may extend over a decade or more and will likely be carried out by a number of different people. To ensure that the data series accurately reflects stream responses and not operator variability or measurement error, robust measurement techniques are required, along with careful documentation of measurement protocols, and personnel training.

Monitoring does not necessarily entail a tremendous amount of extra work because all measurements taken throughout the project can become part of the monitoring record. However, to integrate data collected over a period of many years into a project record, they need to be stored retrievably. Measurements taken by entities outside the project (e.g., stream gauging, fish and fish habitat surveys, vegetation surveys, and water quality sampling), need not be repeated by the project. However, these data need to flow into the project record on a regular basis. Sharing data reduces everyone's monitoring effort, particularly, if all parties involved in a project area communicate their measurement and monitoring needs and coordinate their efforts.

6.1 Monitoring purposes and timing

The questions arising before, immediately after, and within months after the active project phase is completed may be different from those to be answered in the long-term. Monitoring therefore needs to suit different purposes and cover different time periods within a project (Stillwater Sciences 2002) (Table 8). Measurements do not necessarily need to be taken for each monitoring purpose individually, but may be used for multiple purposes.

6.1.1 Pre-project assessments

Detailed knowledge of pre-project channel conditions is necessary to determine the project design and to guide the post-project evaluation (Kondolf and Micheli 1995). Pre-project stream processes due to effects unrelated to the current gravel augmentation project (such as fires, watershed management, continued channel response to the dam,

Table 8: Purpose and timing of project monitoring

Monitoring purpose	Time periods within the project

1. Pre-project assessments for problem statement and goal setting	Before or at the very beginning of a project
2. Baseline data generation	Throughout the lifetime of a project
3. Implementation compliance	Immediately after design implementation
4. Effectiveness evaluation or post-project appraisal	Over several highflow events after design implementation and long-term, up to a few decades
5. Validation of conceptual and mathematical models	Any time post-project

and upstream or downstream elevating or lowering of the channel base level e.g., due to instream mining) cause channel change over time. The current project occurs while the channel is responding to these processes, and their ongoing effects also influence the outcome of the gravel augmentation project. To determine pre-project trends in channel change, monitoring should commence one or several years before the start of actual project measurements (inventory monitoring). Some of the parameters for which the pre-project status may be assessed in gravel augmentation projects are listed below (see Section 4.2.1 for more detailed discussion).

- General geomorphic stream conditions (maps, aerial photography),
- Detailed geomorphic stream conditions (visual assessment, photographic, and topographic surveys),
- Channel geometry (topographic surveys),
- Bedmaterial sizes (pebble counts, subsurface bulk samples),
- Pre-dam and post-dam flows (hydrograph analyses),
- Pre- and post-dam mean annual gravel loads (bedload transport analyses),
- Reduction in spawning activity or success over time (fish counts, redd counts, historic records),
- Any other information concerning the stream of interest and useful for the project.

Data acquired in earlier and unrelated projects (e.g., M.A. thesis, stream study on different subject but similar locality; newspaper accounts on flooding events and their effects) may be used to extend the monitoring record into the past.

6.1.2 Baseline monitoring

Some key parameters are measured as baseline monitoring throughout a gravel augmentation project and may include:

- Stage and discharge records,
- Water quality and temperature (mainstem and major tributaries),
- Bedmaterial particle-size distribution,

- Gravel mobility,
- Geomorphic features (e.g., bank erosion, floodplain width),
- Spatial and temporal dynamics of fish presence,
- Fish species composition,
- Benthic macroinvertebrate surveys, and
- Composition and development of riparian vegetation.

Some of these data are collected as part of routine measurements by government agencies or other entities involved in local stream studies. These measurements need not be repeated, but their results must be integrated into the project record.

6.1.3 Implementation or compliance monitoring

Implementation monitoring assesses how closely the gravel addition has followed the design and may comprise topographical surveys, surface and subsurface bedmaterial measurements and geomorphological surveys that are done right after the design has been implemented. Plan and the "as-built" stream shape are likely to deviate due to implementation errors or deliberate changes. The record of the "as-built" condition rather than the design plan serves as the basis for an evaluation of post-project channel change.

6.1.4 Effectiveness monitoring

Effectiveness monitoring is used to assess whether the implemented design functions as planned. Questions to be evaluated are whether bankfull flow fills the channel to the bankfull stage, whether the augmented gravel has the necessary attributes for spawning, and whether it is mobile at bankfull flow (Section 6.1.4.3). Data should be analyzed and evaluated as soon as they become available in order to make necessary adjustments immediately within the active project phase. This is particularly important if the project commenced with a small-scale pilot project. The cycle of *Project Outcome* → *Monitoring* → *Analysis and Evaluation* → *Adjustment* may need to go through several iterations (Fig. 6.1.4), similar to the cycle of *Problem* → *Goals* → *Conceptual Models* at the beginning of a project (Fig. 4.2.3).

6.1.4.1 Frequency, timing, and temporal extent

The frequency of effectiveness or post-project monitoring depends on how fast monitored parameters are expected to change and on the frequency with which events happen that provoke a geomorphological or biological response. Weekly monitoring may be needed to document the immediate effect of introduced gravel on stream morphology at the augmentation site and slightly downstream. Monthly or annual monitoring may be sufficient after conditions have become more stabilized. Flood events that had the potential to move gravel should definitely prompt a post-project monitoring survey.

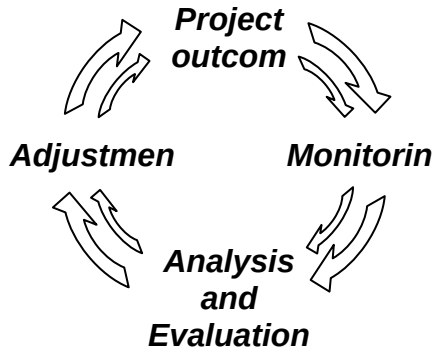


Fig. 6.1.4: Iterations through the circle of project outcomes, monitoring, analysis and evaluation, and adjustment.

6.1.4.2 Long-term monitoring

Long-term monitoring is particularly important to evaluate multi-reach and river-segment-wide gravel augmentation projects. Their effects on a post-project stream channel are likely large and long-lasting and less certain than the effects of smaller scale projects. Ideally, post-project monitoring should extend over the time period through which the stream may respond to the augmented gravel. Currently, it is believed that post-project monitoring should extend (with decreasing intensity) over 10-20 years. However, the time span over which stream morphology and fish might respond to changes induced by gravel augmentation is not definitely known (Kondolf 1995a).

Long-term post-project monitoring is faced with several problems. Adequate funding is one. Although often required by the funding agency, the portion of funding allocated to post-project monitoring may be insufficiently small due to the funding structure for environmental projects. Long-term observations are often considered as “science” and thus fall outside the funding scope for stream restoration projects. This is unfortunate, because not affording the relatively small expense of continued monitoring forgoes learning and is a great loss for science, the environment, and society. Another problem is the publication of project results. If learning is to benefit more people than the project management group, results must be disseminated into the science community through web-published project reports and journal articles. Publishing in peer reviewed journals is, however, a time-consuming effort that the pressure to finish other projects should not prevent. Finally, consistency can be a problem as well in long-term monitoring. Twenty years from now, the trained project personnel may no longer be available for monitoring duties and more pressing tasks than monitoring an old project may have arisen for the consulting companies or agencies who first conducted the project.

6.1.4.3 Parameters to be monitored

The exact set of parameters to be monitored in a gravel augmentation project depends on the project scale and goals. Long-term geomorphological functioning with floodplain flooding, gravel entrainment and the possibility for lateral channel migration is not necessarily part of a local-scale gravel augmentation project. Fulfillment of detailed topographical designs is not the goal of a river segment-wide gravel management plan.

Monitoring needs are most extensive in projects that are faced with the largest uncertainties regarding the project outcome. Not all parameters described below may be needed or feasible in all projects.

Direct influence from gravel augmentation: stream morphology, habitat conditions and spawning gravel quality

Monitoring for evaluation of project success should focus on parameters that gravel augmentation can directly influence, such as stream morphology, habitat conditions and gravel quality. Gravel augmentation also directly affects the conditions of spawning gravel. Thus, surface and bulk bedmaterial particle-size distribution, the temporal or seasonal change in the percent fines, intragravel flows, and the dissolved oxygen content should be monitored.

Monitoring the development of habitat conditions (McBain and Trush 2003c) (Kondolf and Micheli 1995) should be integrated into monitoring of fluvial geomorphology features because these two parameters are closely related in their development. Note, that although all of these influences are considered direct, the stream response to gravel augmentation may be influenced by the ongoing stream response to factors unrelated to gravel augmentation (Section 6.1.1).

Geomorphological and fish habitat parameters

Monitoring results should help to answer specific questions regarding geomorphological and habitat responses to gravel augmentation. These are sorted by the parameter to be measured and the type of measurement (Table 9a). Note the similarity of this list with Table 5 (Section 4.3) that lists parameters for which information is required when designing a gravel augmentation project. Table 9a may be expanded as needed.

Spawning gravel conditions and biological parameters

For monitoring the salmon spawning success, a variety of intragravel conditions and biological parameters are measured (Table 9b) (Carl Mesick Consultants 2001, 2002 a, b, c; CDWR 2003). For comparison of field results over space and time, monitoring reaches need to be spatially well defined. As the details of how gravel augmentations improves spawning habitat are not fully understood, results of biological monitoring need to be analyzed on the background of quality and quantity of the spawning gravel with its intragavel conditions as well as other habitat features.

Parameters that influence egg and alevin development and allow fry emergence are usually known, however, little is known about how the interactions of these parameters affect eggs, alevins and fry. Knowledge about these interwoven processes would not only permit to predict the conditions of eggs, alevins and fry (which are very difficult to measure) from much easier measurable intragravel conditions (Carl Mesick Consultants 2001) but also aid in formulating models on salmon biology.

Table 9a: Geomorphological and flow parameters that may be monitored for post-project evaluation of geomorphological and stream habitat conditions [24]

Monitored parameter	Evaluation of question:
Topographic survey	
Cross-sections	- Does bankfull flow fill the channel to its bankfull stage? - Does floodplain inundation start at bankfull flow? - Did the bed locally aggrade or degrade?
Longitudinal profiles	- Is the longitudinal profile as planned? - Does sediment become stored in a previously sediment starved reach? - Does habitat creation at one location curtail other habitat nearby?
Surface bedmaterial size	
Pebble count D_{84}, and D_{50} size	- Does the augmented spawning gravel have an appropriate particle-size distribution?
Bedload transport processes:	
Tracer experiments	- Is spawning gravel mobile near bankfull flow?
Scour cores	- Is the depth of scour at bankfull flows and above adequate?
Bedload transport measurements	- Did models or calculations accurately predict post-restoration bedload transport rates?
Geomorphological and habitat survey:	
Field mapping	- Did the number and size of riffles and bars increase? - Did undesirable stream features develop such as bank instability or in-filling of pool habitat? - Did the spawning area increase and is it as large as planned? - Did other habitat (e.g., shelter, feeding) increase (discharge dependent)?
(Combined with topographical and long-term tracer study)	- How far has the gravel supplied in the augmentation project traveled? Did it remain in or leave the reach at which it was placed to create spawning habitat? Did it benefit potential spawning areas downstream?
Flow hydraulics:	
At habitat locations	- Are flow conditions at spawning areas suitable for spawning over the range of spawning flows? - Do other potential habitat areas have flow conditions suitable to fulfill their functions?
In cross-sections	- Are flow conditions as predicted from hydraulic models?
Spatial and temporal variability	
Mapping measurement locations, gravel augmentation sites and habitat and preparing time series	- Is there spatial and/or temporal variability in any of these parameters? - Which processes caused the variability?

[24] *The reader should consult the geomorphology literature for details on how to conduct these measurements.*

Table 9b: Parameters that may be monitored for post-project evaluation of spawning gravel conditions[25]

Monitored parameter	Evaluation of question:
Spawning gravel conditions:	
Subsurface percent fines	- Did fines intrude into interstitial spaces or were they flushed out?
Intragravel and surface water upwelling temperature and apparent intragravel flow velocity	- Did the intra-gravel flow rate improve? How important was of oxygen-poor groundwater?
Intragravel water samples from piezometer to analyze water turbidity and dissolved oxygen concentration	- Did a high suspended sediment concentration leave a silty or clayey residue on the eggs that inhibits oxygen uptake? - Did the dissolved oxygen content improve? Was the intragravel dissolved oxygen content sufficiently high?
Biological parameters (Carl Mesick Consultants 2001, 2002a, b, c; CDWR 2003)	
Counts of salmon, spawners, and redds (see comment below)	- Is the spawning habitat accepted by spawners? - Did the number of spawners increase over time compared to unmanged locations? - Do certain designs attract more spawners and have more redds? - Has the targeted number of spawners been reached? - Did the number of redds increase over time compared to unmanged locations? - Is the density of redds per spawning area appropriate?
Size of spawners	- Do differently sizes females prefer spawning gravel of different particle size, habitat area, gravel source?
Redd inspection for fine sediment deposits, number of eggs and alevins, and their condition	- Does redd superimposition occur? - Did alevin entombment occur? - Did the number and percent of living eggs and alevins increase? - What is the percent eggs to fry emergence (accurate measurements are problematic);
Size and weight of alevins	- Did alevins develop properly?
Number and location of juveniles	- Did the number of juveniles increase? - Did juvenile habitat increase and is it occupied? - What is the juvenile survival rate?
Other biological parameters	
Analysis of benthic community	- Did the benthic community benefit from gravel augmentation?
Predator surveys	- Did the number of predators change?
Habitat availability	- Are other habitats for spawners and juveniles within the reach? (see habitat monitoring by McBain and Trush (2003c)).
Spatial and temporal variability	
Mapping redds, sites of gravel augmentation and habitat, as well as preparing time series	- Is there spatial and/or temporal variability in any of these parameters? - Which processes caused the variability?
Quantitative relationship between multiple parameters	- How does the interaction of multiple parameters affect eggs, alevins and fry?

[25] *The reader should consult the fisheries biology literature for details on how to conduct these measurements.*

Number of salmon, spawners and redds are unclear indicators of project success

Although repeated monitoring of salmon populations, their spatial and temporal variability, and the number of spawners and redds is important for analyzing population dynamics and making comparisons to other reaches, interpreting these monitoring results can be problematic. The increase in the absolute number of redds, spawners, and in the salmon population – the declared goal of gravel augmentation projects – is not necessarily a good indicator of project success because salmon numbers are influenced by various processes: (1) Besides from a local gravel augmentation project, the salmon population is also affected by off-site factors such as weather, quantity and quality of flows, general availability of food and shelter, survival of outmigrating smolts, effects that occur in lower stream reaches and in the ocean, as well as the number of returning spawners (Mesick 2001). (2) Spawners may favor or reject augmented spawning sites although they appear to be similar. For example, when spawning gravel was supplied to many locations over a 18-mile stream reach below a dam, and these locations provided apparently suitable spawning habitat, spawners notable favored sites close to the dam that were closest to the pre-dam spawning locations (Carl Mesick Consultants 2001, 2002 a, b, c). Thus when evaluating the attractiveness of different spawning gravels placed at different locations, (at different distance from the dam, with particle-size distribution, into different morphological units and from different gravel sources), it is important to differentiate between the influences of the individual factors - a goal, that necessitates setting up monitoring at unmanaged control sites. (3) There can also be a time factor in the attractiveness of spawning gravel to spawners. Spawners may not accept the augmented gravel immediately, but require the gravel to "season" for several years, particularly if gravel was imported from a different stream. (4) An increase in fish populations, and thus in their redds can also lag years behind the geomorphological response because aquatic and terrestrial food sources take time to develop after gravel has been supplied (Kondolf and Micheli 1995). (5) Finally, the absolute number of redds can be a misleading indicator of project success. If an overly high density of redds per area causes redds to be superimposed, later spawning females may destroy redds constructed by earlier spawners. This reduces spawning success and indicates a lack of spawning habitat (Carl Mesick Consultants 2001). The number of redds must therefore be evaluated with respect to a redd density per spawning area which can then be evaluated for an optimal density.

Relationship between created habitat and habitat use

As the absolute number of redds or juveniles may be strongly influenced by factors unrelated to spawning habitat improvement (Mesick 2001), it is important to find out if improved habitat attracts more redd building and produces more juveniles than unimproved habitat. Use of a hydraulic 2-D model (River 2D) has been proposed for this purpose (Gallager 1999; AFRP – Workplan 2000). Snorkel surveys identify stream locations where redds and juveniles have been sighted. Wading surveys measuring flow depth and velocity and the stream bottom topography at these locations provide the input for habitat suitability modeling using the 2-D hydraulic model. The hypothesis to be tested is whether habitat is more suitable at sites with redd and juvenile presence.

6.1.5 Validation monitoring

Validation monitoring is used to evaluate whether appropriate conceptual models have been used, and whether appropriate assumptions were made in the project computations and models. Unless specific data are needed to test a model outcome, data needed for validation monitoring can generally be obtained by baseline and effectiveness monitoring.

Modeling a channel design that fills the channel to the morphological bankfull stage at bankfull flow, that initiates annual or biennial bed mobility, and that transports a preset amount of gravel supply is not unproblematic (Section 4.4.3 and 4.4.4). Hydraulic models rely on estimated values for roughness, for example, which necessitates that modeled flow hydraulics be validated against measured ones. Validation against measured values is particularly important for evaluating modeled bed mobility and bedload transport rates, as well as the spatial patterns of gravel scour and deposition. Bedload transport is not a mature science. Thus, large uncertainties exist in modeled critical flow for particle entrainment, and not much is known about the effect of channel shape on bedload transport. Similarly, salmon population models or water temperature models that are used to gain insights into complex interactions, and upon which the project designs may have relied, need to be validated against monitored results.

6.2 Analysis, evaluation and adjustment

Project- and post-project evaluation is based on an analysis of the monitoring data (Section 6.1). Many of the analyses are similar to those performed when computing a design for the gravel augmentation project (Sections 4.2, 4.3 and 4.4). Analysis and evaluation of project or pre-project results leads to approval or adjustment of the planned or implemented gravel augmentation project.

6.2.1 Evaluation timing and purposes

Although analysis and evaluation occurs to some degree in all project stages, the most important phases for evaluation are post-planning, post-implementation, and post-project (Table10).

6.2.2 Post project evaluation: quality control and learning

A post-project evaluation is an important part of adaptive management. Apart from the learning experience throughout the project, project evaluation has two general purposes (1) It serves as a quality control tool and (2) is the major opportunity to learn from the project outcome (Kondolf 1995a; Kondolf and Micheli 1995; Downs and Kondolf 2002). As a quality control tool, evaluation allows project managers and funding agencies to determine whether the project was implemented as planned (compliance audit) and whether it has accomplished its planned goals (performance audit) (Kondolf and Micheli 1995; Downs and Kondolf 2002). As a learning tool, project evaluation allows project managers, technicians and scientists to find out *why* the short-term functioning of the

Table 10: Timing and purposes of project evaluation

Timing	Purpose	
	Quality control	Learning
Post-planning	Is the design acceptable?	General learning about the subject matter
Post-implementation	Was the design built as planned? (compliance audit)	
Post-project: 1) short term	Does the design function? (performance audit)	What caused the project design to function or not?
2) long-term	Have geomorphological and biological goals have been attained in the long run?	Was geomorphological and biological functionality attained ?

project conformed or deviated from original plans, and *why* geomorphological and biological functioning was attained or not. What is to be learned from the outcome of a gravel augmentation project are processes governing fluvial geomorphology, the interplay between stream geomorphology and stream habitat, salmon biology, as well as methodological aspects: were methods applied to measure and analyze processes in fluvial geomorphology and salmon spawning questions adequate or should they be improved?

Prerequisite for learning from a project outcome is setting clearly stated and quantifiable goals against which the outcome can be compared. If a precise quantification is not suitable, the goals should at least indicate the expected range of outcomes. The project must have collected data (i.e., done monitoring, Section 6.1) throughout the project, such that development over time can be seen in parameters such as channel shape, bed mobility, bedload transport rates, spawning gravel quality, spawning area and occupation, intragravel salmon development, etc. The exact parameters to be evaluated depend on the project specifics. Some of the questions to be answered by post-project evaluation are listed together with monitoring requirements in Sections 6.1.1 – 6.1.5.

6.2.2.1 Degree of documentation increases degree of learning

Opportunities for learning are highest for the best documented projects and the longest-term post-project appraisals. Good documentation and extensive monitoring are particularly needed when it comes to answering the difficult question of whether a gravel augmentation project achieved geomorphological and biological sustainability in the long run (Downs and Kondolf 2002).

6.2.2.2 Potential and danger of long-term project evaluations

As the stream may take years to fully respond to gravel augmentation, and important responses may show only after moderately large flood events, monitoring and post-

project evaluation should extend over long time periods as well. However, extending geomorphological and biological observations and analyses over a long time brings with it the potential danger of changing background influences unrelated to the gravel augmentation project. These may include changes in: (1) climate patterns with decade-long warm, cold, dry, or wet periods that affect not only the flow regime, but also bedload transport rates, stream morphology, water quality and temperature and thus the quality and quantity of the salmon habitat. Numerous long-term influences unrelated to local gravel augmentation which may include ocean harvest, anchovy landings, population dynamics, and predator populations and food supply may affect the number of salmon in different life stages within a stream reach. (3) Geomorphic influences not related to local gravel augmentation such as upstream or downstream base level changes may cause aggradation or degradation in the project area. (4) Tributary sediment supply may change, due to natural or anthropogenic watershed effects.

6.2.2.3 A gravel augmentation project is still an experiment

Gravel augmentation is still an experimental procedure in which the outcome is not necessarily well predictable. Large-scale gravel augmentation projects are faced with huge uncertainties (Table 11). The prediction uncertainty should be off-set by a clear and well documented project pursuit. Following a study outline suitable for experimentation

Table 11: Uncertainties regarding gravel augmentation identified for the Trinity River, CA (after Krause and McBain 2003), but likely occurring in other gravel augmentation projects as well.

- How should the volume appropriate for the short-term gravel additions be quantified? The methodology of estimating coarse sediment deficits at point bars, pool tails, riffles, etc., and adding volumes applies mainly to geomorphologically suitable locations.
- What is the long-term coarse sediment introduction rate and how does it change over time with increasing coarse sediment supply and decreasing bedmaterial particle-size distributions?
- Are bedload transport data collected at a particular stream location suitable to:
  - estimate coarse sediment introduction needs at other locations?
  - calibrate a transport equation for application to other reaches.
- Are results obtained from 1-D hydraulic and sediment routing models sufficiently accurate?
- What is the largest particle size to be introduced? How precisely does the size of augmented gravel have to be specified?
- Does a balanced coarse sediment budget need to be achieved on a yearly basis, or can the time period be averaged over several years?
- What are appropriate monitoring tools for coarse sediment augmentation?
- What are appropriate placement methods for coarse sediment augmentation?
- How will coarse sediment augmentation effect large pools (holes) formed by geologic control points?

and adopting an adaptive management strategy are imperative. If a project follows the steps of adaptive management and carefully documents them, even unexpected and undesirable project outcomes provide valuable insight into the stream processes. A project for which the outcome was unexpected and undesirable has not failed, if the ability to learn is provided through thorough project documentation. Understanding the processes that caused undesirable effects will prevent other projects from experiencing the same outcome. However, the chance to learn requires dissemination of results, such that the learning experience can be shared and profit others as well.

6.2.2.4 What ought to be known about gravel bedload movement before adding gravel to a stream

Ideally, all major processes of gravel bedload movement should be known and quantifiable before a major project of spawning gravel augmentation is undertaken. Some of the parameters (e.g., bed material properties, bed topography and flow hydraulics) are measurable within a few days of field work, provided the stream is wadeable when the measurements need to be done (Table 12). These are the ones most likely to be measured in a gravel augmentation project. Other parameters (e.g., critical flow for bedload entrainment, the largest transported particle sizes, bedload transport rates, bedload transport path, scour depths, and particle travel distance) require several weeks of intensive field measurements. In wadeable streams, and if the project is geomorphologically oriented, some of these measurements may be obtained. In non-wadeable streams, measurability of these parameters is quite limited and little, if any, of this information is included in gravel augmentation studies.

Only a few of the gravel transport processes are predictable from information on bedmaterial size, flow hydraulics, a modeled bedload transport rating curve and flow duration. However, the predictions are of great uncertainty, unless the results can be least partially based on measured results of bedload transport processes in a specified stream. Thus, the part of gravel augmentation that is based on computed gravel bedload transport processes and transport rates often has a thin foundation, particularly in streams unwadeable during high flows.

Table 12: Feasibility of measurements and computations needed in large-scale gravel-augmentation studies for answering critical question regarding bedload transport processes

Measurable or computable		
With little effort and/or acceptable accuracy	With moderate effort and/or low accuracy	With very large effort, and/or low accuracy
Critical flow for entrainment gravel bedload of different particle sizes		
	Measurable from tracer studies in streams wadeable during low flows	Virtually unmeasurable in non-wadeable flow
Frequency of gravel mobilization		
	Computable from tracer studies and long-term flow record	Virtually unmeasurable in non-wadeable flow
Gravel bedload transport rates at different flows		
	Measurable, in wadeable streams with proper equipment;	Computable using bedload equations Virtually unmeasurable in non-wadeable flow
Event or seasonal gravel bedload transport rates		
	Measurable, in wadeable streams with proper equipment; Pre- and post flood volumetric difference in channel feature supplied with gravel;	Virtually unmeasurable in non-wadeable flow
Mean annual bedload discharge		
Bedload rating curve applied to long-term flow record (**if** accurate measurements are available)	Sediment volume deposited in gravel sinks (e.g., deltas, sed. retention basins) divided by number of years	
Depth of bed scour at different flows		
	Measurable using scour cores	
Gravel travel path for coarse and fine gravel		
	Measurable, in wadeable streams with proper equipment;	Virtually unmeasurable in non-wadeable flow; Predictable from experience
Mean annual travel distance of individual gravel particles		
	Measurable using tracers in streams wadeable at low flow, long-term effort	Computable from tentative relationships with stream size and shape
Locations of gravel deposits and entrainment		
	Measurable using tracers in streams wadeable at low flow	
Movement of bedload waves through stream system		
	Measurable from topographic surveys, long-term effort	Computable from models
Predictability of effects due to non-equilibrium conditions		
		Positive and negative feed back may result in channel instability and unpredictable channel response.

7. Summary and Conclusion

Gravel augmentation has been used to improve spawning habitat for decades. It started to be pursued in a major way in California Central Valley Streams after the Central Valley Project Improvement Act was passed in 1992. The act requested that a sustainable salmon population at least double the size of its state in 1967-1991 was reached by 2002. As not much was known about gravel augmentation, a trial and error approach was often used and projects failed mainly because the applied gravel was scoured away. Besides, a lack of spawning habitat was not the only problem plaguing salmon populations in their riverine life stages. Insufficient habitat providing food, shelter, and rearing space, dam outlet hydrographs not matching salmon needs, and an abundance of predators contributed to dwindling salmon populations.

7.1 Different approaches to gravel augmentation projects

After academia publicly cautioned that failure to consider fluvial dynamics and principles of water and gravel streambed interaction causes poor success in gravel augmentation and stream restoration projects, geomorphologically and biologically oriented consulting companies and academia started to devise gravel augmentation programs that emphasized "working with the stream". To date, there are many different approaches to spawning habitat augmentation that vary widely in temporal and spatial scales. Major approaches to gravel augmentation for spawning habitat improvement are:

1) River segment-wide gravel augmentation and sediment management plan to restore geomorphological and biological functioning of the stream,
2) Detailed, multi-reach stream restoration,
3) Direct creation of spawning habitat by one-time gravel additions in stream areas with apparent low erosion potential,
4) Detailed hydraulic modeling to arrive at the optimum gravel augmentation solution for a reach (SHIRA), and
5) Passive gravel augmentation.

1) Geomorphological and biological functioning of stream segments

The foremost goal of a river segment-wide gravel augmentation and sediment management plan is restoration of the geomorphological functionality of the stream, based on the understanding that if the natural pool-riffle or alternate bar morphology is restored, fish habitat will develop automatically, fulfilling various functions at different stream locations. Measures to restore geomorphologic functionality include a variety of measures: shaping the channel (by adding or removing gravel) to ensure that the post-dam 1.5-year recurrence interval flow fills the channel to its morphological bankfull stage, providing bedmaterial that is partially mobilized at bankfull flow, and long-term gravel additions that match the post-restoration transport capacity. As these projects incorporate the concept of mobile gravel, unimpeded downstream gravel conveyance, and

overall stream and habitat restoration, the spatial project scale extends over stream segments several tens of miles long, while the temporal scale covers multi-year and decade long periods. This approach is meant as a long-term solution that, once a geomorphologically and biologically functioning stream is established, requires little maintenance apart from episodic or regular passive gravel additions for replenishing the insufficient upstream gravel supply. This approach requires expertise in fluvial geomorphology and bedload transport processes, as well as in conducting field measurements and habitat assessments. The project outcome has uncertainty because no such project has been implemented and monitored yet. It provides a great opportunity to expand our knowledge on morphological processes in gravel bed-rivers and how these processes in turn create salmon habitat.

2) Multi-reach stream restoration

This approach focuses on restoring severely disturbed and dysfunctional stream sections (e.g., instream or annexed gravel pits) to attain geomorphological functionality in the post-restoration channel section, to regain stream-wide gravel conveyance, and to make the restored section fit to its upstream and downstream borders. New channels with computed morphological shapes, a new downstream course, and lined with spawning-sized gravel have to be designed. Besides spawning habitat, the designed channel should also provide other salmon habitat.

The design relies heavily on 1-D hydraulic and sediment transport modeling. Design outcomes are faced with relatively high uncertainty because projects often have limited knowledge on actual pre- and post-restoration bedload transport rates. This approach requires expertise in stream restoration and hydraulic/sediment transport modeling. It provides an opportunity to learn how to create geomorphologically and biologically functioning channels “from scratch”.

3) Direct solution of spawning problem at suitable locations

A lack in quality and quantity of spawning habitat is often seen as the major problem inhibiting salmon population growth. Restoring long-term geomorphologic functionality requires years and decades and will not relieve the immediate salmon spawning problem. As a measure to quickly alleviate the shortness of spawning habitat, gravel is added to relatively wide stream locations that will likely experience little scour, and that have habitat providing shelter and food nearby. The gravel is supplied mechanically, but placed remotely (without heavy construction equipment directly in the stream). The newly created spawning habitat is generally accepted by spawning salmon and provides habitat immediately or within a few years. However, spawning habitat created this way may be subject to destruction or deterioration if moderate or large floods scour the gravel or if the gravel is stable during smaller floods and not moved sufficiently to wash out potential infiltration of fines. The approach requires expertise in salmon biology and its monitoring techniques. Monitoring the development of intragravel conditions and salmon embryos at gravel augmented and unaugmented control sites permits insights into physical and biological processes and can help in model development.

4) Spatially detailed hydraulic modeling (S**pawning **H**abitat **I**ntegrated **R**estoration **A**pproach**)

A spatially and temporally relatively confined approach to gravel augmentation but with emphasis on local biological and geomorphological functioning as well as an increased lifespan of the spawning bed is the route of detailed local hydraulic modeling. The first step is to conceptually devise several streambed scenarios of spawning habitat for a selected site. The scenarios vary depending on whether the major focus is placed on creating large and high quality spawning habitat, geomorphological sustainability, beneficial intragravel conditions, availability of habitat for functions other than spawning, and an economical gravel use.

A 2-D hydraulic model calibrated to the site is then used to predict hydraulic conditions for each of the hundreds of grid points covering the reach. Based on modeled flow hydraulics, each design scenario is evaluated regarding 1) the amount of spawning habitat of different quality created within the reach, 2) whether critical flow for entrainment will be reached or exceeded at various flows, 3) the amount of habitat in pool exit slopes, 4) habitat variability, and 5) the amount of gravel needed to implement the design.

Model outputs from each scenario are evaluated with respect to how well they fulfill the design criteria and are ranked in order to determine the optimal spawning habitat design for the reach. This highly controlled and accuracy driven approach to gravel augmentation is based on very detailed field measurements (topographic surveys, flow hydraulics, bed material size, intragravel flow conditions and redd counts) and a deep understanding of salmon spawning habitat requirements. It requires expertise in 2-D modeling and constitutes a large modeling effort. It facilitates creation of optimal and long-lasting spawning habitat in a suitable reach.

5) Passive gravel augmentation

Indirect or passive gravel augmentation supplies spawning gravel to a logistically convenient stream location at which the gravel is likely to be entrained and transported downstream by relatively frequently occurring highflow events. Natural deposits of this gravel can provide spawning habitat. This method is the cheapest approach to gravel augmentation, because the amount of pre-project computation is typically small, and implementation is easy (dumping gravel from a truck without stockpiling, close to a gravel source, whenever gravel becomes available). To have a long-term beneficial effect, the stream must have gravel conveyance (i.e., be free of gravel sinks such as instream mining pits), such that the passively supplied gravel can be transported downstream over time and provide spawning habitat along the way. Flows with a competence to entrain these gravels from the augmentation site and transport them further downstream must occur frequently enough to be geomorphologically effective.

Passive gravel augmentation is either used as the sole measure to gravel augmentation or as the second phase in river restoration and a river segment-wide gravel augmentation and coarse sediment management plan. In this function, a gravel volume equal to the estimated mean annual transport rate is supplied at episodic or regular intervals to maintain the geomorphic and biological functioning after local gravel additions and

mechanical bed shaping provided the foundations for functionality. Unimpeded downstream gravel conveyance is particularly important for the effectiveness of long-term gravel additions.

Strength and weaknesses of each of these approaches are summarized in Table 13. Interdisciplinary approaches to gravel augmentation may be most helpful to achieve the best outcome for gravel augmentation projects based on the largest input of combined knowledge, and provide the largest learning potential for all disciplines involved.

Table 13: Strength and weaknesses of the major five approaches to gravel augmentation

Approach	Strength	Weakness
Geomorphological and biological functioning of stream segments Requires high expertise in fluvial geomorphology;	Achieves long-term and large-scale geomorphological and biological functionality ("fixes long river segments"); May include a mitigated flow regime more in tune with geomorphological and biological needs;	May take a long time to plan and implement; Is based on poor knowledge regarding actual gravel transport processes, thus unsure outcome; Requires large volumes of gravel; Requires episodic gravel augmentation for maintenance; Requires complete gravel conveyance;
Detailed multi-reach stream restoration Requires expertise in hydraulic and sediment transport modeling;	Restores heavily disturbed and dysfunctional reaches to long-term geomorphological and biological functioning ("fixes a river reach"); Re-establishes gravel conveyance.	Relies heavily on 1-D hydraulic and bedload transport modeling that has uncertain outcomes without validation from actually measure transport rates;
Direct solution to spawning problem at suitable locations Requires expertise in fisheries biology;	Provides spawning habitat immediately;	Created spawning habitat may be scoured away in the next big flood event;
Spatially detailed hydraulic modeling (Spawning Habitat Integrated Restoration Approach) Requires high expertise in 2-D hydraulic modeling;	Can provide optimum habitat configuration within a reach (suitable flow hydraulics, habitat diversity, erosion resistance, and economical gravel use); Very controlled approach;	Most suitable for a steady state situation with known input parameters (right below a dam); Restricted to reach-scale;
Passive gravel augmentation	Cheapest and simplest approach, requiring little computational and logistical effort; Uncontrolled.	May take long time for gravel to reach destination, esp. if gravel conveyance is not established; Unsure outcome.

7.2 Adaptive management and project phases

Many factors in water-streambed interactions and gravel transport processes are still poorly understood. The outcome of gravel augmentation projects can therefore not be predicted with a desirable degree of certainty. In order to go forward with gravel augmentation projects, while still lacking complete scientific understanding, adaptive management is generally adopted as a project strategy. Under this strategy, a project is treated as a scientific experiment with potentially unknown outcome. The project is divided into three major phases: 1) pre-project analyses, 2) measuring, computing and modeling, and 3) monitoring, analysis, evaluation and adjustment.

1) Pre-project analyses

In the pre-project part of a gravel augmentation project, current conditions of flow, channel shape and bed material are analyzed and compared to pre-dam conditions to identify the processes hindering geomorphological and biological functioning. The best available geomorphological and biological science is used to formulate a conceptual model that explains how the stream would ideally function. For geomorphological and biological functionality, a channel shape must be attained in which:

- the 1.5-year recurrence interval flow fills the channel to its morphological bankfull stage,
- gravel is partially mobile every 1-2 years,
- the flow regime is seasonally variable, and
- the timing of high and low flows corresponds with the needs of the salmon population.

Goals are then set to state the changes necessary to attain functionality and the desired post-project conditions. The set of tasks *Problem statement* → *Conceptual model* → *Goals and objectives* may have to be cycled through several times during the pre-project phase, each time with a higher understanding due to the results from the previous round until a project plan can be prepared. This is also the stage at which a project proposal would be formulated and submitted to a funding agency.

2) Measuring and modeling

Based on the outcomes of the pre-project analyses, parameters to be measured, computed and modeled can be identified. Once a deficiency in quality and quantity of spawning habitat has been determined as the factor limiting salmon spawning success and population growth, a comprehensive set of field measurements is initiated to obtain the data used to compute the amounts, quality, location and timing of gravel additions. Parameters to be measured (particularly for a gravel augmentation and sediment management plan) include topographic surveys, bedmaterial composition, and bedload transport measurements (incipient motion, scour depth and transport rates). The importance of collecting reliable and sufficient field data which requires time, effort, and well-trained field personnel should not be understated. The field data also provide the basis for modeling of stream hydraulics and sediment transport, tools that are increasingly

being used in gravel augmentation projects. However, the use of sophisticated modeling tools alone cannot overcome the gaps that science has in the knowledge of gravel transport processes.

Based on the outcome of the computations and models, a design is devised for the gravel augmentation project. The cycle of *Measuring → Computing and/or Modeling → Design* may likewise go through several iterations. Acquiring the often large amount of gravel for implementing the design can be problematic and costly.

3) Monitoring and evaluation

Monitoring is the basis for project analysis, evaluation, and if necessary adjustment. The cycle of *Monitoring → Analysis → Evaluation → Adjustment* can occur at different project stages and may also go through several iterations. Project monitoring extends with varying intensity over the entire project period. It sets in at the pre-project phase, continues as baseline monitoring throughout the active project phase, occurs immediately after the design is implemented, serves for model validation, and lasts for years or decades after the project implementation as post-project monitoring. Parameters to be monitored are generally similar to those measured for computing and modeling the project design, but may vary between different approaches to gravel augmentation.

The main aim of project evaluation is to learn from the project outcome, particularly about processes governing the water-sediment interaction, about salmon biology, methods applied, and why the project outcome was as it is. Even unexpected or undesirable project outcomes are not complete failures if something can be learned such that the mistake can either be corrected in the current project or will not be repeated in future projects. To provide the learning opportunity, all projects measurement data, considerations, concepts and modeling assumptions, as well as computation and modeling results must be well documented.

Parameters selected for project evaluation are those directly affected by gravel augmentation, such as stream morphology, bedmaterial sizes and properties, mobility of some portions of the gravel at bankfull flow, and fish habitat quality and quantity at different flows, intragravel conditions, and the development of embryos. The population of salmon, spawners and redds – the expected beneficiaries of gravel augmentation – are affected not only by gravel augmentation but also by a variety of unrelated factors (water quality and quantify, processes in the lower stream reaches and the ocean, predator populations). Their numbers are therefore not necessarily well suited for evaluating the gravel augmentation success.

7.3 Final caveats

Poor understanding of gravel transport processes → uncertain computation and modeling results

Measurements of bedload transport, particularly gravel transport are difficult and time consuming in wadeable flows, and very problematic in unwadeable conditions. The poor measurability has caused a generally slow advancement of science in this area and

continues to cause problems in many gravel augmentation projects. Prediction of gravel transport rates from bedload equations without validation against measured rates is rarely a viable solution, because different equations provide estimates that are orders of magnitude apart. However, the computation of parameters such as mean annual loads and gravel augmentation volumes depends on knowledge of bedload transport processes and rates. Without this information, gravel augmentation amounts needs to be estimated using judgment and field experience.

Modeling of gravel transport processes may be helpful to sort out interactions between several involved parameters, but model outcomes have high uncertainties unless they can be validated by measured results. If the relationship between bedload transport rates and flow is unknown, no degree of bedload transport modeling will produce a result more certain than the uncertainty in transport rates.

Geomorphological and biological understanding and experience is necessary in any case

Because gravel augmentation can exert a large influence onto the stream system, engaging in this undertaking requires a deep understanding of the geomorphological and biological processes involved as well as experience in gravel augmentation projects (to the extent that these processes are known). The larger the spatial and temporal scale of the project, the wider the range of factors that influence the project outcome and are influenced by it. This implies that large-scale projects have a particularly pressing need for an interdisciplinary approach including fluvial geomorphology, fisheries biology, watershed sciences, and riparian ecology.

Acknowledgement

I would like to thank my husband Kurt Swingle for encouragement and proofreading as well as Scott McBain (McBain and Trush) for suggestions to Section 2.4. Bob Deibel and John Potyondy (USDA Forest Service) are thanked for advice and support and for patiently awaiting the completion of the manuscript. Darren Mierau (McBain and Trush), Carl Mesick (Carl Mesick Consultants), and Zooey Diggory (Stillwater Sciences) kindly provided project reports (or access to them) upon request. This study was funded by the USDA Forest Service, Stream Systems Technology Center, Rocky Mountain Research Station, Fort Collins, CO.

8. References

AFRP - Title 34-CVPIA. Anadromous Fish Restoration Program, Title 34 - Central Valley Improvement Act. http://www.delta.dfg.ca.gov/afrp/title34.asp

AFRP 1998. Anadromous Fish Restoration Program. Restore the Stanislaus River channel at the Wilms site. http://www.delta.dfg.ca.gov/afrp/template_frame.asp?code=98%20L%20A-4%20

AFRP 1999. Anadromous Fish Restoration Program. Update and Validate the Spawning Riffle Atlas for the San Joaquin Tributaries. http://www.delta.dfg.ca.gov/afrp/project.asp?code=1999-20

AFRP 2000. Anadromous Fish Restoration Program. Evaluate channel restoration and aggregate source potential for the Two-Mile Bar on the Stanislaus River. http://www.delta.dfg.ca.gov/afrp/project.asp?code=2000-9

AFRP 2002. Anadromous Fish Restoration Program (AFRP), CVPIA §3406 (b)(1), Work Plan for Fiscal Year 2002. http://www.mp.usbr.gov/cvpia/awp/2002/

AFRP 2003. Anadromous Fish Restoration Program (AFRP), CVPIA §3406 (b)(1), Work Plan for Fiscal Year 2003. http://www.mp.usbr.gov/cvpia/awp/2003/

AFRP 2004. Anadromous Fish Restoration Program (AFRP), CVPIA §3406 (b)(1), Work Plan for Fiscal Year 2004. http://www.mp.usbr.gov/cvpia/awp/2004/

AFRP – Annual Workplan 2000. Initial scope of work to evaluate use of a two-dimensional hydraulic and habitat simulation model (River 2D) to assess benefits of channel restoration [Merced River]. http://www.delta.dfg.ca.gov.afrp/documents.asp#MERCR

Annual Report 2002. Calfed Bay - Delta Program, Annual Report 2002. http://calwater.ca.gov/AboutCalfed/AnnualReport2002.shtml

Bagnold, R.A., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society of London,* Series A, 372: 453-473.

Barnes, H.H., 1967. Roughness characteristics of natural channels. U.S. Geological Survey Water Supply Paper 1849, 213 pp.

Buffington, J.M and D.R. Montgomery, 1999a. A procedure for classifying and mapping textural facies in gravel-bed rivers. *Water Resources Research* 35 (6): 1903-1914.

Bunte, K. and L.H. MacDonald, 1999. *Scale Considerations and the Detectability of Sedimentary Cumulative Watershed Effects*. National Council of the Paper Industry for Air and Stream Improvement, North Carolina, Technical Bulletin No. 776, 327 pp.

Bunte, K. and K. Swingle, 2003. Field testing the sampling efficiency of bedload traps at East St. Louis Creek, May - July 2003: Comparison of annual gravel load between bedload traps and debris basin. Report submitted to the Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 86 pp.

Bunte, K. and S.R. Abt, 2001a. Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analysis in Sediment Transport, Hydraulics, and Streambed Monitoring. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, *General Technical Report* RMRS-GTR-74, 428 pp. (Free download from http://www.fs.fed.us/rm/pubs/rmrs/gtr_74.html).

Bunte, K. and S.R. Abt, 2001b. Sampling frame for improving pebble count accuracy in coarse gravel-bed streams. *Journal of the American Water Resources Association* 37 (4): 1001-1014.

Bunte, K. and S.R. Abt, 2003. Sampler size and sampling time affect measured bedload transport rates and particle sizes measured with bedload traps in gravel-bed streams. In: *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances*. J. Bogen, T. Fergus and D.E. Walling (eds.), IAHS-Publication No. 283, p. 126-133.

Bunte, K., S.R. Abt and K. Swingle, 2004b. Spatial variability of coarse bedload transport and its temporal changes over highflow seasons. *Proceedings of the twenty-fourth annual AGU Hydrology Days,* [electronic resource] March 10-12, 2004, Colorado State University, Fort Collins, CO. Jorge A. Ramírez (ed.). Fort Collins, CO, J.A. Ramirez, c2004.

Bunte, K., S.R. Abt, J.P. Potyondy, and S.E. Ryan, 2004a. Measurement of coarse gravel and cobble transport using a portable bedload trap. *Journal of Hydraulic Engineering,* 130(9): 879-893.

CDWR 2001. The Merced River Salmon Habitat Enhancement Project, Robinson Reach (Phase III) Engineering Report. California Department of Water Resources, San Joaquin District, River Management Section, 70 pp. http://wwwdpla.water.gov/sjd/envirorest/rms_site/publications.html

CDWR 2002a. The Merced River Salmon Habitat Enhancement Project, Robinson Reach (Phase III) Final Report. California Department of Water Resources, San Joaquin District, River Management Section. 39 pp http://wwwdpla.water.gov/sjd/envirorest/rms_site/publications.html

CDWR 2002b. Merced River – Hatchery project. California Department of Water Resources, San Joaquin District, River Management Section. http://www.sjd.water.ca.gov/rivermanagement/Completed/projects/merchatch/index.cfm

CDWR 2003. Evaluating the success of spawning habitat enhancement on the Merced River, Robinson Reach. Final proposal by California Department of Water Resources, San Joaquin District River, Management Section submitted to CalFed. http://www.delta.dfg.ca.gov/afrp/documents.asp#MERCR.

Childers, D., 1999. Field comparison of six-pressure-difference bedload samplers in high energy flow. U.S. Geological Survey, Water Resources Investigations Report 92-4068, Vancouver, WA, 59 pp.

Church, M., D.G. McLean and J.F. Walcott, 1987. River bed gravels: sampling and analysis. In: *Sediment Transport in Gravel-Bed Rivers*, C.R. Thorne, J.C. Bathurst and R.D. Hey (eds.), John Wiley and Sons, Chichester, p. 43-87.

Clear Creek 2002. Clear Creek Restoration Program, CVPIA §3406 (b)(12), Work Plan for Fiscal Year 2002. http://www.mp.usbr.gov/cvpia/awp/2002/

Clear Creek 2003. Clear Creek Restoration Program, CVPIA §3406 (b)(12), Work Plan for Fiscal Year 2003. http://www.mp.usbr.gov/cvpia/awp/2003/

Clear Creek 2004. Clear Creek Restoration Program, CVPIA §3406 (b)(12), Work Plan for Fiscal Year 2004. http://www.mp.usbr.gov/cvpia/awp/2004/

Carl Mesick Consultants 2001. Continued Studies for the Knights Ferry [Stanislaus River] Gravel Replenishment Project, Phase 2. Project Proposal # 39 submitted to CalFed. https://www.ecosystem.calfed.ca.gov/WRRC/CalFed/proposals/selection_panel_report_static *Identical with*: Carl Mesick Consultants 2001. Continued monitoring for the Knights Ferry Gravel Replenishment Project, Phase 2. http://www.delta.dfg.ca.gov/afrp/template_frame.asp?code=02%20L%20A-2%20

Carl Mesick Consultants 2002a. Initial post-project evaluation report, Knights Ferry Gravel Replenishment Project. Carl Mesick Consultants, El Dorado, CA, 41 pp plus appendices. http://www.delta.dfg.ca.gov/srfg/docs.asp.

Carl Mesick Consultants 2002b. Knights Ferry Gravel Replenishment Project. Final Report. Carl Mesick Consultants, El Dorado, CA, 13 pp. http://www.delta.dfg.ca.gov/srfg/docs.asp.

Carl Mesick Consultants 2002c. Second year post-project evaluation report, Fall 2000, Knights Ferry Gravel Replenishment Project. Carl Mesick Consultants, El Dorado, CA, 48 pp plus appendices. http://www.delta.dfg.ca.gov/srfg/docs.asp.

Cui, Y., 2004. Numerical modeling of gravel augmentation. PowerPoint Presentation given at the CalFed Science Program, California Bay Delta Authority Workshop on Rivers, Rocks, and Restoration, July 13-14, 2004, Sacramento, CA. http://science.calwater.ca.gov/pdf/workshops/presentation_071404_yantao_cui.pdf)

Cui, Y. G. Parker, T.E. Lisle, J. Gott, M.E. Hansler-Ball, J.E. Pizzuto, N.E. Allmendinger and J.M. Reed, 2003. Sediment pulses in mountain rivers: 1. Experiments. *Water Resources Research* 39(9):1239, doi:10.1029/2002WR001803, 2003.

Cui, Y. G. Parker, T.E. Lisle and J.E. Pizzuto, 2003. Sediment pulses in mountain rivers: 2. Comparison between experiments and numerical prediction. *Water Resources Research* 39(9):1240, doi:10.1029/2002WR001805, 2003.

Dalby, C., L. Dolan and M. Downey, 1999. Implementation of flushing flows to remove fine-grained sediments released from Ruby Dam, southwestern Montana. In: *Wildland Hydrology*. D.S. Olsen and J.P. Potyondy (eds.), American Water Resources Association, Herndon VA, TPS-99-3, p. 125-132.

Dietrich, W.B., 1987. Mechanics of flow and sediment transport in river bends. In: *River Channels. Environment and Process*. K.S. Richards (ed.), The Institute of British Geographer Special Publication Series, Basil Blackwell, Oxford, p. 199-227.

Dinehart, R.L., 1992. Evolution of coarse gravel bedforms: field measurements at flood stage. *Water Resources Research* 28(10): 2667-2689.

Duizendstra, A.D., 2001. Determination of the sediment transport in an armoured gravel-bed river. *Earth Surface Processes and Landforms* 26: 1381-1393.

Duizendstra, H.D., 2001. Measuring, observing and pattern recognition of sediment transport in an armoured river using a sampler with attached underwater camera. *Physics and Chemistry of the Earth, Part B* 26(1): 59-64.

Edwards, T.K. and Glysson, G.D., 1999. Field methods for measurement of fluvial sediment. *Techniques of Water-Resources Investigations of the U.S. Geological Survey*, Book 3, Applications of Hydraulics, Chapter C2. U.S. Geological Survey, Reston, Virginia, 89 pp.

Ferguson, R.I., 1986. River loads underestimated by rating curves. *Water Resources Research* 22(1): 74-76.

Ferguson, R.I., 1987. Accuracy and precision of methods for estimating river loads. *Earth Surface Processes and Landforms* 12: 95-104.

Fish Habitat Rehabilitation Procedures, 1997. P.A. Slaney and D. Zaldokas (eds.). Water Restoration Technical Circular No. 9. Watershed Restoration Program, Ministry of Environment, Lands and Parks, Vancouver, BC.

Gallagher, S.P., 1999. Use of two dimensional hydrodynamic modeling to evaluate channel rehabilitation in the Trinity River, California, USA. U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata, CA, 36 pp.

Gordon, N.D., T.A. McMahon and B.L. Finlayson, 1992. *Stream Hydrology*. *An Introduction for Ecologists*. John Wiley and Sons, Chichester, GB, 526 pp.

Harrelson, C.C., C.L. Rawlins and J.P. Potyondy, 1994. Stream channel reference sites: an illustrated guide to field technique. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-245.

Hirsch R.M., D.R. Helsel, T.A. Cohn and E.J. Gilroy et al. 1993. Statistical analysis of hydrological data. In: *Handbook of Hydrology*. D.R. Maidment, (ed.), McGraw-Hill, New York.

Hooke, J.M., 1997. Styles of channel change. In: *Applied Fluvial Geomorphology for River Engineering and Management*, C.R. Thorne, R.,D. Hey and M.D. Newson (eds.), John Wiley & Sons, Chichester, p. 237-268.

Jarrett, R.D., 1985. Determination of roughness coefficients for streams in Colorado. *U.S. Geological Survey, Water-Resources Investigations Report 85-4004*. State of Colorado Department of Natural Resources Conservation Board, Lakewood, Colorado, pp. 54.

Julien, P.Y. and D.J. Anthony, 2002. Bed load motion and grain sorting in a meandering stream. *Journal of Hydraulic Research* 40(2): 125-133.

Kimball, C., 2003. Alternative gravel placement methods. Report prepared at Mid-Pacific Region, Design and Construction Division, Sacramento, CA, USDI Bureau of Reclamation, 17 pp. http://www.delta.dfg.ca.gov/srfg (click documents)

Koch, R.W. and G.M. Smillie, 1986. Comment on "River loads underestimated by rating curves" by R.I. Ferguson. *Water Resources Research* 22: 2121-2122.

Kondolf, G.M., 1995a. Managing bedload sediment in regulated rivers: examples from California, U.S.A.. In: *Natural and Anthropogenic Influences in Fluvial Geomorphology*. J.E. Costa, A.J. Miller, K.W. Potter, and P.R. Wilcock, (eds.), Geophysical Monograph 89: 165-176.

Kondolf, G.M., 1995b. Five elements for effective evaluation of stream restoration. *Restoration Ecology* 3(2): 133-136.

Kondolf, G.M., 1997. Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management* 21(4): 533-551.

Kondolf, G.M., 2000a. Assessing salmon spawning gravel quality. Transactions of the *American Fisheries Society* 129: 262-281.

Kondolf, G.M., 2000b. Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. *Restoration Ecology* 8(1): 48-56.

Kondolf, G.M., 2004. Gravel augmentation on rivers: Geomorphic perspectives and lessons learned from some past projects. PowerPoint Presentation given at the Calfed Science Program, California Bay Delta Authority Workshop on Rivers, Rocks and Restoration held in Sacramento, CA on July 13/14, 2004. http://science.calwater.ca.gov/pdf/workshops/presentation_071404_Matt_Kondolf.pdf

Kondolf, G.M. and R.R. Curry, 1986. Channel erosion along the Carmal River, Monterey County, California. *Earth Surface Processes and Landforms* 11: 307-319.

Kondolf, G.M. and W.V.G. Matthews, 1993. Management of Coarse Sediment on Regulated Rivers. University of California, Water Resources Center, University of California Report No. 80, 123 pp.

Kondolf, G.M. and E.R. Micheli, 1995. Evaluating stream restoration projects. *Environmental Management* 19(1): 1-15.

Kondolf, G.M. and H. Piégay, 2003. *Tools in Fluvial Geomorphology*. John Wiley and Sons, Chichester, GB.

Kondolf, G.M. and P.R. Wilcock, 1996. The flushing flow problem: defining and evaluating objectives. *Water Resources Research* 32 (8): 2589-2599.

Kondolf, G.M. and M.G. Wolman, 1993. The sizes of salmonid spawning gravels. *Water Resources Research* 29 (7): 2275-2285.

Kondolf, G.M., A. Falzone and K.S. Schneider, 2001. Reconnaissance-Level Assessment of Channel Change and Spawning Habitat on the Stanislaus River Below Goodwin Dam. Report to the U.S. Fish and Wildlife Service, Sacramento, CA., 52 pp. http://www.delta.dfg.ca.gov/srfg/doc.asp

Kondolf, G.M., M. J. Sale and M.G. Wolman, 1993. Modification of fluvial gravel size by spawning salmonids. *Water Resources Research* 29 (7): 2265-2274.

Kondolf, G.M., M.W. Smeltzer, and S.F. Railsback, 2001. Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. *Environmental Management* 28(6): 761-776. DOI:10.1007/s002670010260.

Krause, A. and S. McBain, 2003. Summary of Trinity River Restoration Program Sediment Management Briefing for the May 29, 2003 meeting in Weaverville, Ca. Trinity River Restoration Program, Bureau of Reclamation, Weaverville, CA, 13 pp.

Leopold, L.B, M.G. Wolman and J. P. Miller, 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman & Co., San Francisco, 522 pp.

Ligon, F.K., W.E. Dietrich, and W.J. Trush, 1995. Downstream ecological effects of dams. *BioScience* 45 (3): 183-192.

Limerinos, J.T., 1970. Determination of the Manning coefficient from measured bed roughness in natural channels. *Geological Survey Water-Supply Paper* 1898-B, B1-B47.

Loomis, J., 2002. Quantifying recreation use values from removing dams and restoring free-flowing rivers: A contingent behavior travel cost demand model for the Lower Snake River. *Water Resources Research* 38(6), 10.1029/2000WR000136,2002.

McBain and Trush, 1999a. Tuolumne River Restoration Project Monitoring: Special Run Pools 9, 7/11 Mining Reach, and Ruddy Mining Reach. Report to the Tuolumne River Technical Advisory Committee, USFWS Anadromous Fish Restoration Program, and the CBDA Ecosystem Restoration Program.

McBain and Trush, 1999b. Conceptual Plan for Restoration of the Lower Clear Creek Floodway. (Illustrated Overview) Prepared for the Lower Clear Creek Technical Work Group. McBain and Trush, Arcata, CA.10 pp. Appendix A of Proposal #252 "Lower Clear Creek Floodway Rehabilitation Phase 3" submitted by Western Shasta Resources Conservation District, 2001. https://www.ecosystem.calfed.ca.gov/WRRC/CalFed/proposals/selection_panel_report_static

McBain and Trush, 2000a. Trinity River Restoration Program. Summary of the United States Secretary of the Interior Records of Decision, December 19, 2000. Trinity River Restoration Program, Weaverville, CA, 11 pp. http://www.ccfwo.r1.fws.gov/fisheries/reports/trrp/trrp_rod_19Dec2000.pdf

McBain and Trush 2001. Tuolumne River Phase II Gravel Introduction Technical Memorandum. Report prepared on behalf of the Tuolumne River Technical Advisory Committee and the Department of Fish and Game. McBain and Trush, Arcata, CA.16 pp.

McBain and Trush, 2003a. Coarse Sediment Management Plan, Lewiston Dam to Grass Valley Creek, Trinity River, CA. Administrative Draft. Report prepared for U.S. Bureau of Reclamation. McBain and Trush, Arcata, CA., 62 pp. http://www.krisweb.com/biblio/trinity_usbor_mcbaintrush_2003_draftgrvlmgmt.pdf

McBain and Trush, 2003b. Coarse Sediment Management Plan for the Lower Tuolumne River. Final Report. Prepared for the Tuolumne River Advisory Committee, McBain and Trush, Arcata, CA, 306 pp. http://www.delta.dfg.ca.gov/afrp/Project.asp?code=2000-41 In July 2004, this report has been replaced by the report McBain and Trush (2004) which supersedes the 2003 version.

McBain and Trush, 2003c. Estimating Salmon Habitat Availability in the Lower Oak Grove Fork Using Expert Habitat Mapping. Summary of methods and Preliminary Results. Report prepared for the Clackamas Instream Flow / Geomorphology Subgroup, Portland General Electric – Clackamas River Project (FERC No. 123/2195), McBain and Trush, Arcata, CA, 96 pp. http://www.pge-hl.com/documents.cfm?docs=Clackamas%20Reports

McBain and Trush, 2004a. Coarse Sediment Management Plan for the Lower Tuolumne River. Revised Final Report. Prepared for the Tuolumne River Advisory Committee, McBain and Trush, Arcata, CA, 306 pp. http://www.delta.dfg.ca.gov/afrp/Project.asp?code=2000-41

McBain and Trush, 2004b. Synthesis of geomorphic, vegetation and instream flow studies. Oak Grove Project, Oak Grove Fork and Clackamas River upstream from North Fork Reservoir. Report prepared for Portland General Electric, McBain and Trush, Arcata, CA, ca. 500 pp. http://www.pge-hl.com/documents.cfm?docs=Clackamas%20Reports

McBain and Trush, Graham Matthews, and North State Resources, 2000. Lower Clear Creek Floodway Rehabilitation Project. Channel Restoration, Riparian Vegetation, and Wetland Creation Design Document. Prepared for Clear Creek Restoration Team, et al., McBain and Trush, Arcata, CA.75 pp. Appendix B of Proposal #252 "Lower Clear Creek Floodway Rehabilitation Phase 3" submitted by Western Shasta Resources Conservation District, 2001. https://www.ecosystem.calfed.ca.gov/WRRC/CalFed/proposals/selection_panel_report_static

McLain, R.J. and R.G. Lee, 1996. Adaptive management: Promises and pitfalls. *Environmental Management* 20(4): 437-448.

Merced Irrigation District and Natural Resource Scientists, Inc. (2003). Merced River Wing-Dam Gravel Monitoring. Final Report. Funded by U.S. Fish and Wildlife Service, Anadromous Fish Restoration Program. http://www.delta.dfg.gov/afrp/template_frame.asp?

Mesick, C. F., 2001. Factors that potentially limit the population of fall-run Chinook in the San Joaquin River tributaries. Unpublished manuscript, Carl Mesick Consultants, El Dorado, CA., 65 pp. http://www.delta.dfg.ca.gov/srfg/docs.asp

Meyer-Peter, E. and R. Müller, 1948. Formulas for bed-load transport. In: *International Association of Hydraulic Research*, 2nd Meeting, Stockholm, p. 39-64.

Milhous, R.T., 1998. Numerical modeling of flushing flows in gravel-bed rivers. *Gravel-Bed Rivers in the Environment.* P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, eds., 579-608, Water Resources Publications LLC, Highlands Ranch, Colorado.

Montgomery, D.R., J.M. Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn, 1996. Stream-bed scour, egg burial depth, and the influence of salmonid spawning on bed surface mobility and embryo survival. *Canadian Journal of Fisheries and Aquatic Sciences* 53: 1061-1070.

Multi-Year Program Plan, Year 4-7. Calfed Bay - Delta Program, Ecosystem Restoration, Year 4 Work Plan Activities. http://calwater.ca.gov/Programs/EcosystemRestoration/Ecosystem.shtml "Multi-Year Program Plan (Year 4-7)".

Natural Resource Scientists (2001). Merced River Gravel Replenishment and Monitoring Project, Proposal #100. https://ecosystem.calfed.ca.gov/WRRC/CalFed/proposals/selectionpanel report_static

Parker, G., 1990. Surface based bedload transport relation for gravel rivers. *Journal of Hydraulic Research* 28(4): 417-436.

Parker, G., P.C. Klingeman and D.G. McLean, 1982. Bedload and the size distribution of paved gravel-bed streams. *Journal of the Hydraulics Division*, ASCE, 108 (HY4): 544-571.

Pasternack, G.B., C.L. Wang and J. Merz (2004). Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California. *River Research and Application* 20: 205-225.

Potyondy, J.P. and K. Bunte, 2001. Analyzing Pebble Count Data Collected By Size Classes Using Templates. (spreadsheet; free download from http://www.fs.fed.us/rm/pubs/rmrs….)

Potyondy, J.P. and K. Bunte, 2002. Sampling with the US SAH-97 hand-held particle-size analyzer. Federal Interagency Sedimenation Project, Waterways Experiment Station, Vicksburg, MS, 6 pp. (product description, user instruction, and general sampling information; free download from http://fisp.wes.army.mil).

Power, M.E., W.E. Dietrich and J.C. Finlay, 1996. Dams and downstream aquatic biodiversity: potential Food web consequences of hydrologic and geomorphologic change. *Environmental Management* 20(6): 887-895.

Program Tracking January 2003. Calfed Bay - Delta Program, Ecosystem Restoration, Ecosystem Restoration Program Element Overview. http://calwater.ca.gov/ProgramTracking_2003/ProgramTrackingJanuary2003.shmtl

Project Evaluation Phase 2 Report (2003). Ecosystem Restoration Program, Project Evaluation Phase 2 Report 2003, prepared for Calfed Bay - Delta Program, prepared by Kleinschmidt, Energy and Water Resources Consultants and Jones & Stokes. http://calwater.ca.gov/Programs/EcosystemRestoration/Ecosystem.shtml "ERP Project Evaluation Phase 2"

R2 Resource Consultants, Inc., 1994. Gravel supplementation feasibility study in the Madison River bypass reach below Madison Dam. Final Report prepared for Montana Power Company, Butte, Montana.

Ramos, C., 1996. Quantification of stream channel morphological features: recommended procedures for use in watershed analysis and TFW ambient monitoring. Report submitted to Northwest Indian Fisheries Commission. Timber, Fish & Wildlife, Report No. TFW-AM9-96-006, 193 pp.

Reiser, D. and J.B. Bradley, 1993. Fine sediment intrusion and salmonid habitat. In: *Advances in Hydro-Science and -Engineering*, Vol. 1, S.S.Y. Wang (ed.), p. 257-264.

Reiser, D.W., 1998. Sediment in gravel-bed rivers: ecological and biological considerations. *Gravel-Bed Rivers in the Environment.* P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, eds., 197-228, Water Resources Publications LLC, Highlands Ranch, Colorado.

Reiser, D.W., M.P. Ramay and T.A. Wesche, 1989. Flushing flows. In: *Alternatives in Regulated River Management*. J.A. Gore and G.E. Petts (eds.), CRC Press, Boca Raton, Florida, p. 91-135.

Reiser, D.W., M.P. Ramay and T.R, Lambert, 1987. Considerations in assessing flushing flows. In: *Regulated Streams - Advances in Ecology, Proceedings of the Third International Symposium on Regulated Streams*, J.F. Craig and J.B. Kemper (eds.), Aug. 4-8, 1985, p. 45-57.

Rice, S. and M. Church, 1996. Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. *Journal of Sedimentary Research* 66 (3): 654-665.

Rice, S., 1995. The spatial variation and routine sampling of spawning gravels in small coastal streams. Research Branch, British Columbia Ministry of Forests, Victoria, B.C., Working Paper 06/1995, 41 pp.

Roe, E., 1996. Why ecosystem management can't work without social science: an example from the California northern spotted owl controversy. *Environmental Management* 20(5): 667-674.

Ryan, S.E. and C.A. Troendle, 1997. Measuring bedload in coarse-grained mountain channels: procedures, problems, and recommendations. In: *Water Resources Education, Training, and Practice: Opportunities for the Next Century.* American Water Resources Association Conference, June 29-July 3, Keystone, CO, p. 949-958.

Ryan, S.E., 2001. The influence of sediment supply on rates of bedload transport: a case study of three streams on the San Juan National Forest. *Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25-29, Reno, Nevada*, Vol. 1, III 48 - III 54.

Schoklitsch, A., 1962. *Handbuch des Wasserbaus*. [Handbook of Hydraulic Engineering.]. Springer Verlag, Wien.

Schuett-Hames, D., B. Conrad, A. Pleus, and D. Smith, 1996. Field comparison of the McNeil sampler with three shovel-based methods used to sample spawning substrate composition in small streams. Timber, Fish and Wildlife, TFW-AM-9-96-005, 33 pp.

Schumm, S.A., 1969. River metamorphosis. *Journal of the Hydraulic Division*, Proceedings of the American Society of Civil Engineers, 95(HY1): 255-273.

Schumm, S.A., 1971. Fluvial geomorphology: channel adjustment and river metamorphosis. In: *River Mechanics, Vol. 1.* H.W. Shen (ed.), Colorado State University, Fort Collins, Colorado, 5.1-5.22.

Schumm, S.A., 1977. *The Fluvial System*. Wiley Interscience, New York.

Searcy, J.K., 1959. Flow duration curves. *US Geological Survey, Water Supply Paper*1542-A, 33pp.

Spawning Gravel 2002. Spawning Gravel Restoration Program, CVPIA §3406 (b)(13), Work Plan for Fiscal Year 2002. http://www.mp.usbr.gov/cvpia/awp/2002/

Spawning gravel 2003. Spawning Gravel Restoration Program, CVPIA §3406 (b)(13), Work Plan for Fiscal Year 2003. http://www.mp.usbr.gov/cvpia/awp/2003/

Spawning gravel 2004. Spawning Gravel Restoration Program, CVPIA §3406 (b)(13), Work Plan for Fiscal Year 2004. http://www.mp.usbr.gov/cvpia/awp/2004/

Status of Fishery Programs (2003). Status of Fishery Programs in the Sacramento Valley. http://www.norcalwater.org/pdf/status

Steffler, P. and J. Blackburn, 2002. Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat Introduction to Depth Averaged Modeling and User's Manual. University of Alberta, Canada, 220 pp. http://www.river2d.ualberta.ca/software/River2D.pdf

Stillwater Sciences, 2001a. Merced River Corridor Restoration Plan Baseline Studies. Volume II: Geomorphic and Riparian Vegetation Investigations Report. http://www.stillwatersci.com/publications.html

Stillwater Sciences, 2001b. Merced River Corridor Restoration Plan: Task 2 Technical Memorandum: Channel and Floodplain design Guidelines. Report prepared by Stillwater Sciences, Berkeley, CA. ca. 200 pp.

Stillwater Sciences, 2002. Merced River Corridor Restoration Plan. Report prepared by Stillwater Sciences, Berkeley, CA, 245 pp. http://www.stillwatersci.com/publications.html

Trinity Associates 2000. An evaluation of regulations, effects and management of aggregate mining in northern and central coastal California. Report prepared for the National Marine Fisheries Service, Southwest Region, Trinity Associates, Arcata, CA, 94pp.

Turlock Irrigation District 2001. Tuolumne River Sediment Acquisition and spawning gravel transfusion project. Proposal submitted by the Turlock Irrigation District to the CalFed Bay Delta Program. https://ecosystem.calfed.ca.gov/WRRC/CalFed/proposals/selection_panel_report_static

Wilcock, P.R. and J.C. Crow, 2003. Surface-based transport model for mixed-size sediment. *Journal of Hydraulic Engineering* 129(2): 120-128.

Trinity River 2002. Trinity River Restoration Program, CVPIA §3406 (b)(23), Work Plan for Fiscal Year 2002. http://www.mp.usbr.gov/cvpia/awp/2002/

Trinity River 2003. Trinity River Restoration Program, CVPIA §3406 (b)(23), Work Plan for Fiscal Year 2003. http://www.mp.usbr.gov/cvpia/awp/2003/

Trinity River 2004. Trinity River Restoration Program: Implementation of Non-Flow Related Items, Phase II. CVPIA §3406 (b)(23), Work Plan for Fiscal Year 2003. http://www.mp.usbr.gov/cvpia/awp/2004/

Trinity River Sediment Management Briefing Summary (2003). Summary of Trinity River Restoration Program Sediment Management Briefing for the May 29, 2003 meeting in Weaverville, CA. 13 pp.

Trush, W.J., S.M. McBain and L.B. Leopold, 2000. Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences of the United States of America*, 97 (22): 11858-11863.

USFWS (2003). Flow habitat relationship for steelhead and fall, late fall and winter-run chinook salmon spawning in the Sacramento River between Keswick Dam and Battle Creek. US Fish and Wildlife Service, Energy Planning and Instream Flow Branch, Sacramento, CA., 79 pp. http://www.delta.dfg.ca.gov/afrp/documents/Sacramento_River_Spawning_Final_Report_Feb_4_2003.pdf

Wheaton, J.M. and G.B. Pasternack, 2002. The integrated design approach to designing in-stream spawning habitat enhancement projects. Draft Final Report, presented to East Bay Municipal Utility District. University of California at Davis, Department of Land, Air and Water Resources, Watershed Geomorphology Lab, 111 pp.

Wheaton, J.M., G.B. Pasternack and J.E. Merz, 2004a. Spawning habitat rehabilitation – I. Conceptual approach and methods. *International Journal of River Management* 2(1): 3-20.

Wheaton, J.M., G.B. Pasternack and J.E. Merz, 2004b. Spawning habitat rehabilitation – II.Using hypothesis development and testing in design, Mokulumne River, California, U.S.A. *International Journal of River Management* 2(1): 21-37.

Whiting, P.J. and W.E. Dietrich, 1993. Experimental studies of bed topography and flow patterns in large-amplitude meanders. 1. Observations. *Water Resources Research* 29 (11): 3605-3614.

Whyte, I.W., S. Babakaiff, M.A Adams and P.A. Giroux, 1997. Restoring fish access and rehabilitation of spawning sites. In: Fish Habitat Rehabilitation Procedures. Watershed Restoration Technical Circular No. 9, P.A. Slaney and D. Zaldokas (eds.). British Columbia Watershed Restoration Program, Ministry of Environment, Lands and Parks, Vancouver, BC.

Wilcock, P.R., G.M. Kondolf, W.V.G. Matthews, and A.F. Barta, 1996b. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* 32 (9): 2911-2921.

Wilcock, P.R., 1998. Sediment maintenance flows: feasibility and basis for prescription. *Gravel-Bed Rivers in the Environment.* P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, eds., 609-636, Water Resources Publications LLC, Highlands Ranch, Colorado.

Wilcock, P.R., A.F. Barta, C.C. Shea, G.M. Kondolf, W.V.G. Matthews, and J. Pitlick, 1996a. Observations of flow and sediment entrainment on a large gravel-bed river. *Water Resources Research* 32 (9): 2897-2909.

Wu, F.-C., 2000. Modeling embryo survival affected by sediment deposition into salmonid spawning gravels: Application to flushing flow prescriptions. *Water Resources Research* 36 (6): 1595-1603.

Yang, C.T., 1996. *Sediment Transport. Theory and Practice.* McGraw-Hill, New York.

Appendix A: General information on California gravel augmentation studies

A.1 California streams with gravel augmentation studies

Most Gravel augmentation studies are located in California and occur on dammed Central Valley streams as well as on the Trinity River (Fig. A1). The studies are typically funded and supervised by one of two large programs in California (Stillwater Sciences 2002, Section 2.4): the CalFed or California Bay – Delta Authority Ecosystem Restoration Program (CBDA, ERP) and the Central Valley Project Improvement Act (CVPIA). Both programs work closely together and have a common proposal and review process. Gravel augmentation projects outside California were found for only a few locations:

1. British Columbia: Campbell R. Spawning - Gravel Placement Project;
2. Montana: Madison River bypass reach below Madison Dam (R2 Resource Consultants, Inc., 1994)
3. Oregon: North Umpqua R., Slide Creek Boulder Enhancement Reach;
4. North Carolina: Cheoah R., and
5. Washington: Cowlits River.

A.2 The Central Valley Project Improvement Act (CVPIA)

In 1992, Congress passed Title 3406 of the Public Law 102-575, the "Central Valley Project Improvement Act (CVPIA)". Title 3406(b) concerns Fish and Wildlife Restoration Activities. The aim of this program is to increase the natural production of anadromous fish in Central Valley rivers and streams such that a long-term, sustainable population develops that is at least twice the average levels attained during the period of 1967-1991 (AFRP - 34-CVPIA). The legislative text is provided in Appendix B. Out of a total of 23 programs funded through CVPIA in 2003 and the 21 in 2004, three include gravel augmentation in 11 different California streams (Table A1).

Table A1: CVPIA 3406(b) Programs that include gravel augmentation in the years of 2002, 2003 and 2004 (compiled from: http://www.mp.usbr.gov/cvpia/awp/2003/ and …/2004/).

Program Title Title	Streams involved	Paragraph of
Anadromous Fish Restoration Program (AFRP)	Big Chico Creek, Yuba River Mokelumne River, Tuolumne River, Stanislaus River, Merced River)	3406(b)(1)
Clear Creek Restoration	Clear Creek	3406(b)(12)
Spawning Gravel/Riparian Habitat Restoration	Upper Sacramento River, American River, Stanislaus River	3406(b)(13)
Trinity River Restoration	Trinity River	3406(b)(23)

Fig. A1: Sketch map of streams in the Central Valley (copied from http://www.delta.dfg.ca.gov/afrp/projects.asp.

A listing of current gravel augmentation studies funded by CVPIA under the Title 3406(b) is provided in Table A2. Depending on whether neighboring sites are counted individually or as one group, there are about 23 projects in the California Central Valley and the Trinity River that involve gravel augmentation as the major or a minor project goal.

Table A2: Projects managed through the **Anadromous Fish Restoration Program** of the Central Valley Project Improvement Act (CVPIA) under title 3406(b)(1), the **Clear Creek Program** (3406(b)(12)), the **Spawning Gravel Restoration Program** (3406(b)(13)), and the **Triniti River Program** (3406(b)(23)) that involve gravel augmentation. Sources: AFRP (2002, 2003, 2004) for projects and streams managed under the Title 3406(b)(1); Clear Creek (2002, 2003, 2004) for projects managed under the Title 3406(b)(12); Spawning gravel 2002, 2003, 2004) for projects and streams managed under the Title 3406(b))(13), and Trinity River (2002, 2003, 2004) for the project managed under the Title 3406(b)(23).

Stream site	Objective and priority gap	Priority target	Year	Re-port (1)
Big Chico Cr. **3406(b)(1) below One-Mile Dam and Five-Mile Diversion**	Introduce spawning gravel lost behind One-Mile Dam and the Lindo Channel complex at Five-Mile Diversion; Move gravel trapped at man-made structures back into Big Chico Cr.	1) Habitat restoration; 2) Fish passage improvement project (addresses both passage and gravel replenishment)	'03	
	Acquire and restore anadromous fish habitat. Add spawning gravel	Add spawning gravel at Five-Mile Diversion	'04	
Yuba R. **3406(b)(1)**	Improve anadromous salmonid spawning habitat to increase salmonid natural production. Implement gravel additions in upper reaches of Yuba River.	Gravel additions above and below Narrows Pool.	'03	
		1) Gravel additions above and below Narrows Pool (US Army Corps of Engineers mitigation); 2) SHIRA-based River analysis, Phase II.	'04	
Mokelumne R. **3406(b)(1) below Camanche Dam**	Improve salmonid spawning habitat below Camanche Dam Demonstration of an Integrated approach to designing in-stream spawning gravel rehabilitation.	Funds provided to UC Davis (Greg Pasternack). Three design scenarios developed for placement of 3,072 tons of spawning gravel in the channel; Gravel augmentation for enhancing spawning habitat and fluvial complexity is greatly improved when aided by the new integrated design approach.	'02	a)
	Acquire and restore anadromous fish habitat. Determine optimal design for gravel replenishment in Central Valley rivers and continue enhancing spawning habitat	1) Spawning Habitat Rehabilitation Project; 2) Spawning Habitat Improvement	'03	b)
		1) Implement the Demonstration Project to Rehabilitate Salmonid Spawning Habitat; 2) Continuation of Mokelumne River Spawning habitat Improvement.	'04	

Tuolumne R. **3406(b)(1)**		Channel and floodplain Restoration of the 7-11 reach nearly completed; Special Run Pool Restoration (SRP9) and (SRP10) construction phase nearly completed and pre-project monitoring has started. Initiation of CEQA documentation for La Grange gravel addition. Implementation of an Adaptive Management Plan.	'01 & '02	
	Restore natural river function. Enhance instream and riparian habitat for salmonid use. Replenish spawning gravel and reduce sedimentation.	1) CALFED #181 Warner-Deardorff channel and floodplain restoration site: preliminary design engineering is complete and environmental permitting and right of way has started. 2) CALFED #179 Big Bend project; 3) CALFED #73 Bobcat Flat restoration project.	'03	
	Acquire and restore anadromous fish habitat. Acquire instream and riparian habitat for salmonid use; Replenish spawning gravel and reduce sedimentation.	1) Restore the Warner-Deardorff segment No. 3 (CBDA); 2) Implement Big project (CBDA); 3) Implement MJ Ruddy Restoration Project (CBDA); 4) Implement La Grange Gravel Introduction (AFRP and DWR); 5) Bobcat Flat Restoration Project (CBDA); 6) Implement Special Run Pool 10 (SR P10) Restoration and Pre-project Monitoring (AFRP); 7) Implement Sediment Acquisition and Spawning Gravel Transfusion Project (CBDA).	'04	c)
Stanislaus R. **3406(b)(1)**	Investigate benefits and methods of restoring spawning habitat for fall-run Chinook salmon at 18 restoration sites between Goodwin Dam and Oakdale.	Provided funding for Spawning habitat and Floodplain Restoration Phase I. Project will acquire gravel sources and restore spawning and floodplain habitat at Two-Mile Bar. CALFED #39: Continued Studies for the Knights Ferry Gravel Replenishment Project Phase 2. Funds provided to Carl Mesick Consultants.	'01 & '02	d)

Stanislaus R. **3406(b)(1)**	Restore natural stream channel functions, including geomorphology and sediment budgets (e.g., proportion of coarse vs. fine sediments). Acquire and restore anadromous fish habitat Develop geomorphic and restoration assessments and implement sediment Restoration actions.	1) CALFED #40: Frymire Ranch project, spawning habitat restoration; 2) Gravel addition, floodplain restoration and monitoring at Knights Ferry; 3) gravel addition and monitoring at Lovers Leap; 4) Identify sediment problems and create a management plan with potential solutions.	'03	
		1) Identify sediment problems and create a management plan with potential solutions; 3) Implement the Spawning Gravel Augmentation Program (USBR)	'04	
Merced R. **3406(b)(1)**		Completed: Ratzlaff segment of the Robinson Ratzlaff Mining Reach in-channel habitat restoration project and initiated post-project monitoring. Initiated Adaptive Management Forum for restoration on the Robinson Ranch reach. Identified a source of 300,000 tons of aggregate useable for spawning gravel.	'01 & '02	e) f)
	Enhance instream and riparian habitat for salmonid use. Replenish spawning gravel and reduce sedimentation. Restore natural river function.	1) CALFED #158, Dredger tailings reach restoration;	'03	
	Acquire and restore anadromous fish habitat. Replenish spawning gravel and reduce sedimentation; acquire instream and riparian habitat for salmonid use; investigate reintroduction of anadromous salmonids above existing barriers.	1)Implement the Dredger Tailings Reach Restoration project Phase IV, CALFED #158 (CBDA); 3) Evaluate success of gravel enhancement, Robinson Reach (AFRP)	'04	
Clear Cr. **3406(b)(12) below Wiskeytown Dam**	Implement spawning gravel augmentation and monitoring Clear Creek Fish Restoration Program. Provide spawning gravel to replace supply blocked by Whiskeytown Dam. Monitor project results. Augment the supply of spawning-sized gravel	Spawning gravel has been introduced since 1996 and created a high density spawning habitat. FY '02: Added spawning gravel: 1) 3,000 tons to Placer Bridge and City of Redding site (injection method). 2) Added 2,173 tons to 9 locations (instream placement) related to the Channel Rehabilitation Project. Additional funding needed from CVPIA to facilitate adding more spawning gravel as recommended by Clear Creek Gravel Management Plan	'02	g)

	Augment the supply of spawning-sized gravel	1) Implement spawning gravel augmentation at the Whiskeytown Dam, Placer Road, and City of Redding injection locations 2) Monitor geomorphic characteristics of spawning gravel downstream movement 3) Place gravel at several new gravel instream placement sites Inject and place 10,000 tons of spawning gravel. Provide annual Report and recommendations for the future. Monitoring indicated increased spawning activity on injected spawning gravel.	'03	
		Implement spawning gravel augmentation and monitoring program.	'04	plan ned.
Upper Sacramento River below Keswick Dam **3406(b)(13)**	Increase the availability of spawning and rearing habitat for Chinook salmon and steelhead trout.	Replenish spawning gravel in the reach of the mainstem Upper Sacramento River from Keswick Dam to the Red Bluff Diversion Dam.	'03	
		Assess need for gravel placement including amount and site	'04	
American River below Nimbus Dam **3406(b)(13)**	Increase the availability of spawning and rearing habitat for Chinook salmon and steelhead trout.	Monitor the replenishment of spawning gravel in the reach downstream of Nimbus Dam.	'03	
		Continue monitoring.	'04	plan ned
Stanislaus River below Goodwin Dam 3406(b)(13)	Increase the availability of spawning and rearing habitat for Chinook salmon and steelhead trout.	Replenish spawning gravel downstream of Goodwin Dam and monitor those placements.	'03	
		Coordinate spawning gravel placement activities with staff.	'04	
Trinity R. **3406(b)(23)**	Sediment management, including supplementation of spawning gravel below Lewiston Dam and reduction in fine sediments which degrade fish habitats;	Possible gravel introductions. Completion of a gravel management plan.	'03	

(1) Only reports found and used for the preparation of this document are listed here. Other reports or documentation may exit.

a) Wheaton and Pasternack 2002; Pasternack et al. 2004
b) Wheaton et al. (2004a and b)
c) McBain and Trush (1999a, 2001, 2003b, 2004)
d) Carl Mesick Consultants (2002 a, b, c)
e) Stillwater Sciences (2001 a, b, 2002)
f) CDWR (2001, 2002a, b, 2003)
g) McBain and Trush (1999b); McBain et al. (2000)

A.3 Status of programs funded through CVPIA and Calfed's ERP

Ecosystem Restoration Programs funded by The California Bay-Delta-Authority (formerly Calfed) seem to have fully started in 2002 only, and as of spring 2004, projects are still ongoing and in their active field work phase. A summary report on the status of Ecosystem Restoration programs was published by Calfed (Project Evaluation Phase 2 Report 2003) and states that although progress in generally made, delays are due to funding, contracting, and permitting issues (Annual Report 2002). Only about 20% of the projects funded between 1995 and 1999 have been completed (as of June 2003). A number of projects seemed to lack a well-articulated experimental design and post-project monitoring, and the steps involved in adaptive management were neither well-known nor well followed. As most of the projects are not completed, final project reports are rarely available.

A.4 Entities involved in gravel augmentation (in California studies)

Gravel augmentation studies before the late 1990ies were often carried out by government agencies (e.g., US Bureau of Reclamation, California Department of Fish and Game, California Department of Water Resources). With introduction of the proposal and review process for restoration studies funded by Calfed and CVPIA in the late 1990ies, and a better understanding of the geomorphological and biological complexities of gravel augmentation projects in the late 1990ies, government agencies started to involve consulting companies with geomorphological and biological background into the planning and preparation of project proposals. The consulting companies formulate extensive (200-300 page) study plans that lay out scientific concepts behind a restoration effort. The consulting companies also perform preliminary stream studies, gather general information (e.g., areal photographs) and put together study results and information previously collected by government agencies or in local Master's Theses relevant to the study. Government agencies are still often executing a project, while personnel of the Anadromous Fish Restoration Program (AFRP) of the Central Valley Project Improvement Act (CVPIA) under title 3406(b)(1) often oversees the projects. Projects are not only awarded to government agencies, but also to universities, consulting companies and special interest groups such as "The Friends of the Toulumne" who then have the project performed by consulting companies. A large body of different entities is involved in gravel augmentation studies (Table A3).

Table A3: Entities involved in gravel augmentation projects (mainly) in California such as government agencies, consulting companies, academia, special interest groups*.

1. Government agencies:
   - US Bureau of Reclamation (USBR),
   - US Bureau of Land Management (USBLM)
   - US Fish and Wildlife Service (USFWS), Anadromous Fish Restoration Program (AFRP)
   - California Department of Fish and Game (CDFG),
   - California Department of Water Resources (CDWR),
   - US Army corps or Engineers (USACE)
   - US Forest Service (USFS)
   - Turlock Irrigation District and Modesto Irrigation District (Tuolumne River)
   - Merced Irrigation District (Merced River)
   - Western Shasta Resource Conservation District
2. Consulting companies: (small and large, with geomorphological, engineering, or fisheries biology backgrounds. The different backgrounds lead to different approaches and emphasis in the restoration work).
   - Carl Mesick Consultants, El Dorado, CA
   - Graham Matthews Consultants, Weaverville, CA
   - McBain & Trush, Arcata, CA
   - Natural Resource Consultants, Portland, OR
   - R2 Consultants, Redmond, WA
   - Stillwater Sciences, Berkeley, CA
3. Academia:
   - G.M. Kondolf, UC Berkeley
   - G.B. Pasternack, UC Davis
4. Special interest groups such as:
   - Friends of the Tuolumne,
   - The Tuolumne River Preservation Trust,
   - Local stakeholder groups.

* This list is not comprehensive and other entities involved in gravel augmentation projects may exist.

A.5 Amount of gravel augmented to various streams in the CVPIA projects 3406(b)(12), (13) and (23)

Information on approximate amounts of gravel used in gravel augmentation projects is available for some of the CVPIA funded projects and summarized in Table A4 (see also Table 7 in Section 5.2). Gravel added amounted up to 32,000 tons annually (one dump truck typically used at construction sites holds about 15 tons of gravel).

Table A4: Locations and amounts of gravel augmentation in California Streams in several CVPIA Projects as well as the Trinity River (1 ton gravel has a volume of 0.60 yd^3; 1 yd3 = 1.67 tons)

Stream and approximate location	**Gravel Augmentation Sites**	**References**	**Gravel amount added and year**	**Total amount per stream**
Clear Creek below Wiskeytown dam 3406(b) (12)	at Placer Bridge, City of Redding, Clear Creek Road Bridge, Reading Bar, below Wiskeytown Dam	Clear Creek (2002, 2003, 2004); (Status of Fishery Programs 2003)	unknown annually since '96; 32,000 tons in '00 12,000 tons in '01, 6,000 tons in '02; 12,000 tons in '03	>62,000 tons
Upper Sacramento River below Keswick Dam to Red Bluff Diversion Dam 3406(b) (13)	Immediately below Keswick Dam, below confluence with Salt Creek, at Tobiason property near southern end of Redding city limits	Spawning Gravel (2003, 2004)	unknown in 1997 15,000 tons in '02, 8,800 tons in '03	> 24,000 tons
American River below Nimbus Dam 3406(b) (13)		Spawning Gravel (2003, 2004)	in 1999	
Stanislaus River below Goodwin Dam 3406(b) (13)	Immediately below Goodwin Dam	Spawning Gravel (2003, 2004)	unknown in 1997, 488 tons in 2002	> 500 tons
Mokelumne River below Camanche Dam 3406(b) (1)	within a few miles below Camanche Dam	Pasternack et al. (2004)	within 1-mile reach btw. '90-'02: avg. 664 tons ann. within 2-mile reach btw. '96-'98: avg. 253 tons	21,506 tons
Trinity River below Lewiston Dam to confluence with Grass Creek	within a few miles below Lewiston Dam	McBain and Trush (2003a)	unknown in '76/77. Within 7.8 mile reach: 4,600 yd^3 (7,600 tons) in '83/84; 6,800 yd^3 (11,000 tons) in '89, '98, and '00.	>18,600 tons
	in the upper reaches.	Trinity River (2003, 2004)	unknown in '03; planned for 2005	

Appendix B:

Legislative text of CVPIA (3406)(b) programs that include gravel augmentation

b) FISH AND WILDLIFE RESTORATION ACTIVITIES. - The Secretary, immediately upon the enactment of this title, shall operate the Central Valley Project to meet all obligations under state and federal law, including but not limited to the federal Endangered Species Act, 16 U.S.C. s 1531, et seq., and all decisions of the California State Water Resources Control Board establishing conditions on applicable licenses and permits for the project. The Secretary, in consultation with other State and Federal agencies, Indian tribes, and affected interests, is further authorized and directed to:

(1) **develop within three years of enactment and implement a program which makes all reasonable efforts to ensure that, by the year 2002, natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967-1991**; …. Provided further, That the programs and activities authorized by this section shall, when fully implemented, be deemed to meet the mitigation, protection, restoration, and enhancement purposes established by subsection 3406(a) of this title; And provided further, That in the course of developing and implementing this program the Secretary shall make all reasonable efforts consistent with the requirements of this section to address other identified adverse environmental impacts of the Central Valley Project not specifically enumerated in this section (AFRP - Title 34-CVPIA).

(12) develop and implement a comprehensive program to provide flows to allow sufficient spawning, incubation, rearing, and outmigration for salmon and steelhead from Whiskeytown Dam as determined by instream flow studies conducted by the California Department of Fish and Game after Clear Creek has been restored and a new fish ladder has been constructed at the McCormick-Saeltzer Dam. Costs associated with **channel restoration**, passage improvements, and fish ladder construction required by this paragraph shall be allocated 50 percent to the United States as a nonreimbursable expenditure and 50 percent to the State of California. Costs associated with providing the flows required by this paragraph shall be allocated among project purposes.

(13) develop and implement a continuing program for the purpose of **restoring and replenishing, as needed, spawning gravel lost due to the construction and operation of Central Valley Project dams, bank protection projects, and other actions that have reduced the availability of spawning gravel and rearing habitat** in the Upper Sacramento River from Keswick Dam to Red Bluff Diversion Dam in the American and Stanislaus Rivers downstream from the Nimbus and Goodwin Dams, respectively. The program shall include preventive measures, such as re-establishment of meander belts and limitations on future bank protection activities, in order to avoid further losses of instream and riparian habitat. Costs associated with implementation of this paragraph shall be reimbursed in accordance with the following formula: 37.5 percent shall be reimbursed as main project features, 37.5 percent shall be considered a nonreimbursable Federal expenditure, and 25 percent shall be paid by the State of California (AFRP - Title 34-CVPIA).

If the Secretary and the State of California determine that long-term natural fishery productivity in all Central Valley Project controlled rivers and streams resulting from implementation of this section exceeds that which existed in the absence of Central Valley Project facilities, the costs of implementing those measures which are determined to provide such enhancement shall become credits to offset reimbursable costs associated with implementation of this subsection (from: AFRP - Title 34-CVPIA).