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7.1 Introduction

Monitoring geomorphological changes in response to river restoration interventions through the use of repeat topographic surveying is becoming more common in long-term\textsuperscript{1} monitoring (Downs & Kondolf 2002, Golet \textit{et al.} 2003). Typically a pre-project survey is performed, with a post-project (or as-built) survey immediately following the construction or intervention. Beyond that, repeat monitoring surveys are often performed on a defined-interval (typically annually initially) or an event-basis. How uncertainties in these surveys are managed to decipher what changes can be taken as meaningful and how one interprets restoration works is a question that requires careful consideration.

Arguably, two factors are and will continue to drive an increase in repeat topographic surveying as part of restoration monitoring. First, improvements in ground-based and aerial surveying technology have made the rapid-acquisition of high density topographic survey data easier to acquire and more affordable.\textsuperscript{2} Secondly, the restoration community has been under increasing pressure to be accountable for their often expensive restoration interventions.\textsuperscript{3} Restoration monitoring is one way to gather data that can be used to assess whether restoration projects are meeting their objectives and/or whether they are causing unintended consequences or benefits (Downs & Kondolf 2002). However, how does one account for uncertainties in the monitoring process? Monitoring is a key part of any adaptive management program, whereby restoration of complex systems is accepted as uncertain and treated as an iterative process of

\textsuperscript{1}Note that long-term in a restoration context usually means 3 to 5 years or up to 10 years.
\textsuperscript{2}These surveying developments were reviewed in § 3.3.1.1.
\textsuperscript{3}See Darby & Sear (2008) and Sear \textit{et al.} (2008) for justification.
learning-by-doing (Clark 2002). In this context, the monitoring helps complete the feedback loop, but it needs to articulate the uncertainties discovered in the process.

Within the restoration literature, there is nearly unanimous consent for monitoring and subsequent reporting and sharing of ‘lesson’s learnt’ with fellow restoration practitioners and scientists (Bernhardt et al. 2005, Wheaton et al. 2006, Wheaton et al. 2008). Although monitoring has been advocated in the restoration literature extensively for some time, and restoration monitoring is increasingly taking place (Wheaton et al. 2006), relative to the number of projects there are few examples of published monitoring efforts articulating what the monitoring has revealed (Bernhardt et al. 2005, Bash & Ryan 2002). There are even fewer examples of how that information is then used to feedback adaptively to the original and/or future restoration efforts (Sabine et al. 2004, Walters 1997). Practitioners have already successfully convinced clients and funding agencies of the importance of restoration efforts (Bernhardt et al. 2005). Assuming the subsequent trend of convincing clients and funders of the merits of monitoring also increases, it is argued that practitioners will need some more sophisticated tools for making sensible interpretations from the analysis of monitoring data. In the case of repeat topographic surveying, the surveying technology has developed rather rapidly; but, analysis and interpretation tools addressing what the data can be used to say naturally lags behind.

Even with topographic surveying becoming more affordable, restoration monitoring is generally an expensive endeavour with monitoring costs potentially exceeding the actual costs of the restoration intervention (Downs & Kondolf 2002). Nonetheless, there is growing recognition amongst clients and managers paying for restoration (as opposed to just amongst practitioners and scientists) of the importance of monitoring and the associated ‘cost of knowing’. It is speculated that, as the restoration community becomes more accustomed to undertaking monitoring, topographic surveying will play a larger role. The challenge of being able to make sensible interpretations of repeat topographic surveys that robustly account for uncertainties is therefore very topical.

The purpose of this chapter is to demonstrate how the methods developed in Chapter 5 for making geomorphological interpretations from morphological sediment budgets can be used in a PHR context. This is the second of the three stories of geomorphological change. Like Chapter 6, the DoD Uncertainty Analysis techniques developed in Chapter 4 are used to derive thresholded DoDs from the morphological sediment budgeting that can reliably distinguish real changes from noise. Again, this is merely the starting point and the focus is on using various masking techniques proposed in Chapter 5 to make meaningful geomorphological interpretations of the changes captured in the DoD. However, unlike Chapter 6 where the narrative was organised around the different types of masks; here, the narrative is geared to specific questions about PHR. Namely, the questions are divided into those from four separate ‘as-built’ surveys and those from two periods of monitoring subsequent adjustments and changes to salmonid habitat restoration (SHR) projects. These four SHR projects all come from the

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4Monitoring costs are thought to typically be around 30% to 50% of total project value (p. comm River Restoration Centre).

5SHR is a sub-class of PHR (see acronym list at front).
Mokelumne River in Northern California and represent an example of typical monitoring associated with reach-scale restoration consisting of pre-project, as-built and repeated post project topographic surveys on an annual basis. The ‘as-built’ questions addressed are:

- What is the total volume of gravel that was placed? (§ 7.4.1)
- How much gravel was used to produce what types of morphological units or habitat? (§ 7.4.2)
- How much gravel was used to produce what quality of habitat? (§ 7.4.3)

The monitoring questions addressed are:

- What are the geomorphological interpretations of the DoD predicted changes that took place one wet season after construction? (§ 7.5.1)
- What impact did the changes that took place have on habitat quality? (§ 7.5.2)
- What changes took place where salmon spawned? (§ 7.5.3)

First the study site and SHR context (§ 7.2) is described. Then the results of the DoD uncertainty analysis applied to six analysis periods on the Mokelumne are briefly presented (§ 7.3). Then the remainder of the chapter is focused around the specific questions defined above.

### 7.2 Study Site and SHR Context

The study site on the Mokelumne River is a heavily regulated and modified reach located less than 200 m downstream of a major dam, which is described briefly in § 3.5. A full study site description can be found in Appendix G. Starting in the mid 1990’s, East Bay Municipal Utility District began constructing one spawning habitat rehabilitation (SHR) project each year for chinook salmon. The projects each consisted of placing between 600 and 3000 m$^3$ of clean, triple-washed spawning gravels in the channel with a rubber-tired front loader to create spawning habitat (Figure 1.1). Up until 2000, these projects were constructed on an ad-hoc basis at the direction of a fisheries biologist in the field; from 2001 onwards the projects were constructed from detailed designs developed using the SHIRA (Spawning Habitat Integrated Rehabilitation Approach) framework developed by Wheaton (2003) and Wheaton et al. (2004c).\(^7\)

The focus of this case study is on the geomorphological monitoring of a 510 m long reach of the Mokelumne located approximately 200 m downstream of Camanche Dam (Figure 7.1). The

\(^6\)Note that SHR is just a subset of the physical habitat restoration (PHR) discussed in Chapter 1, § 1.2.1.
\(^7\)For further details of SHIRA, visit http://shira.lawr.ucdavis.edu/.
reach begins upstream at a fish guidance fence, which blocks fish migration upstream and is intended to divert migrating salmon into a fish hatchery. The reach extends virtually due west downstream, until it is diverted left by a prominent Mehrten formation rock outcrop, roughly 150 m downstream of the Murphy Creek confluence. SHR began within this reach in 1997 and 1998, with ad-hoc construction of two small riffles downstream of Murphy Creek. In 1999, a more substantial ad hoc project was constructed between 110 m and 240 m downstream of the fish guidance fence. Detailed pre and post project monitoring and assessment were performed at this site and are reported in Pasternack et al. (2004) and Merz & Setka (2004), with other elements reported in Merz et al. (2004) and Merz et al. (2006). Further downstream, other SHR efforts were also undertaken using SHIRA. By 2003, the focus returned to the 510 m reach described here. As of 2007, five consecutive years of staged SHR projects have been constructed in the reach, all relying on the Elkins et al. (2007) design concept of slope creation (Figure 7.2).

The essence of the slope creation design concept is as follows. If plan form is held fixed within pool-riffle morphology reaches, there is a finite amount of elevation head available for redistribution by changing local bed slopes along a longitudinal profile and altering habitat conditions. Wheaton et al. (2004c, Figure 4) showed that changing the distribution of slopes

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8See Table G.2 for hatchery take numbers.
cannot fully corroborate the slope creation procedure, specific predictions (formally defined later) were evaluated to better understand the role of slope in regulated streams: (1) slope creation improves salmon spawning habitat quality, (2) spawning salmon prefer areas predicted in advance to be high-quality habitat, and (3) slope creation can provide a sediment transport regime that keeps high-quality habitat stable during spawning and incubation life stages. These predictions were tested by analyzing patterns of flow, scour potential, and spawning habitat quality at a site on the Mokelumne River in northern California prior to (preproject), after the first (midproject) and after the second (postproject) channel manipulation. Observed counts of up-migrating fish, hatchery take, and redds for each spawning season were also used to test predictions and assess the slope creation approach. The significance of this study is that specific predictions regarding hydrogeomorphic and fish response to slope creation were tested to reveal mechanisms underlying complex linkages among flow, morphology, and habitat regimes.

2. Slope Creation

When examining geomorphic units at a subreach scale, slope and discharge control in-channel hydraulics (Knighton, 1998). In regulated reaches where channel slope has declined slowly over decades, depth is increased, velocity is decreased, and substrates become clogged, yielding poor habitat quality (Figure 1a). Bed relief typically yielding riffles and pools decreases to produce a single long glide. Moreover, in most cases reinstatement of the historic (or a ’naturalized’) flow regime is politically infeasible. Thus raising slope back to its predam state can quickly undo decades of degradation. Not only might this improve physical habitat quality, but it is hypothesized to restore many key geomorphic processes that maintain high-quality habitat.

To address this complex water resources issue a slope creation approach was developed, implemented, and assessed. Slope creation involves adding coarse sediment to the channel below a dam in a staged manner (Figures 1b and 1c) heavily relying on iterative design development, design evaluation, and adaptive monitoring over many years (Figure 2). It was conceived of in response to observations of detrimental backwater effects at 4 previous isolated gravel augmentation projects (Wheaton et al., 2004a). It was also added onto the previously reported SHIRA gravel augmentation framework (Wheaton et al., 2004a, 2004b). Because it is often unaffordable or infeasible to undo decades of degradation in a single, 1-year project, the slope can be used to improve physical habitat quality locally, but in reaches where slope is limiting this can be at the expense of habitat quality in the next upstream unit(s) as a backwater effect from placed gravel will lessen the available elevation head for upstream use. In the context of a regulated river, the riffle crest elevation closest to the dam determines the available elevation head for downstream reaches. If this elevation crest can be raised without impacting dam operations, this elevation head can be redistributed in the downstream reaches to improve physical habitat conditions (Elkins et al. 2007). Figure 7.2 illustrates this concept for two years, but such a strategy can be implemented over many years.

On the Mokelumne, Elkins et al. (2007) envisaged raising the upstream riffle crest by roughly 1 metre. However, the total volume of gravel required to create such a fill was economically and logistically unfeasible within a single year. As such, the uppermost riffle crest was raised by 0.5 metre originally, and then that elevation head was redistributed amongst the entire study reach over the course of four years in 2004, 2005 and 2006. In 2007 (not included in this thesis), EBMUD raised the riffle crest and the entire study reach again by another 0.5 metres. Thus, in five years of SHR, the original slope creation design afforded by raising the

![Figure 7.2: The slope creation design concept used on the Mokelumne River SHR projects. A fixed amount of elevation head is available for redistribution within the reach, unless the uppermost riffle crest elevation is raised. When this is done, this creates a new amount of elevation head, which can be subsequently redistributed throughout the reach. Figure reproduced from Elkins et al. (2007).](image)
Table 7.1: Definition of Mokelumne DoD Analysis Periods. *NOTE: TS4 does not actually exist as the 2005 Pre Project Survey could not be performed prior to construction due to high flows. PPA refers to post project appraisal, in this case appraising the adjustment over roughly one year of the PHR placed gravel.

<table>
<thead>
<tr>
<th>Analysis Period</th>
<th>Older Survey</th>
<th>Newer Survey</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>2003 Pre Project</td>
<td>2003 Post Project</td>
<td>As-Built</td>
</tr>
<tr>
<td>TS2</td>
<td>2003 Post Project</td>
<td>2004 Pre Project</td>
<td>PPA Adjustment</td>
</tr>
<tr>
<td>TS3</td>
<td>2004 Pre Project</td>
<td>2004 Post Project</td>
<td>As-Built</td>
</tr>
<tr>
<td>TS4*</td>
<td>2004 Post Project</td>
<td>2004 Post Project</td>
<td>PPA Adjustment</td>
</tr>
<tr>
<td>TS5</td>
<td>2004 Post Project</td>
<td>2005 Post Project</td>
<td>As-Built</td>
</tr>
<tr>
<td>TS6</td>
<td>2005 Post Project</td>
<td>2006 Pre Project</td>
<td>PPA Adjustment</td>
</tr>
<tr>
<td>TS7</td>
<td>2006 Pre Project</td>
<td>2006 Post Project</td>
<td>As-Built</td>
</tr>
</tbody>
</table>

uppermost riffle crest by 1 metre was realised, bringing the bed up to the point where some degree of floodplain connectivity was restored (p. comm Greg Pasternack).

7.2.1 The Analysis Periods

There are seven potential (six actual) analysis periods10 (Table 7.1). The study period extended from the Summer of 2003 to the Summer of 2006 and captures the construction of four phases of the SHR project within the study reach. These are referred to as ‘As-Built’ surveys and they represent geomorphological changes due to the artificial placement of gravel according to SHIRA-guided SHR designs (TS1, TS3, TS5 and TS7). Questions related to the interpretation of these four as-built surveys are addressed in § 7.4.

In addition there are two survey intervals that capture the natural adjustment of the SHR projects due to fluvial processes alone (TS2 and TS6). These are referred to as post project appraisals (PPA)11 or monitoring surveys and are addressed in § 7.5. The hydrological drivers of this style of change are represented by the hydrograph in Figure 7.3. Two hydrographs are shown in the figure12 to highlight the highly regulated and artificial nature of the flow regime at the site. TS2, was the tail end of a drought and the study site experienced no competent flows. By contrast, TS4 was a decent water year enabling a controlled pulse flow experiment to be conducted (Merz et al. 2006); while TS6 was the biggest flow year in over a decade on the Mokelumne, with the maximum possible dam release of 141.6 cumecs being realised.

Thus, two distinct styles of change on the Mokelumne River are captured in the dataset presented here. One is primarily due to the injection of gravel during the construction process

9Note that prior to SHR gravel augmentation starting in 1996, the there was no input of gravel to the reach since the construction of Camanche Dam. On top of this 40 year gravel deficit, the reach was extensively gravel mined prior to that.

10Analysis periods are labeled TS# for time step.

11In keeping with Downs & Kondolf (2002).

12The actual Camanche Dam release in black (experienced by the site), and the Mokelumne Hill gauge upstream of Pardee reservoir.
Figure 7.3: Hydrographs for Mokelumne River reflecting the four year study period and the preceding decade (inset box) for context. The thick black line represents the flows experienced at the study site with the Camanche Dam release. The gray line represents the hydrograph at the Mokelumne Hill gauge near Highway 49 and upstream of both Camanche and Pardee reservoirs (reasonable proxy for natural flow regime). The seven analysis intervals are labeled as TS1 through TS7 (time step) and are defined by the dates of the topographic surveys. The blue shaded time steps indicate the period when the PHR projects were constructed. The pink shaded areas represent the spawning seasons.

7.3 Application of Morphological Method and DoD Uncertainty Analysis

Seven DEMs were used to apply the morphological method and DoD Uncertainty Analysis (Figure 7.4). These DEMs were all derived at resolutions of 25 cm from the point data used for a 2D hydrodynamic model mesh construction under SHIRA. A pathway 4 DoD analysis was conducted using the DoD Uncertainty software developed in Chapter 4. Figure 7.5 shows all seven DoDs for direct inter-comparison. Their respective ECDs are shown in the right hand column of Figure 7.6 (the left-hand column shows a pathway 3 DoD analysis for comparison). As the spatial extent of the surveys varied from year to year, different DoD analysis extents of SHR projects, and the other is the subsequent adjustment of those gravels post-placement due to various processes (Merz et al. 2006).

13The original DEMs and the derived DoDs can be found in Appendix G.4 for all six analysis periods (TS1-TS7). Details on the topographic surveys and methods used to derive the DEMs and DoDs can be found there as well.
were used. For TS1, TS2 and TS3, an analysis extent covering the 2003 and 2004 SHR projects was used. For TS5 and TS6, an analysis extent covering the 2005 SHR project was used. For TS7, an analysis extent covering the 2006 SHR project was used.

7.4 Interpreting As-Built Surveys

In this section three types of masks are used to address three simple questions regarding the effectiveness of construction that arise in the SHR process. In the simplest sense, SHR here is about placing gravel in a river to improve spawning habitat. This is fundamentally a geomorphological change brought about by an anthropogenic process (i.e. a front end loader dumping gravel in the channel; see Figures 1.1 and 7.18). As Merz et al. (2006, Figure 1) showed for four other earlier projects on the Mokelumne River, there are many potential sinks for the purchased gravels, which are artifacts of the construction process (e.g. loss in staging). Thus, not all of the purchased gravel is placed in the channel in exactly the configuration suggested by the best intentioned design. As stated in the introduction, the questions requiring further consideration for each of the four SHR projects (TS1, TS3, TS5 and TS7) are:

1. What is the total volume of gravel that was placed? (§ 7.4.1)
2. How much gravel was used to produce what types of morphological units or habitat? (§ 7.4.2)
3. How much gravel was used to produce what quality of habitat? (§ 7.4.3)

Table 7.2 highlights the availability of masks for each timestep. An expert based geomorphological interpretation mask14, as suggested in § 5.2.1.3, to address the first question; a morphological unit mask is used, as suggested in § 5.2.1.1, is used to address the second question; and a mask based on an estimate of spawning habitat quality derived from a 2D CFD simulation, as suggested in § 5.2.1.4, is used to address the third question. These are presented in order in the next three sub-sections. In the first sub-section, the backgrounds and design goals for each project are also elaborated.

7.4.1 What is the total volume of gravel that was placed?

This question arises from the fact that discrepancies typically exist between the design volume, DoD predicted volumes and actual placed volume of gravel in PHR projects (Merz et al. 2006, Sawyer et al. Submitted). A related question is whether or not all the DoD predicted changes are due to PHR construction? The answer to this question depends on the extent of the survey and the analysis extent of the DoD. If the survey and analysis extent boundaries were

14Similar to that used in § 6.6.3 for Sulphur Creek.
Figure 7.4: DEMs used in DoD Analysis. A) 2006 Post Project; B) 2006 Pre Project; C) 2005 Post Project; D) 2004 Post Project; E) 2004 Pre Project; F) 2003 Post Project; and G) 2003 Pre Project. Flow is from right to left.
Figure 7.5: Thresholded DoDs for the six analysis periods. DoDs were thresholded using a Pathway 4 analysis and 95% confidence interval (see Chapter 4 for explanation). The large contiguous blue areas in TS1, TS3, TS5 and TS7 are the placed gravel fills from the SHR projects. Hillshades derived from the more recent DEM in each time step are shown in the background for context. Flow is from right to left.
**Figure 7.6:** Elevation change distributions for Pathway 3 (left hand side) and Pathway 4 (right hand side) thresholded DoDs for the seven analysis periods. DoDs were thresholded using a Pathway 4 analysis and 95% confidence interval (see Chapter 4 for explanation). The progression is from most recent (top) to oldest (bottom) down the page: A and B correspond to TS7; C and D to TS6; E and F to TS5; G and H to TS4; I and J to TS3; K and L to TS2; and finally M and N to TS1. *TS4 does not technically exist (see Appendix G.4.4 for explanation).
specifically clipped to the boundaries of the project, then if one was confident that all the DoD predicted changes were real, the DoD would be a reliable estimate of the total volume of gravel placed. However, an unthresholded DoD is not necessarily a reliable estimate of the total volume of gravel placed; hence, the need for a DoD uncertainty analysis (i.e. § 7.3). If by contrast the survey and analysis extents extended beyond the SHR gravel placement boundaries, then the DoD has the potential of reflecting changes (real or erroneous) that took place outside the placement area. It may seem reasonable to assume, under conditions of low flows and only a limited time window between the pre-project survey and post-project survey (e.g. TS1, TS3 and TS7), that the only changes that could take place are those from the placement of gravel. However, there are a number of plausible explanations of other changes (e.g. SHR induced erosion, fluvial deposition of project gravels placed in project area but transported hydraulically downstream of project boundaries).

In this section, the best estimate of the total volume of gravel placed during SHR is calculated by accounting for unreliability uncertainties in the DoD (i.e. thresholding DoD under pathway 4) and using a mask defined by the actual project placement boundaries in the field to eliminate the possibility of changes outside the placement boundaries being erroneously included. However, to make sure that the other DoD calculated changes should not be included in the total volume of gravel placed, an informed geomorphological interpretation of these changes is necessary. As in § 6.6.3, an expert geomorphological interpretation based on a mix of field evidence, survey notes, and the DEMs and derived surface are used to interpret the DoD. The geomorphological categories in the classification used on the Mokelumne were tailored to the observed changes and included:

- **SHR Placed Gravel**: Areas where gravel was placed with a front-end loader as part of a SHR project (the key category of interest for answering this section’s question)
- **Fluvial Deposition**: Areas where natural fluvial deposition occurred.
- **SHR Induced Erosion**: Areas that experienced erosion during construction as a result of altered hydraulics and morphology from SHR construction (not by design or by grading)
- **SHR Grading (cut)**: Areas that were specifically graded with the front end loader as part of SHR construction to achieve design grades.

Table 7.2: Use of four mask types in analysing DoDs from each time step. Where a ✓ is shown, the mask type derived from that TS was used. Where NA is shown, data to produce the mask type was not available.

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Description</th>
<th>GI</th>
<th>MU</th>
<th>GHSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>2003 As-Built</td>
<td>✓</td>
<td>✓</td>
<td>NA</td>
</tr>
<tr>
<td>TS3</td>
<td>2004 As-Built</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TS5</td>
<td>2005 As-Built</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TS7</td>
<td>2006 As-Built</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
• *Changes to SHR Placed Gravel*: Changes to areas where gravel was previously placed as part of SHR.

• *Fluvial Erosion*: Areas that experienced natural fluvial erosion.

• *Questionable Change*: Areas where no field evidence for change was present and/or where suspect interpolation errors exist.

• *Placed Boulder*: The footprint of placed boulders (erosion indicates that boulders are sinking, deposition indicates they are either buried or raising).

• *Not Resurveyed*: Areas where both DEMs in a DoD were derived from the same survey data.

• *SHR Placed Pea Gravel*: Areas where pea gravel (as opposed to medium to coarse gravels) were placed as part of the 2005 SHR project

Next the four SHR projects will be worked through in order and a summary presented at the end of this sub-section.

### 7.4.1.1 TS1: 2003 As Built

The 2003 project was designed by Elkins *et al.* (2007) as part of the four year ‘slope creation’ design. This project consisted of placing a design volume of 2020 m$^3$ of gravel at the upstream-most SHR site in the c. 510 m long study reach (Table 7.3). The boundaries of the SHR Placed Gravel extent are delineated with a black polygon in Figure 7.7 (light blue area in A). Applying this mask revealed that only 1500 m$^3$ of the 2020.4 m$^3$ design volume was actually placed in the channel (Figure 7.8).\(^{15}\) Although the SHR Placed Gravel mask accounts for only 43% of the surface area in Figure 7.7A, it accounts for over 99% of the volume of deposition and 96.8% of the total volumetric changes. A very minor extent of erosion (4.9 m$^3$) was induced by the construction process and minor amount of grading (16.6 m$^3$) and/or compaction from the front-end loader tracks was recorded.

In Figure 7.7A, roughly 49.7% of the analysis area was not resurveyed following construction (yellow shaded area in Figure 7.7A), but the DoD suggests a very low magnitude of erosion across this entire area. At 6.6 m$^3$ over such a large area, this volume is essentially negligible. Upon closer inspection of the raw point data used for each DEM, the difference is due to a minor rounding error with different numbers of significant figures ($10^{-4}$ versus $10^{-6}$ m) being saved in each of the raw point files. In practise, such a rounding error\(^{16}\) could be easily avoided or corrected by reformatting the raw input point data. However, it is left here to highlight the utility of the masking approach for easily filtering out erroneous data without

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\(^{15}\)See Merz *et al.* (2006, Figure 1) for a discussion of sinks and sources for gravel purchased for SHR projects. It is quite typical for the final placed volume to be significantly less than the design volume.

\(^{16}\)Refer to § 2.2.1 for difference between uncertainty and an error. This is an error because the true *unchanged* value is actually known.
having to redo the entire analysis. Initially, such errors might not be obvious, but the DEM uncertainty analysis and simple inspection of the plausibility of the results can highlight such problems. Reassuringly, Figure 7.8 demonstrates that in this case the error represents a negligible proportion (<0.5%) of the total budget from the elevation change distribution in Figure 7.6B.

The geomorphological interpretation of TS1 is useful, but not particularly interesting from a geomorphological perspective because there is virtually no geomorphological change due to fluvial processes. Instead, a new assemblage of geomorphic units has been put together through the artificial placement of spawning gravels. These changes will be discussed in §7.4.2.

7.4.1.2 TS3: 2004 As Built

As described in Elkins et al. (2007), the 2004 project was the second phase in what was initially a two year slope-creation design SHR project. The goal of the project was to redistribute the slope created by the 2003 project upstream to improve the habitat at the next pool-riffle unit downstream (raising the riffle crest by roughly 0.5 metres). As Figure 7.9 indicates, this included roughly equal placement of gravel in both the 2003 and 2004 project. Upon applying the SHR Placed Gravel mask to the DoD, the ECD in the upper left corner of Figure 7.10 shows a dual peaked depositional ECD with a peak at 35-40 cm and a second peak at 65-75 cm of fill. This analysis suggests that the total volume of gravel placed in both the 2003 project area and 2004 project areas in 2004 was 1735.8 m$^3$.

\footnote{Under SHIRA adaptive management, this later turned into a five year project (four of which are reported here).}
Chapter 7: The Mokelumne River

No Fluvial Deposition in this TS
No Changes to SHR
Placed Gravel in this TS
No Placed Boulders in this TS
No SHR Placed Gravel in this TS
No SHR Grading in this TS
No Questionable Changes in this TS
No SHR Induced Erosion in this TS
No Fluvial Scour in this TS
No Not Surveyed Areas in this TS

Figure 7.8: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2003 Project (TS1).
A second tier mask was produced to segregate the SHR Placed Gravel area into its 2003 and 2004 components. The resulting ECDs are shown in the centre-left (2003) and bottom-left (2004) in Figure 7.10. These reveal that 52.8% of the total placed gravel was placed in the 2003 site, with the rest in the 2004 site. Additionally, the second ECD peak is primarily the result of the filling of the pool upstream of the 2003 site to expand the riffle, whereas the 2004 ECD contributes more to the first ECD peak.

Modest amounts of secondary processes were also inferred from the DoD and the application of their masks constitute the rest of the ECDs in Figure 7.10. There was roughly an order of magnitude more natural fluvial scour (90.5 m$^3$) than fluvial deposition (8.3 m$^3$) and this is likely due to the moderately elevated flows during the gap between the pre-project survey and construction. By contrast, roughly a third less (60.5 m$^3$) erosion was deemed to be SHR induced (from altered hydraulics associated with construction), but not due to direct modification. A similar amount (58.2 m$^3$) of cut was recorded and attributed to very shallow grading of the 2003 site riffle crest, to accommodate the extension of the riffle crest upstream and produce hydraulic conditions in accordance with the 2004 design. This was achieved by the front end loader using the backside of its bucket and reversing, skimming a shallow depth of gravel off the crest. Interestingly, the ECD demonstrates this shallow grading nicely with its pronounced peak at 15 to 20 cm of cut and a maximum cut of less than 45 cm. Even smaller amounts of questionable changes around the periphery that were likely due to TIN artifacts along the banks in heavily vegetated areas, were filtered out (total volume of 79.6 m$^3$; only accounting for 3.8% of the total volume of thresholded DoD recorded changes).
Figure 7.10: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2004 Project (TS3). See text for explanation. Note that the vertical scale on the SHR Placed Gravel ECD is different than the other ECDs.
7.4.1.3 TS5: 2005 As Built

Nine designs were considered under SHIRA for the 2005 site (p. comm Pasternack, 2007). Design objectives included a) increasing the lateral variability, b) filling a former mining hole in the channel, possibly leaving a pool of more appropriate depth, c) increasing flow complexity and habitat heterogeneity, and d) preserving the existing thalweg dictated by channel confinement. No new elevation head was created as part of this project, instead a redistribution of the head created in 2003\(^\text{18}\) was relied on. As Figure 7.11 indicates (with black outlined polygons), the vast majority of the SHR placed gravel was in the 2005 project area, but there were small zones of shallow gravel replenishment in both the 2004 and 2003 areas.

Applying the SHR placement boundary mask, the ECD in the upper left corner of Figure 7.12 shows that roughly 2017.9 m\(^3\) of gravel was placed in 2005. Applying site specific (by year) masks to the SHR Placed Gravel Mask, ECDs can be calculated to show the proportion of placed gravel for the 2003, 2004 and 2005 site respectively (Figure 7.13). From this, 1827.6 m\(^3\) (90.3\%) was used to create new features in the 2005 site and only 4.8\% and 4.9\% were used in the 2003 and 2004 sites, respectively. Both the 2003 and 2004 site ECDs show peaks of very shallow fill (around 20-30 cm), reflecting the fact these sites were already built up in previous years and were merely being replenished. By contrast, the 2005 site ECD has a massive pronounced peak at about 1.6 m of fill reflecting the large volume of gravel needed

\(^{18}\)This head was set by building up the uppermost riffle crest at the top of the reach.
to fill in the deep mining hole.

Returning to the other ECDs in Figure 7.12, there are a variety of DoD calculated changes that were not from placed gravel and which collectively account for over 37% of the total volume of change. Over 32% (12% of total) of these are complete artifacts of TIN construction with low point density or areas that were not actually resurveyed and therefore changes can not be assessed (yellow area in Figure 7.11A; bottom left ECD in Figure 7.13). Another 13.5% (5% of total) of these are areas of questionable change around the margins\(^{19}\) (orange area in Figure 7.11A; bottom right ECD in Figure 7.13). Thus, roughly 17% of the volumetric budget can be discarded.

The remaining 54.5% (20% of total change) of these non placed gravel changes deserve some mention as they constitute a much larger percentage of the total volume of change than in the other as-built survey timesteps. About 80 m\(^3\) of this is interpreted to be SHR induced erosion occurring during construction. There was no pre project survey that summer due to sustained high flow releases from the dam, the DoD is calculated with respect to the 2004 post project DEM.\(^{20}\) Accordingly, changes outside the SHR placement areas could have occurred at any point over the past year. Thus the majority of these changes are most likely due to natural fluvial processes associated with high flow releases\(^{21}\) through the spring and summer (see hydrograph in Figure 7.3). The fluvial scour ECD (middle right ECD in Figure 7.13) reflects a mix of shallow scour of the riffle downstream at Murphy Creek and deep scour at the riffle head of the 2004 site reflecting expansion of the pool-exit slope into the riffle. Within the 2003 and 2004 site areas (pink area in Figure 7.11A), a fair amount (352 m\(^3\)) of erosion and some minor deposition (29.4 m\(^3\)) was recorded (indicated in middle ECD in Figure 7.12).

7.4.1.4 TS7: 2006 As Built

The final and largest of the four SHR projects discussed in this chapter was built in 2006. The 2006 project objectives were: a) to raise the bed elevation in an old mining hole between the 2005 project site and the Murphy Creek confluence to create more suitable pool habitat for native species, b) to continue the effort to redistribute the slope and elevation head created in 2003 further downstream, and c) to increase the amount and quality of spawning habitat. In Figure 7.14 there are three primary focal points for the placement of gravel: 1) the filling of a deep gravel mining hole upstream of Murphy Creek, 2) the extension of two small riffles into one another downstream of Murphy Creek, and 3) the extension of the slope downstream into a lateral bar. The upper left ECD in Figure 7.15 shows that 2971.8 m\(^3\) of gravel was placed to accomplish this. Of that, 89.6% was used in building new habitat at the 2006 site, largely consumed by creating the changes described above. Similar to previous years, much

\(^{19}\)As the lower Mokelumne in this area has artificially stable (due to flow regime) banks heavily armoured with alders, there is virtually no field evidence of bank erosion where most of these questionable areas are shown.

\(^{20}\)See § G.4.5 for full explanation.

\(^{21}\)Note the circa 84 cm3 flows were the highest flows in the decade leading up to 2005 and were capable of producing limited transport (Pasternack et al. 2006).
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No Fluvial Deposition in this TS
No Changes to SHR
Placed Gravel in this TS
No Placed Boulders in this TS
No SHR Placed Gravel in this TS
No SHR Grading in this TS
No Questionable Changes in this TS
No SHR Induced Erosion in this TS
No Fluvial Scour in this TS
No Not Surveyed Areas in this TS

Figure 7.12: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2005 Project (TS5).
more modest percentages at low fill depths (4.3%, 1.3% and 4.8% for 2005, 2004 and 2003 sites respectively) were used to top up the previous sites (Figure 7.16).

Returning to the secondary geomorphological interpretations associated with the classification masks in Figure 7.14A and the remaining ECDs in Figure 7.15, these other calculated changes accounted for 18.4% of the total volumetric changes. Of these, 39% fall under questionable changes in areas where either there was no field evidence of change or in which poor TIN interpolation is producing suspect patterns. These were discarded from consideration. During TS7, there were no appreciable flows but there were coherent zones of fluvial deposition (176.5 m$^3$) that roughly balanced with coherent patterns of fluvial scour further upstream on the point bar and the SHR induced erosion around the edge of the sites (141.4 m$^3$ and 39.6 m$^3$, respectively) on the point bar downstream of the project. These changes could plausibly be attributed to altered hydraulics over relatively short durations during construction. The fraction that doesn’t balance is largely explained by the SHR induced erosion at the top of the
reach in the 2003 site. There is a small volume (37.3 m³) of SHR-grading that was performed at the riffle crest to match design criteria and produce the desired hydraulic conditions.

### 7.4.1.5 Overall Observations of Total Volume of Gravel Placed

Figure 7.17 and Table 7.3 show directly the best estimates of the total volume of gravel placed for each project, amounting to a total of 8226.3 m³. Figure 7.17 shows a gradual increase from year to year in the scope of the projects, with increasing volumes, and a willingness to venture into deeper water. In earlier projects on the Mokelumne, there was more concern about the efficiency of gravel placement, in terms of creating better spawning habitat. For example, it is more economical to convert a glide into a riffle then converting a deep mining pit into a riffle (or even raising a pit to a pool of more natural depth). Thus, the broader slope creation design philosophy and staged implementation to redistribute that slope in a manner most effective for geomorphological functioning and provision of suitable spawning habitat came to dominate over short-term economic efficiency of the designs.

Table 7.3 is probably the most direct comparison that can be used to address the secondary question of whether or not all the DoD predicted changes are due to PHR construction.

The ’GM Calc’ (geomorphological mask calculation) column in Table 7.3 always show a lower value than the total DoD predicted changes. This is typically between 1% and 5% lower than the pathway 4 thresholded value. In the case of the UC Davis calculation (UCD Calc

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22Question posed in § 7.4.1.

232005 (TS5) is an anomaly at 28%, due to the lack of a pre-project survey.
Figure 7.15: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2006 Project (TS7).
Column 3 in Table 7.3, the gross calculation (Gross Calc - column 4 in Table 7.3) and the pathway 4 analysis (PW4 Calc - column 5 in Table 7.3), all three were taken from the total deposition volume recorded in their respective DoDs. The first thing to highlight is the difference between the UC Davis calculation and gross calculation. The gross calculation is the unthresholded DoD. The UC Davis calculation is also an unthresholded DoD, but was calculated independently using slightly different survey extents as well as being derived from a different TIN and DEM surfaces. As such there is no consistent relationship between the two. Both the 2003 and 2004 comparisons are within 5% of each other, but the 2005 has a 23% discrepancy. Thus, two independent calculations are of the same approximate magnitude, but it is difficult to assess how reliable either estimate is as an approximation of the actual fill volume from PHR construction.

The pathway 4 analysis (PW4 Calc) of the DoD presented in § 7.3 represents a thresholding of the gross DoD calculation and shows a consistently smaller volume (between 2.6% and 7.3% 24A pathway 1 analysis from Chapter 4, which is a straight DoD with no accounting for uncertainty.
### Table 7.3: Comparison of design versus calculated fill volumes for each SHR project. UCD Calc refers to the original calculation from UC Davis (p. comm. Greg Pasternack). Gross Calculated is the total unthresholded fill volume. PW4 Calc is the thresholded fill volume from a Pathway 4 analysis. GM Calc refers to the geomorphological mask a field-based mask of the actual SHR construction extents with a PW4 Analysis.

<table>
<thead>
<tr>
<th>SHR Year</th>
<th>Design (m$^3$)</th>
<th>UCD Calc (m$^3$)</th>
<th>Gross Calc (m$^3$)</th>
<th>PW4 Calc (m$^3$)</th>
<th>GM Calc (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003 (TS1)</td>
<td>2020.4</td>
<td>1517.0</td>
<td>1556.5</td>
<td>1514.9</td>
<td><strong>1500.8</strong></td>
</tr>
<tr>
<td>2004 (TS3)</td>
<td>1667.4</td>
<td>2005.0</td>
<td>1924.5</td>
<td>1805.3</td>
<td><strong>1735.8</strong></td>
</tr>
<tr>
<td>2005 (TS5)</td>
<td>1950.1</td>
<td>2359.0</td>
<td>3042.5</td>
<td>2819.1</td>
<td><strong>2017.9</strong></td>
</tr>
<tr>
<td>2006 (TS7)</td>
<td>3402.0</td>
<td>NA</td>
<td>3333.6</td>
<td>3138.2</td>
<td><strong>2971.8</strong></td>
</tr>
<tr>
<td>TOTAL</td>
<td>9039.8</td>
<td>5881.0</td>
<td>9857.1</td>
<td>9277.5</td>
<td><strong>8226.3</strong></td>
</tr>
</tbody>
</table>

This estimate of deposition represents the best estimate of the total deposition reliably recorded by the DoD. The sixth column of table 7.3 summarises the use of a geomorphological mask (GM Calc) based on the actual delineated boundaries in the field of the gravel placement extent.

One of the interesting tangential points that arose from these analyses was the presence of a minor, but coherent, erosional signal in the SHR areas. This erosional signal was inferred to be due to a process of SHR induced erosion\(^\text{25}\) induced over very short periods (e.g. seconds to hours) during the construction process itself (Figure 7.18). On the longer timescale of hours, during construction exceptionally steep water-surface slopes can be created by temporary morphologies (Figure 7.18B, C, D and E), which in turn dramatically alter hydraulics locally producing temporarily competent flows. Another mechanism, which occurs on the scale of seconds to minutes, are highly accentuated velocities and turbulent bursts associated simply with the rapid displacement of water in the wake of the front end loader navigating the site and when the loader drops its bucket (Figure 7.18F). Anecdotal evidence\(^\text{26}\) from the field certainly supports the plausibility of these inferred mechanisms and the spatial patterns of scour observed are also consistent with this (e.g. on the periphery of projects and in the thalwegs of pools where flows are concentrated anyway). In fact, the recording of the mechanisms with an erosional signature in the DoD is almost certainly conservative, with the final grading and placement of gravel compensating for intermediate erosion occurring within the core zones of gravel placement itself.

#### 7.4.2 How Much Gravel was used to Produce what Types of Morphological Units or Habitat?

From the perspective of monitoring PHR and restoration projects, another useful way of segregating the DoD budget for interpretation is in terms of the constructed morphological

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\(^{25}\)Will also be described in § 7.4.2.

\(^{26}\)See [http://shira.lawr.ucdavis.edu/moke_2004_archive_movie2.htm](http://shira.lawr.ucdavis.edu/moke_2004_archive_movie2.htm) for video showing visual evidence of these mechanisms.
features. Of the 1500 m$^3$, 1735 m$^3$, 2017 m$^3$ and 2971 m$^3$ of gravel placed in SHR projects in 2003, 2004, 2005 and 2006, respectively (Figure 7.17), it would be helpful to know how much of the gravel was used creating what types of habitat. This could highlight the relative cost of different components of SHR projects. For example, of the total volume of placed gravel in a PHR project, how much was used in building a riffle crest versus building a point bar? For each of the SHR projects, a geomorphic unit classification was performed showing what the final types of habitat were for each area. By using the geomorphological design as a mask, these questions can be answered directly. The geomorphological categories in the classification used on the Mokelumne were tailored to the constructed and existing morphologies and included:

- **Riffle Crest**: The actual constructed crest of the riffle (separated out from the rest of riffle as riffle crest construction can account for greater fill depths and this is the critical component in slope creation)
- **Riffle**: The riffles are one of the primary SHR features
- **Chute**: Shallow notches through bars and riffles for encouraging specific flow patterns
- **Lateral Bar**: Bank-attached bars
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Figure 7.18: Examples of altered hydraulics during construction process due to grading (A), temporary staging of gravel producing altered morphologies (B-E) and rapid displacement of water from the gravel ‘drop’ (F). Photos A-D are from the 2003 project, photo E is from the 2004 project and photo F is from the 2002 project (see Figure 7.1 for site map).
7.4.2.1 TS1: 2003 As Built

An SHR project is fundamentally designed to create a new assemblage of geomorphic units through the artificial placement of spawning gravels. Thus, in Figure 7.20B, the SHR Placed Gravel area in Figure 7.20A is sub-divided by a classification of the geomorphic units which were created. This allows one to assess how much gravel was used in creating each such feature. For example, from Figure 7.20 roughly 374 m$^3$ was used building the riffle crest; 826 m$^3$ building the rest of the large riffle; 41 m$^3$ building a smooth transition for the chute on river left; 130 m$^3$ on the lateral bars; and 99 m$^3$ building the central bar. Additionally, four large boulder clusters were placed for habitat heterogeneity (Elkins et al. 2007) equating to
roughly 6 m$^3$ of deposition; and 30 m$^3$ was used building a smoother transition into the pool habitat on river right. Each of these morphologies exhibit distinctive ECDs in Figure 7.20, which are largely a reflection of the underlying pre-project morphology and the amount of fill required to achieve the design morphologies. The only ECD showing a pronounced erosional signature is the lateral bar ECD with roughly 18 m$^3$ of low magnitude erosion ranging from 0 to 55 cm. This ECD is virtually identical to the SHR grading ECD in Figure 7.8 and is a reflection of very minor grading associated with carving a peripheral chute on river left to prevent excessive scour from the increased elevation head between the 2003 and 2004 project construction (Elkins et al. 2007).

7.4.2.2 TS3: 2004 As Built

Figure 7.22A shows the spatial arrangement of geomorphic units following the 2004 project construction in relationship to the TS3 DoD in Figure 7.22B for the SHR Placed Gravel area. Again, the riffle and riffle crest dominates the volumetric consumption of gravel, together comprising 74% of the 1735 m$^3$ of placed gravel. Interestingly, they also comprise 45% of the more minor 177.3 m$^3$ of erosion recorded within the SHR project area (largely made up of the SHR Induced Erosion and SHR Grading reported in Figure 7.10). Roughly 52% (92.4 m$^3$) of the total volume of calculated erosion was recorded in the pool area (particularly in the thalweg), suggesting that altered hydraulics during construction was concentrating high energy flows locally in the pool and promoting erosion. Roughly 178.5 m$^3$ of gravel deposition was reported on the pool-exit slope downstream of the two pools experiencing scour, and was likely a combination of placed gravel and gravel depositing having been eroded from its own pool upstream. A very minor amount of gravel (35.7 m$^3$) was used in accentuating and topping up the central bar in the 2003 site upstream. Finally 169.3 m$^3$ of gravel was used building up existing lateral bars to force pool confinement in both the 2003 and 2004 sites.

7.4.2.3 TS5: 2005 As Built

Figure 7.23 shows the relatively modest spatial extent of the 2005 project, which extended the 2004 project downstream with two new lateral bars and an elevated central thalweg. However, as Figure 7.17 showed, it did this with more gravel as the pre-existing morphology was so deep (a legacy of gravel mining). In contrast to TS1 and TS3, the riffle and riffle crests were not the dominant consumer of gravel in this project, constituting a combined total of only 10% of the placed gravel volume. In contrast, the majority (56% or 1262.5 m$^3$) was used constructing two large lateral bars, which were logical extensions of the 2004 project. The lateral bar ECDs (centre-left ECD in Figure 7.24) exhibit a strong peak at about 160

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29 See also description in § 7.4.1.3.
Figure 7.20: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2003 Project (TS1).
to 175 cm fill depth, reflecting the large volume of gravel needed to bring the bed levels up on the channel margins. The construction of the elevated chute as the new channel thalweg had a similar ECD (top-right ECD in Figure 7.24), reflecting roughly 30% of the total volume of placed gravel. As in previous years, the pool had a minor but primarily erosional ECD signature (bottom-left ECD in Figure 7.24) that in this case could be reflecting both erosion due to construction (as discussed previously) and erosion due to natural fluvial processes over the 2004-2005 season.\textsuperscript{30} The pool exit slope again showed a mix of shallow deposition and shallow scour, but only amounted to 3.7% of the total volume of change.

7.4.2.4 TS7: 2006 As Built

As the most ambitious of the four SHR projects in terms of spatial extent and volume of gravel placed, the 2006 project (TS7) represents the most varied mix of morphologies (Figure 7.25). As such, no single morphological unit dominates in terms of gravel consumption, with the riffle, chute, lateral bar and point bar all within 13% of each other at 23%, 15%, 22% and 28% of the total volume of placed gravel (2971.8 m$^3$), respectively. The riffle and lateral bar ECDs (centre-left and centre top ECDs in Figure 7.26) both exhibit reasonably uniform ECDs over a broad range of fill depths up to roughly 1.8 m. The chute ECD has a more exponentially shaped distribution that grows towards a fill depth peak of about 1.5 m and then drops to nothing by about 1.7 m. The point bar ECD has the most symmetrically shaped ECD, with a peak at approximately 80 to 85 cm.

\textsuperscript{30}Recall there was no 2005 pre project survey to difference against.
Figure 7.22: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2004 Project (TS1).
7.4.2.5 Summary of Gravel Consumption by Geomorphic Units

Using the geomorphic units as masks of the DoD across all four SHR projects, resolves directly the question of how much gravel is consumed by different geomorphic units. Not surprisingly, the morphological units that dominate across all four years are the morphological units known to provide the best spawning habitat. This is by design. Table 7.4 shows a complete summary of the results presented for each project in the preceding subsections. Overall, 41% of the volume placed over the four years was used in constructing riffles (riffles + riffle crests). The next most consumptive units were lateral bars (26%), chutes (14%), and point bars (10%). In addition, the ECDs of all these units show some interesting patterns, which help highlight differences between designs and the pre-project morphologies.

31 Note that the slight discrepancy between total volumes in Table 7.3 and Table 7.4 is a reflection of slightly different analysis extents, largely because of the inclusion of pool morphologies in this analysis.
Figure 7.24: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2005 Project (TS5).
Figure 7.25: Morphological unit mask (A) and DoD (B) associated with the As-Built 2006 Project (TS7). Hillshade from 2006 Post Project DEM shown in background for context. Flow is from right to left.

Table 7.4: Segregation of fill volumes for each SHR project by morphological unit masks, to show the relative consumption of gravel in constructing each type of unit.
Figure 7.26: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2006 Project (TS7).
7.4.3 How Much Gravel was used to Produce what Quality of Habitat?

To address the question of habitat quality, spawning habitat suitability simulations of the post project conditions are compared to the DoD changes that describe the construction process leading to the as-built condition. This was done to investigate whether there is any correlation between how much gravel was used in relation to the quality of habitat it produces. By using the habitat suitability classes from the habitat suitability simulation as a mask for the DoD, ECDs were derived to address this question directly.

The habitat suitability model used is based off of depth and velocity habitat suitability curves for Fall-Run chinook from the Mokelumne River as reported in Elkins et al. (2007, p.6, Figure 5) and Wheaton (2003). Those curves are modelled using high-order polynomial equations to calculate suitability based on velocity and depth separately. The two univariate suitability measures are then combined using a weighted sum (equal weighting of 0.5) to produce a global habitat suitability index (GHSI) that ranges from zero to one, with one being the highest
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Habitat quality is calculated on a node-by-node basis using velocity and depth predictions from a 2D hydraulic model simulation at a given flow (Leclerc et al. 1995, Crowder & Diplas 2000, Wheaton et al. 2004d, e.g.). The model simulations were all performed by members of the UC Davis Watershed Hydrology and Geomorphology Lab under SHIRA implementation (Elkins et al. 2007, e.g. for 2003 and 2004). For the Mokelumne, with over 14 years of complete redd surveys and seven years of 2D hydraulic model simulations at spawning flows, there is a high degree of confidence in the predictive capability of the GHSI model. That is, the documented occurrence of spawning on the Mokelumne is extremely well correlated to the model predicted high and medium quality habitat suitability classes in the GHSI with only very rare utilisation of predicted low and poor quality habitat areas, and virtually no utilisation of GHSI-predicted non-habitat (Pasternack et al. 2004, Elkins et al. 2007, Wheaton et al. 2004d). Where spawning is tending toward lower quality classes, it has always been explainable on the Mokelumne in terms of a close proximity of the redd to habitat heterogeneity elements like shear zone refugia or structural cover (Wheaton et al. 2004e).

GHSI simulations were only available for the 2004, 2005 and 2006 as-built surveys. The GHSI masks were clipped to match the extent of SHR placed gravel for that year and this is indicated by the non-grayed out area in Figures 7.27G, 7.28G, and 7.29G for 2004, 2005 and 2006 respectively. Between the three Non-Habitat ECDs (Figures 7.27A, 7.28A, and 7.29A), they all show bimodal distributions with a strong peak of low magnitude erosion (c. 15 cm) and a more subdued peak of low magnitude deposition (c. 15 cm). By contrast, all of the other ECDs for all three periods (Figures 7.27B-F, 7.28B-F, and 7.29B-F) show entirely depositional distributions representative of the mask indicating that these are in the SHR placement zone.

In all three periods, the ECDs for the non-habitat and poor quality habitat areas are dwarfed by their low, medium and high quality habitat counter-parts (Figures 7.27B & C versus D, E & F, 7.28B & C versus D, E & F, and 7.29B & C versus D, E & F). This is another way of saying that the projects used most of their gravel making higher quality habitat as opposed to using it on poor quality habitat. This is a good measure of project performance, but hardly surprising given the detailed, hypothesis-testing driven design approach used under SHIRA (Wheaton et al. 2004d). The iterative design process hones in on a final design that provides the best compromise between providing high quality habitat, optimising the efficiency of gravel used, and a hopefully geomorphologically functional and/or sustainable design.

Table 7.5 summarises these results in terms of volume of gravel placed to create each type of habitat quality. Only 3.4% of the total volume of gravel placed over the three years (2004-2006) was used to create poor quality habitat or non-spawning habitat. Roughly 37.9% was used creating low quality spawning habitat as defined by GHSI. Approximately 38.2% was used creating low quality habitat as defined by GHSI. Approximately 38.2% was used creating
Figure 7.28: Elevation change distributions (A-F) corresponding to masks of the DoD from GHSI-predicted spawning habitat suitability classes (G) for TS5 (2005).

<table>
<thead>
<tr>
<th>Habitat Quality</th>
<th>Volume (m$^3$) by Project Year</th>
<th>Total Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2004</td>
<td>2005</td>
</tr>
<tr>
<td>Outside SHR Placement Area</td>
<td>69.5</td>
<td>402.6</td>
</tr>
<tr>
<td>Non Habitat</td>
<td>61.6</td>
<td>14.6</td>
</tr>
<tr>
<td>Very Poor Quality</td>
<td>28.9</td>
<td>30.5</td>
</tr>
<tr>
<td>Low Quality</td>
<td>597.4</td>
<td>408.8</td>
</tr>
<tr>
<td>Medium Quality</td>
<td>478.0</td>
<td>1048.2</td>
</tr>
<tr>
<td>High Quality</td>
<td>569.9</td>
<td>685.2</td>
</tr>
<tr>
<td>Total Volume Placed (m$^3$)$\dagger$</td>
<td>1735.7</td>
<td>2187.3</td>
</tr>
</tbody>
</table>

Table 7.5: Segregation of fill volumes for each SHR project by the quality of spawning habitat (as defined by GHSI) it was used to create, showing the relative consumption of gravel constructing each type of unit. $\dagger$ Note that the total volume is calculated by summing just the portion of recorded deposition in the SHR placement area.
Figure 7.29: Elevation change distributions (A-F) corresponding to masks of the DoD from GHSI-predicted spawning habitat suitability classes (G) for TS7 (2006).
Table 7.6: Use of three mask types in analysing DoDs from each time step. Where a ✓ is shown, the mask type derived from that TS was used. Where NA is shown, data to produce the mask type was not available. Where CoD is shown, a classification of difference between the two surveys in the time step was used. KEY: GI - Geomorphological Interpretation; GHSI - Global Habitat Suitability Index; Redds - Redd surveys.

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Description</th>
<th>GI</th>
<th>GHSI</th>
<th>Redds</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS2</td>
<td>2004 Pre Project (1 Year after 2003 Project)</td>
<td>✓</td>
<td>NA</td>
<td>✓</td>
</tr>
<tr>
<td>TS6</td>
<td>2006 Pre Project (1 Year after 2005 Project)</td>
<td>✓</td>
<td>CoD</td>
<td>✓</td>
</tr>
</tbody>
</table>

medium quality habitat and only 20.5% was used creating the highest quality habitats.

7.5 Interpreting Monitoring Surveys

In restoration, a common problem is interpreting changes to a restored reach through time (Merz et al. 2006, Wohl et al. 2005, Gillilan et al. 2005). Although there are four years of monitoring data presented here, because the SHR was a multi-year effort it does not represent the response of the system to a single restoration intervention and its subsequent annual adjustment over the following years. This was a five-year project that iteratively improved the same reach of river. As such the monitoring surveys here really only represent the response to the system after a single year. There are only two timesteps (TS2 and TS6), which meet this ‘post-project appraisal / monitoring’ criteria.35 For these two annual post project appraisal surveys, the following questions are of interest:

1. What are the geomorphological interpretations of the DoD predicted changes one wet season after construction? (§ 7.5.1)
2. What impact did the changes have on habitat quality? (§ 7.5.2)
3. What changes took place where salmon spawned? (§ 7.5.3)

The same types of masks used in § 7.4 will be used, but in addition redd surveys will be used as a mask to address the third question. Table 7.6 shows the availability of these masks for each time step.

7.5.1 What are the Geomorphological Interpretations?

Perhaps the most common restoration monitoring question is simply to interpret the geomorphological changes that took place to a project and attempt to attribute what mechanisms of structural cover for both resting and hiding from predation (Wheaton et al. 2004e). See also, § 7.5.2.

35TS4 would have, but does not exist (see § G.4.4).
change and/or what processes were responsible for these changes. The same classes used for this expert-based geomorphological interpretation which were used in § 7.4.1 will be used here, but some of the categories will not apply (e.g. the SHR gravel placement categories). TS2 and TS6 are a nice contrast here because TS2 represents a drought water-year subjected to a flat-lined flow regime with virtually no competent flows, whereas TS6 represents a very wet water-year in which the maximum controlled dam release from Camanche Reservoir (141.6 cumecs) was realised (see Figure 7.3).

7.5.1.1 TS2: 2003 Post Project to 2004 Pre Project

The year following the 2003 SHR Project placement only produced a peak discharge of 42.7 cumecs (Figure 7.3) and Elkins et al. (2007, p. 13) reported no measurable differences from the DoDs and predicted 'little to no intermittent or partial sediment transport' from modelling analyses. However, a closer look at the DoD in Figure 7.30C reveals the suggestion of some small magnitude changes and a couple of areas of larger, seemingly coherent, areas of deposition and scour within some of the pools. As the large portion of yellow in Figure 7.30A suggests, these seemingly coherent areas of change actually fall outside the area that was resurveyed and are therefore not real changes.\(^{36}\) In Figure 7.31, the majority (69%) of volumetric changes in the DoD are shown to be entirely artifacts of TIN interpolation (101.8 m\(^3\) of erroneous erosion and 330.3 m\(^3\) of erroneous deposition).

\(^{36}\)This is discussed in § G.4.4, whereby the DEM analysis extent was inherited by the CFD modelling domain, and did not necessarily always reflect the true extent of the topographic survey. In other words, areas that did not show evidence of change and were outside the SHR boundaries were not always resurveyed.
Figure 7.31: The elevation change distributions for masks associated with the geomorphological interpretation classification of the 2003 Post Project to 2004 Pre Project (TS2).
However, after this noise is filtered out, roughly 78.4 m$^3$ of erosion and 100.7 m$^3$ of deposition are shown to have taken place within the 2003 SHR project area (Figure 7.31). Despite the lack of any significant flow events, these small magnitude changes are certainly plausible. Merz et al. (2006, pp. 209-210) postulated that SHR placed gravels exhibit compaction or settling and some degree of gravitational sloughing (particularly around the project periphery where over steepened fill slopes may have resulted). The magnitude of DoD calculated erosion is in keeping with the magnitude of changes Merz et al. (2006) estimated theoretically for such mechanisms.

Gottesfeld et al. (2004) found that as a result of redd construction, salmonids can play a significant role both in mobilising quantities of bed material locally and, potentially more importantly, in breaking up the armour layer and subsequently lowering entrainment thresholds for subsequent floods. On the Mokelumne Merz et al. (2006, pp. 220) measured an average volume of 2.26 m$^3$ being excavated locally during redd construction.\footnote{Refer back to § 3.2.1 and Figure 3.3 for review of redd construction.} 73 redds were recorded within the 2003 project area in the Fall of 2003.\footnote{Note, changes produced by the 2003 fall run would correspond to those captured in TS2.} Using the Merz et al. (2006) estimate, this would equate to roughly 165 m$^3$ of potential erosion from redd construction. Thus, the combination of plausible mechanisms of change exceeds the actual measured magnitude of change.\footnote{Refer to § 7.5.3 to see how much change was actually measured in areas where redds were found.}

The slight (22.3 m$^3$) imbalance in favour of net aggradation within the 2003 SHR Project Area raises some questions. Given the lack of competent flows and the nature of the heavily armoured and sediment starved bed in the 200 m between the top of the project and Camanche Dam, it is highly unlikely that a) an upstream source of sediment would be mobilised to provide this net input; or b) that if sediment was mobilised that its step lengths would be long enough to transport it to within the project area. However, the overall magnitudes (c. 75-100 m$^3$) of material moving are certainly plausible in terms of the settling/compaction and gravitational sloughing mechanisms discussed above. The erosional fraction can be explained by redd construction, settling and/or sloughing mechanisms, and the very short step-lengths material would travel under such mechanisms can explain the depositional fraction. However, even with these mechanisms at work, one would expect a net balance or potentially a slight loss (i.e. net degradation) with losses out of the project area to downstream.\footnote{Unfortunately, because the deep pool areas downstream of the project were not resurveyed since the 2003 Pre Project, it is not possible for TS2 to infer this on the basis of changes in the downstream pools.} Instead the slight aggradation imbalance calculated might be explained in terms of low magnitude elevation changes that fall beneath the minimum level of detection ($min_{LoD}$) threshold and are discarded. This could be exacerbated slightly by a bias in that the $min_{LoD}$ is applied equally about zero, which may have a tendency to influence deposition values more than erosion values (Brasington et al. 2003).

Although it is difficult with the available data for TS2 to establish accurately what proportion of the changes to the SHR placed gravels are due to which mechanisms, it is relatively straightforward to calculate the magnitude of change in each of the morphological units. This is

\footnote{Refer back to § 3.2.1 and Figure 3.3 for review of redd construction.}
Figure 7.32: The elevation change distributions for masks associated with the SHR interpretation classification of the 2004 Pre Project (TS2).
achieved using the same morphological unit classification masks as were originally constructed and delineated in Figure 7.19B. The fate of those constructed morphological units over the course of their first year is explained by the ECDs in Figure 7.32. Roughly 75% of the total volumetric changes are occurring to the constructed riffle or riffle crest.

7.5.1.2 TS6: 2005 Post Project to 2006 Pre Project

The 2005-2006 season (TS6) is the best possible test of the maximum magnitude of event that the study reach is capable of responding to in its current form. Figure 7.1 shows the location of the study site in proximity to Camanche Reservoir. Camanche is only capable of releasing a maximum of 141.6 cumecs as a controlled release, and this is all that can physically be delivered to the study site (barring dam removal or failure). There is a spillway for uncontrolled releases (see again Figure 7.1), but it joins the Mokelumne well downstream of the study site. As shown in Figure 7.3, the 141.6 cumecs release was maintained for over a week as part of the spring snow melt. Although smaller controlled ‘pulse flow’ releases were released in 2003 and 2005, these 2006 flows were the first real geomorphological test in a high-flow setting of the SHIRA projects.

Figure 7.33A shows the geomorphological interpretation of the observed changes that took place in TS6, in relationship to the DoD (Figure 7.33B). Unlike TS2, the role of natural fluvial erosion and fluvial deposition are playing a larger role. Here the aim is to separate those changes that took place within the SHR project boundary (i.e. to get at the fate of placed gravel) from those changes which took place outside (e.g. fluvial erosion and
deposition). The overall ECD of change for this event can be found in Figure 7.6L. This ECD contrasts with all the others in that it shows a much more balanced bimodal distribution, with a prominent erosional fraction. The ECD signature of this water year is characteristic of a natural river: with a high depositional peak of low-magnitude deposition (i.e. broad sheets of deposition) and a more spread out and uniform erosional distribution, reflecting more spatially concentrated areas of erosion but spanning a greater range of scour depths. The magnitude of this ‘natural’ event pales in significance to the artificial SHR injection events, which are dominated by depositional ECDs (Figure 7.6). However, its 1000 m$^3$ of erosion and 810 m$^3$ of deposition are still very significant in the context of the heavily regulated Mokelumne flow regime. The question this subsection wishes to address is what fraction of that overall budget is due to what mechanisms of change?

Figure 7.34 shows the segregation of the budget into five ECDs based on the masks defined in Figure 7.33A. Table 7.7 summarises this information in tabular form and adds the areas. First, the questionable changes are discarded, which account for about 8% of the total volume of change. Outside the SHR area (primarily pools), fluvial scour outpaces fluvial deposition at 25% versus 14% of the total volume of change (i.e. pool maintenance is occurring). It is interesting to note that 47% of the total volume of erosion is taking place outside the SHR placement boundaries (44% inside the SHR boundaries). Within the SHR boundaries, 51% of the total volumetric changes are taking place and here deposition is slightly outpacing erosion (476.0 m$^3$ versus 445.3 m$^3$). Figure 7.35 shows the segregation of the TS6 budget by the morphological units defined in TS5 (Figure 7.11A). The ECDs show the phenomenon discussed previously of the riffles and bars generally growing and building, whereas the pools are being scoured out and maintained at high flows. In the context of the SHR, this is quite good because although the habitat is changing the riffles and bars are continuing to build as places of net deposition and the pools are being maintained. This is the first real test of the pool-maintenance design hypotheses proposed in Wheaton et al. (2004d). Another test is of the Merz et al. (2006) observation that boulders were tending to lower themselves through time after placement. Although the placed boulders occupy a negligible fraction of the budget here, they are mentioned in passing as they are almost entirely recording degradation (Table 7.7), which is supportive of the boulder sinking mechanism Merz et al. (2006) reported.

### 7.5.2 What Impact did the Changes that Took Place have on Habitat Quality?

To address this question, the classification of difference technique proposed in § 5.2.1.2 is used. The two classifications employed are the GHSI spawning habitat suitability predictions from the 2005 Post Project to the 2006 Pre Project (Figure 7.36A & B). In each, six categories were considered:

1. Outside 2005 SHR Placement Area
2. Non Spawning Habitat
No SHR Induced Erosion in this TS

No SHR Placed Gravel in this TS

No SHR Grading in this TS

No SHR Placed Boulders in this TS

No SHR Induced Erosion in this TS

No Fluvial Scour in this TS

No Not Surveyed Areas in this TS

Figure 7.34: The elevation change distributions for masks associated with the geomorphological interpretation classification of the 2005 Post Project to 2006 Pre Project (TS6).
No Riffle in this TS
No Point Bar in this TS
No Pool Exit Slope in this TS
No Riffle Crest in this TS
No Lateral Bar in this TS
No Pool in this TS
No Chute in this TS
No Central Bar in this TS
No Run in this TS

Figure 7.35: The elevation change distributions for masks associated with the SHR interpretation classification of the 2006 Pre Project (TS6).
### Table 7.7: Segregation of the TS6 budget by geomorphological interpretation.

<table>
<thead>
<tr>
<th>Category</th>
<th>Erosion Volume (m$^3$)</th>
<th>Deposition Volume (m$^3$)</th>
<th>Total Volume (m$^3$)</th>
<th>Erosion Area (m$^2$)</th>
<th>Deposition Area (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluvial Deposition</td>
<td>2.4</td>
<td>257.6</td>
<td>260.1</td>
<td>45072.0</td>
<td>1487.8</td>
</tr>
<tr>
<td>Changes to SHR Placed Gravel</td>
<td>445.3</td>
<td>476.0</td>
<td>921.4</td>
<td>111393.0</td>
<td>3003.8</td>
</tr>
<tr>
<td>Fluvial Scour</td>
<td>464.8</td>
<td>3.0</td>
<td>467.8</td>
<td>21396.0</td>
<td>26.6</td>
</tr>
<tr>
<td>Questionable Change</td>
<td>81.9</td>
<td>66.2</td>
<td>148.0</td>
<td>139257.0</td>
<td>1238.3</td>
</tr>
<tr>
<td>Placed Boulder</td>
<td>5.1</td>
<td>0.4</td>
<td>5.5</td>
<td>613.0</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>999.5</strong></td>
<td><strong>803.3</strong></td>
<td><strong>1802.8</strong></td>
<td><strong>317731.0</strong></td>
<td><strong>5759.9</strong></td>
</tr>
</tbody>
</table>

3. Very Poor Quality Spawning Habitat

4. Low Quality Spawning Habitat

5. Medium Quality Spawning Habitat

6. High Quality Spawning Habitat

Thus the classification of difference had 36 categories. The six CoD categories for the areas outside the 2005 SHR placement area were discarded so the analysis focused on the project itself. The remaining 32 categories were simplified into three classes whereby habitat quality either remained the same, improved or degraded (Figure 7.36C). This question is only addressed for TS6 because there were negligible geomorphological changes in TS2 and the GHSI mask for the 2003 Post Project (necessary to calculate a difference in TS2) was not available.

Figures 7.37 A, B & C show the primary results of the analysis with three ECDs for the habitat change categories. The top portion of Table 7.8 tabulates the same results. Over 53% of the area in which gravel was placed in 2005 retained the same habitat quality characteristics, as predicted by GHSI. Interestingly, this stable habitat class shows the most balanced ECD (although it is depositionally biased; Figures 7.37A) and only accounts for 19.5% of the total volumetric change to the SHR area. By contrast, the improved and degraded habitat quality class masks account for 34.5% and 46.0% of the total volumetric change, respectively (Figures 7.37 A & B). The improved and degraded classes also make an interesting contrast geomorphically through their ECDs. In general, habitat degradation was associated with erosion and habitat improvement was associated with deposition. Both the stable and improved class ECDs have their most pronounced peak in areas of shallow deposition (10 to 25 cm), with the stable class favouring shallower deposition. The habitat degradation class ECD has its erosional peak at about 75 cm. This is primarily due to the erosion and resculpting of the pool-exit slope\textsuperscript{41}. While such a change does result in a reduction in habitat quality by simple hydraulic criteria, pool-exit slopes tend to be hot-spots of spawning activity due

\textsuperscript{41}Described in § 7.5.1.2.
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Figure 7.36: The derivation of the habitat suitability classification of difference for TS6. Habitat quality was compared on a cell by cell basis from the beginning of the time step (Fall 2005: sub-figure A) to the end of the time step (Summer 2006: sub-figure B) to calculate where habitat quality remained stable, improved or degraded in sub-figure C. The changes in habitat are due to the geomorphological changes which occurred during TS6 (see text and § 7.5.1.2). The grayed out areas reflect those areas outside the SHR placement zone and outside the analysis extent.
to their proximity to deep pool refugia from predation and increased hyporheic downwelling (Geist 2000, Wheaton et al. 2004e, Geist & Dauble 1998).

To further differentiate these results, the specifics of habitat stability, degradation and improvement CoDs are shown in the bottom three-fourths of Table 7.8. From the fourth column, it is encouraging to note that the highest recorded percentage of the SHR area remained high quality (at 29%). As these percentages of the area are largely a reflection of the distribution of habitat qualities, it can be helpful to normalise the percentages by calculating them with respect to their specific habitat quality class (e.g. very poor, low, medium or high) (column five in Table 7.8). From this, the majority of high quality habitat remained high quality habitat (67%). Additionally, across the habitat quality classes there are consistently higher percentages of habitat improvement than habitat degradation.

Thus, it can be concluded that changes associated with a wet water year and the largest possible flow releases from Camanche Dam actually resulted in a net improvement to constructed habitat quality. Whether this result is transferable through time or just represents a natural initial adjustment following a restoration intervention can not be said. However, it is inter-
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### Table 7.8: Summary of classification of difference between 2005 Post Project and 2006 Pre Project GHSI-predicted habitat suitability for TS6. The percentage of SHR Area is calculated by comparing the area of the said CoD class to the total area within the SHR placement boundary mask. The percentage of habitat class is calculated by comparing the area of the said CoD category (e.g. improved, degraded or remained) to the total area in the quality class (e.g. low, medium or high quality).

<table>
<thead>
<tr>
<th></th>
<th>Erosion Volume $m^3$</th>
<th>Deposition Volume $m^3$</th>
<th>Percentage of SHR Area %</th>
<th>Percentage of Habitat Class %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Habitat Improvement</td>
<td>19.0</td>
<td>69.6</td>
<td>22%</td>
<td>NA</td>
</tr>
<tr>
<td>Habitat Degradation</td>
<td>185.1</td>
<td>24.0</td>
<td>25%</td>
<td>NA</td>
</tr>
<tr>
<td>Habitat Stable</td>
<td>58.3</td>
<td>98.3</td>
<td>53%</td>
<td>NA</td>
</tr>
</tbody>
</table>

#### Improvement Details

<table>
<thead>
<tr>
<th>Improvements</th>
<th>Volume $m^3$</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Poor Quality Improvement</td>
<td>0.4</td>
<td>0%</td>
</tr>
<tr>
<td>Low Quality Improvement</td>
<td>3.6</td>
<td>6%</td>
</tr>
<tr>
<td>Medium Quality Improvement</td>
<td>14.9</td>
<td>15%</td>
</tr>
<tr>
<td>High Quality Improvement</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

#### Degradation Details

<table>
<thead>
<tr>
<th>Degradation</th>
<th>Volume $m^3$</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Poor Quality Degradation</td>
<td>0.5</td>
<td>0%</td>
</tr>
<tr>
<td>Low Quality Degradation</td>
<td>15.4</td>
<td>2%</td>
</tr>
<tr>
<td>Medium Quality Degradation</td>
<td>58.3</td>
<td>8%</td>
</tr>
<tr>
<td>High Quality Degradation</td>
<td>110.9</td>
<td>14%</td>
</tr>
</tbody>
</table>

#### Stable Details

<table>
<thead>
<tr>
<th>Stability</th>
<th>Volume $m^3$</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remained Very Poor Quality</td>
<td>0.9</td>
<td>0%</td>
</tr>
<tr>
<td>Remained Low Quality</td>
<td>6.9</td>
<td>6%</td>
</tr>
<tr>
<td>Remained Medium Quality</td>
<td>17.6</td>
<td>16%</td>
</tr>
<tr>
<td>Remained High Quality</td>
<td>31.9</td>
<td>29%</td>
</tr>
</tbody>
</table>

Interesting to note that the patterns of habitat degradation were consistently more closely related with higher magnitude scour (generally above typical egg burial depths); habitat improvement was associated more with shallow deposition; and that habitat stability (not surprisingly) was associated with lower magnitude changes altogether. It is speculated that these correlations as revealed by the ECD masks are probably more generally transferable. It is also encouraging that these geomorphological changes are occurring spatially where they were designed to (i.e. degradation at flow with constrictions and aggradation at flow width expansions) even at the highest possible flows for the Mokelumne (Wheaton et al. 2004d).

#### 7.5.3 What Changes Took Place where Salmon Spawned?

A related question to the changes in spawning habitat quality is whether or not the types of habitat that attract spawners are prone to particular types of change. Wheaton et al. (2004d, Figure 8) showed that for spawning flows, the habitat patches that attract spawners are typically not prone to erosion. This is not a surprising result - fish are not going to spawn...
where erosion is actively taking place as they will not be able to safely bury their eggs. However, following spawning, the occurrence of erosion producing scour beyond the burial depth of eggs is certainly possible if high (competent) flows concur with the incubation period. On the Mokelumne, two factors make such events highly unlikely. First, the Mokelumne is naturally a spring snow-melt dominated river, which typically produce such events later in the spring well after the incubation period. Secondly, the Mokelumne now suffers from a completely regulated flow regime, and dam operations are such that competent flow releases are not made during the incubation period. Thus, in the context of the Mokelumne, this is not so much a question of whether changes to spawning habitat will be detrimental to spawning or incubation success, but rather whether spawners tend to select sites that are likely to change (geomorphologically) or stay the same. There are two possible time steps this question can be asked of (TS2 and TS6).

For the TS2 (2003-2004) season, there were no competent flows to make major changes to the 2003 SHR project morphology. Of the 807 redds in the 2003 Fall run on the Lower Mokelumne, 72 spawned in the 2003 site following its construction (Table G.1). According to Figure 7.38A, changes where redds took place only amounted to 7 m$^3$ of erosion and 4 m$^3$ of deposition. Although this is a far cry from the 2.25 m$^3$ per redd that Merz et al. (2006) estimated, it is not necessarily surprising. The redds covered only 83.2 m$^2$ of surface area (lots of superimposition) of an area that only received 190 m$^3$ of erosion and 436 m$^3$ of fill. In reality, redd construction might have been responsible for moving a much greater volume of sediment locally, but the resolution of the topographic surveys was not fine enough to discriminate redd morphologies. Therefore, the small volumes of erosion and deposition calculated in areas where there were redds should not be expected to resolve differences due to redd construction. Instead, this mask is just picking up a fraction of the small magnitude changes to the 2003 SHR Placed gravel area. These changes were attributed largely to compaction and sloughing mechanisms in § 7.5.1.1. Although the magnitude of change was small in TS2, it can be said that 58% (48.3 m$^2$) of the redds were found in areas that experienced some erosion and 42% (34.9 m$^2$) were found in areas that experienced some deposition. None of the erosion was greater than 45 cm, with most peaking below average burial depths for Chinook redds at 15-20 cm.

In contrast to TS2, the TS6 (2005-2006) season produced the maximum controlled release available to the lower Mokelumne River. As described in § 7.5.1.2, a reasonably interesting suite of geomorphological changes due to natural fluvial processes accompanied this event. As such, it is probably a better test of the question posed in this section as to whether or not fish tend to spawn in areas that are more or less prone to either depositional, erosional or stable areas. There were 196 redds found in areas where gravel was placed in 2005 (478 in the study reach and 2157 in the entire LMR - the highest ever recorded; see Table G.1). Of these 196 redds, 45% (600.3 m$^2$) covered areas that came to experience erosion later in the season and 55% (729.0 m$^2$) covered areas that came to experience deposition later in the season. Thus,

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42 See also discussion of scour during incubation period in § 6.7.
43 Uncontrolled releases only occur on a spillway that is positioned to overflow downstream of the entire study reach.
Figure 7.38: The use of redd surveys as a DoD Mask. The redd surveys for 2003 (C) and 2005 (D) are shown overlaid on top of the corresponding DoDs for TS2 and TS6 respectively. Using each redd as a mask, the ECDs in A (for TS2) and B (for TS6) show what proportion of the total thresholded DoD ECD reflects subsequent geomorphological changes in areas where redds were observed.
between the two years, there is no consistent preference on the binary test for erosional versus depositional areas.

With the higher density of redds in 2005, the redd mask came to cover a higher percentage of the overall volumetric budget at 18% of the total erosion and 14% of total deposition. The redd ECD in Figure 7.38B also spanned a greater range of erosion and fill depths with up to 1.5 m of erosion and up to 1 m of deposition. In terms of the longer-term significance of these observations (i.e. to the next spawning season), the analysis in the previous section on habitat quality are worth reviewing (§ 7.5.2). Over 54% of the redds were in areas where habitat quality remained the same, only 20% were in areas where habitat quality improved, and 26% were in areas where habitat quality decreased. Thus, 74% of redds were located in areas that would still be suitable habitat in the next spawning season.

In summary, on the basis of this limited dataset, there is inconclusive evidence to support or refute the idea that redds may have a preference for habitat types that are prone to either erosion or deposition versus stability. The technique of using redd surveys as a DoD mask might prove more fruitful as a tool for assessing threats to egg survival during the incubation period if surveys were performed following events during the incubation period. The technique would also be interesting to apply to datasets where topographic surveys were specifically performed at resolutions to resolve the morphology of redds. There, the mask could be used to calculate the net amount of material moved by salmon versus floods, a question considered by Gottesfeld et al. (2004) and Hassan et al. (2002). In this context, the technique is still insightful for directly answering the question of what changes took place where salmon spawned.

7.6 Conclusions

The purpose of this chapter was to demonstrate how various masking techniques for segregating morphological sediment budgets in conjunction with a DoD uncertainty analysis can be interpretively powerful in a restoration monitoring context. Three questions related to interpreting as-built surveys and three questions related to interpreting monitoring surveys were addressed.

Focusing first on the as-built questions, the main findings as they relate to four consecutive years of construction of spawning habitat rehabilitation (SHR) projects on the Mokelumne River in California are as follows. Using simple construction masks and DoD uncertainty analyses, 8226.3 m$^3$ of gravel actually placed as part of the four SHR projects was separated from the total of 9277.5 m$^3$ of deposition calculated in the DoDs after accounting for uncertainty. A further segregation of these areas into the constructed geomorphic units revealed that over 41% of the total volume of gravel placed was in the form of riffles, 26% in lateral bars, 14% in chutes and 10% in point bars. In terms of the quality of spawning habitat these gravel placements helped produce, more gravel was spent creating low and medium quality habitat then high quality habitat. Each of these analyses are useful in terms of a) addressing how well
the constructed project matched the design, b) considering whether or not project objectives were met, and c) articulating specifically how the projects were implemented.

Only two years of post-project appraisal annual monitoring surveys were available from the Mokelumne River projects. These represented two end-members of flow-regulation on the lower Mokelumne. The first was a drought year in which the flow regime was flat-lined throughout the year with only a minor 42.7 cumec release associated with spring snow-melt. The second was a large water year in which the maximum possible flow release from Camanche Dam was realised (141.6 cumecs). In the drought year there were essentially negligible geomorphological changes (78.4 m$^3$ of erosion and 100.7 m$^3$ of deposition) to the SHR project from the previous year. These changes are thought to be largely due to compaction, settling and gravitational sloughing of the newly placed gravels as well as salmonid redd construction. In the high-flow year, by contrast, fluvial processes both within the SHR placement boundaries and outside it produced over 1000 m$^3$ of erosion and 810 m$^3$ of deposition (compared with 2018 m$^3$ of gravel placed in the reach the year before). Although there was a net loss of material from the project area, most of the reworked gravels remained in the project areas. Of key importance was that during high-flows deposition was taking place in the best spawning habitat areas such as riffles and the large regions of scour were focused in and along pools.

During the high-flow year (Fall 2005 to Summer 2006) net changes in spawning habitat quality (as predicted by a 2D habitat suitability model) were compared against the DoD changes. These revealed that 53% of the reach retained its same habitat quality as a result of the high flows, but that 22% improved and 25% degraded. Only 19.5% of the total volumetric changes took place in areas that retained the same habitat quality, with over 46% of the volumetric changes taking place where habitat quality improved. In general, the areas experiencing habitat degradation were associated with higher magnitude scour and areas experiencing habitat improvement were associated with shallow deposition; whereas areas retaining their habitat quality were generally only subjected to even lower magnitude changes. Redd surveys were used as masks to address whether or not salmon may naturally select redd locations that are prone to erosion, or deposition or stable areas. The survey data was not dense enough to resolve redd morphologies themselves, so the changes were not reflecting redd construction. As there was only one year of significant fluvial changes, the dataset was not large enough to definitively answer this question. However, in the 2005-2006 water year, over 74% of the 2005 Fall-run redds were located in areas that would still provide suitable spawning habitat the following year.

From a restoration monitoring perspective, the DoD uncertainty analysis and masking tools aid in making much more meaningful and informed interpretations of the topographic monitoring data then previously possible. From a geomorphological perspective, the heavily regulated flow regime of the Mokelumne River provides only rare opportunities to explore significant geomorphological changes post-restoration. However, when such changes did present themselves, the DoD uncertainty analysis and masking tools enabled direct answers to a range of geomorphological and ecohydraulic questions.