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Authors
Sawyer, April M
Pasternack, Gregory B
Merz, Joseph E
et al.

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Title:

Construction constraints for geomorphic-unit rehabilitation on regulated gravel-bed rivers

Running Head:

Construction constraints on river rehabilitation

Authors:

April M. Sawyer[1], Gregory B. Pasternack[1*], Joseph E. Merz[2], Marisa Escobar[1], Anne E. Senter[1]

Addresses:

[1]Department of Land, Air, and Water Resources, University of California, One Shields Avenue, Davis, CA 95616-8626, USA;

[2] Cramer Fish Sciences, 636 Hedburg Way #22, Oakdale, CA 95361.

*Corresponding author

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ABSTRACT

The emergent practice of applied river restoration uses best available equipment and contouring methods to construct detailed designs with some features at scales as small as 0.5-m relief. As part of adaptive management, it is necessary to determine the practicability of design features and construction methods before widespread adoption. In this study, we compared design versus as-built topography for 5 salmonid spawning habitat rehabilitation projects at riffle-pool geomorphic units on the lower Mokelumne River, California, U.S.A. These were built instream using rubber tire front loaders. Digital Elevation Models (DEMs) of each site were produced for pre-project, design and as-built conditions. DEM differencing was used to compare the as-built surface against corresponding design surfaces at each site to identify deviations. Causes of each identified deviation were assessed based on subjective observations by a team during construction. Across the projects, 70% of as-built topography was within ±0.15 m of design specifications. Of the 30% deviating from the design, 41% was overfilled and 59% underfilled. The 30% of rehabilitated channel area that deviated from designs did not affect predicted areas of high-quality spawning habitat. On-site factors that hindered accurate construction of designs included front loader fording depth, poor operator elevation estimation, operator spatial disorientation and wood obstructions. In addition, funding and project management uncertainties caused gravel supply deficits and gravel bulk density estimation errors. It is concluded that constructing broad (> 0.5-m relief) features of process-based salmonid spawning habitat rehabilitation projects by gravel augmentation is practicable. However, uncertainties attributed to human error and available methods inhibit detailed (< 0.5-m relief) rehabilitation. Despite uncertainties, limitations and errors, following the recommendations reported in this study would improve the as-built adherence to design specifications of future projects.

Keywords: river restoration; fluvial geomorphology; river engineering; spawning habitat; adaptive management; post-project appraisals

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1. INTRODUCTION

1.1 Background

Modern human activities have degraded the natural state of many river ecosystems, creating the need for river rehabilitation. In the United States alone, over 30,000 projects have cost nearly US $10 billion dollars (Malakoff, 2004; Bernhardt *et al*., 2005). The goals of river rehabilitation commonly include restoring ecological, geomorphic, and hydraulic processes by altering channel dimensions or replacing lost morphological elements, such as gravel bars, logjams, and boulders (Seehorn, 1992; Stanford *et al.*, 1996; Shields *et al.*, 2003; Wohl *et al.*, 2005). As an emergent practice, river restoration is commonly criticized because channel form design using empirical hydraulic geometry relations may not account for fundamental geomorphic, ecological or hydraulic processes nor inherent channel variability (e.g. Brookes and Shields, 1996; Kondolf, 2000; Downs and Kondolf, 2002; Palmer *et al.*, 2005; Wohl *et al.*, 2005). Currently, the success or failure of many projects is unknown (Wohl *et al.*, 2005), although consistent and reputable literature databases reporting evaluated restoration projects from which to gage success are being synthesized regionally and nationally (Roni *et al.*, 2002; Palmer *et al.*, 2003; Bernhardt *et al.* 2005; Bernhardt *et al*. 2007). Adaptive management may enhance restoration through continually planning, monitoring, evaluating, and adjusting project designs and method implementation (Johnson, 1999; Lee, 1999; NRC, 2004; Florsheim *et al.*, 2006).

In California, U.S.A., managers often use gravel augmentation, or the addition of washed gravel and cobble to a river, to restore degraded gravel supplies below reservoirs; the costs and scales of such projects range from small placements on the Carmel River to multi-year placements on the Mokelumne River below Camanche Dam (Kondolf and Matthews, 1993; Merz *et al.*, 2006; Elkins *et al.*, 2007). In Northern California, instream habitat improvement for

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anadromous salmonids has been a major activity for the last 20 years (Kondolf *et al.*, 2007). Gravel augmentation aims to improve physical parameters such as depth, velocity and dissolved oxygen content that influence the hyporheic environment, salmonid spawning and embryo development (Merz and Setka, 2004; Merz *et al*., 2004). Research on abiotic-biotic linkages on the lower Mokelumne River (LMR), California, U.S.A., has found that the quality and quantity of Chinook salmon (*Oncorhynchus tschawytscha*) spawning habitat serves as an effective ecological indicator of the health of this regulated river's aquatic ecosystem. High-quality spawning habitat was found to have high intergravel permeability and dissolved oxygen content (Merz and Setka, 2004), high abundance of macroinvertebrates (Merz and Ochikubo Chan, 2005) and high survival of embryos to the fry life stage (Merz *et al.*, 2004). In addition, spawning riffle proximity to pools, flow separations (eddies), boulders, instream woody material and other refugia are essential to spawners and overall biodiversity (NRC, 1992).

Restoration monitoring should include both pre- and post-project data collection (Downs and Kondolf, 2002; Palmer *et al.*, 2005). Pre-project data, including success criteria, baseline surveys for parameters of interest, process-based design rationale, and thorough design drawings facilitate accurate design implementation and provide a basis for comparison when defining post-project success (Downs and Kondolf, 2002; Wheaton *et al.*, 2004a). Post-project appraisals, including as-built characterization and long term monitoring, drive adaptive management to evaluate restoration effectiveness, to define appropriate monitoring variables and scales and to link science with implementation (Downs and Kondolf, 2002; Wohl *et al.*, 2005). The combined effort of stakeholders, scientists and practitioners to acknowledge the uncertainty and complexity of rehabilitation projects would contribute to the development of effective methods within present constraints (Wohl *et al.*, 2005).

Currently, the goals of rehabilitation vary but many use river self-sustainability as an

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approximation of pre-disturbance ecosystem functions and geomorphic-processes (Downs and Kondolf, 2002; Bernhardt *et al.* 2005; Palmer *et al.*, 2005). Unfortunately, scientific ideals for what restoration projects ought to achieve, such as holistic watershed management and comprehensive sediment budgeting, have proven unrealistic or not practicable as of yet (Wheaton *et al.*, 2004a; Wohl *et al.* 2005; Pasternack, in press). River restoration becomes practicable science as new technologies and methods are developed to apply advanced science and engineering at the reach and sub-reach scales, while still considering watershed and regional processes affecting local conditions (Kondolf, 1993). For example, rapid advancements in ecological and geomorphic applications of hydrodynamic modeling can be used to design detailed restoration plans of instream morphologic features (Pasternack *et al.*, 2004; Wheaton *et al.*, 2004b; Elkins *et al.*, 2007). In particular, features such as riffle crest elevations may need to be built within 0.15 m of design specifications to achieve model-predicted outcomes of water depth, velocity, and water surface elevation and avoid backwater effects on upstream habitat (Clifford and French, 1998). Whether most engineering contractors and watershed stakeholders could fulfill project specifications based on advanced science at a reasonable cost remains to be reported by individual project managers.

As an example of restoration post-project monitoring and adaptive management, this study uses analyses of pre-project, design, and as-built digital elevation models (DEMs) for five instream construction projects that emphasized salmonid spawning habitat rehabilitation. The main research goal was to evaluate the practicability of constructing highly detailed (<0.5-m relief) riverbed topography with rubber-tire front loaders in a regulated gravel-bed river. Project grading plans were designed using the Spawning Habitat Integrated Rehabilitation Approach (Wheaton *et al.*, 2004a,b), which has been shown to yield significant ecological benefits based on habitat suitability curves for salmonid spawners (Leclerc *et al.*, 1995; Elkins *et al.*, 2007).

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Grading plans include topographic and volumetric cut-fill maps of the design that direct the front loader operators during construction. For the five projects investigated, the grading plans were designed to re-configure the channel based on geomorphic, ecological, and hydraulic processes, to build hydraulic structures using boulders and wood (Wheaton *et al.*, 2004c) and to mitigate the gravel deficit. While this study focuses on construction constraints determining post-project accuracy, it does not intend to justify the rehabilitation principles (i.e. Wheaton *et al.*, 2004a,b; Elkins *et al.*, 2007) used in the specific projects evaluated. As one of the first studies of its kind, this research offers practical information to the river management community about constraints to process-based design implementation. Future river restoration efforts can benefit from lessons learned in this study.

1.2 Construction Constraints

Before beginning the study, possible sources of uncertainty and error associated with in-channel construction were identified to help understand why as-built topography might deviate from a design. In this study, sources are grouped into supply uncertainties, construction operation errors, and as-built bulk density uncertainty.

Several economic and political factors influence the available gravel supply for design implementation. First, project sponsors may adjust financial support immediately before construction causing design changes. Second, project approval and funding allocation timing may allow fluctuations in gravel purchase and transport costs between the dates of budget specification, funding allocation, and construction. Third, gravel quarry companies may be unable or unwilling to deliver the specified material. Sometimes quarries hit a vein of excessively coarse or fine material, limiting the needed supply. Other times quarry managers may deal with river rehabilitation projects unfavorably because these infrequent and carefully supervised projects place special demands upon them.

During gravel augmentation, construction operation errors arise because front loaders and operators work in a unique aquatic environment. Key constraints include front loader fording depth, poor operator elevation estimation, operator spatial disorientation, and obstructions by wood and boulders. Front loaders have a maximum fording depth before engine flooding occurs and operators have differing experience in aquatic construction. Each operator must decide how far to push gravel into deep areas such as pool/riffle transitions, while risking potential engine, transmission and gear box damage in excess of US $200,000 to repair. Such risk makes construction near deep areas susceptible to error. The operator's ability to place gravel in the channel depends on their spatial awareness in relation to the designed grading plan. Decreased visibility in underwater construction impedes the operator's ability to build the desired topographic grade. Suspended sediments, waves, riffles, reflection and refraction decrease visibility. Tire submergence acts as the best depth reference estimate for front loader operators. Stakes and other marking devices improve orientation. However, since operators are not involved in the design process, they are unfamiliar with the morphologicfeatures designed by project planners and their intended hydrodynamic functionality. Finally, overhanging vegetation, submerged wood, and boulders may limit tractor accessibility. In some cases it may be possible to move these materials during construction and replace them afterwards. When working in deep water it is necessary to work around these in-channel features.

Grading plans include topographic maps that show the volumetric difference between design and pre-project conditions. A gravel placement design uses pre-determined gravel volumes to meet project goals within set cost constraints. However, quarries sell gravel by weight not by volume. Placed gravel's as-built bulk density is an unknown variable determining whether the available supply of gravel is adequate to build the design. Unfortunately, gravel

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bulk density is inconsistent and variable at different spatial scales. This study reports that actual as-built bulk density is variable without conclusive explanation.

2. STUDY AREA

The snow-fed Mokelumne River in California drains 1624 km^2 of the central Sierra Nevada (Fig. 1). It presently has 16 major water impoundments, including Salt Springs (175,032,089 m^3, completed in 1931), Pardee (258,909,341 m^3, completed in 1929) and Camanche (531,387,061 m^3, completed in 1964) reservoirs that have dramatically altered the late spring snowmelt flow regime (Pasternack *et al.*, 2004). Pre-Camanche Dam bankfull discharge defined as the 1.5 to 2 year return interval flood was 120 m^3/s; after the dam closure in 1964, bankfull discharge was reduced to 40 m^3/s. Below Camanche Dam, the lower Mokelumne River (LMR) bed slope ranges from 0.10% near Camanche Dam to 0.02% near the Cosumnes River confluence, with the active channel now half its former width (present average 30 m; range 19-43 m). Post-dam channel incision has disconnected the remaining floodplain from the channel during all but the highest infrequent flow releases.

Camanche Dam inhibits downstream coarse-sediment delivery and blocks spawners traveling upstream. Coarse sediment- gravel, cobble, and boulders- is important to several salmonid lifestages, including spawning, incubation and rearing. Historic mining operations depleted instream gravel and cobble storage at and near the selected sites, creating deep sediment-transport barrier pits. Channel-mining tailings exist along the upper third of the LMR, but flow releases cannot access and mobilize them due to isolation behind berms and levees. Channel incision, bank reinforcement, and moderate vegetation encroachment lead to highly stable banks; thus, gravel recruitment from bank scour is minimal. As far as ~15 km downstream of Camanche Dam, the channel consists of shallow riffles and glides with compacted gravel and

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cobble as well as deep runs and pools. During the 1980s and 1990s, limited amounts of gravel were placed in the river to enhance spawning riffles. Murphy Creek (Fig. 1), a small tributary, contributes some sand and fine gravels, with a slight increase since its most-downstream dam was removed in 2003.

The LMR is primarily managed for native anadromous salmonids (FERC 1993). Presently, the river supports over 35 native and non-native fish species including Chinook salmon (*Oncorhynchus tschawytscha*) and steelhead (*O. mykiss*) (Merz *et al.*, 2004). For the 19 year period (1940 to 1942, 1945, and 1948 to 1963) before Camanche Reservoir was impounded, runs averaged ~3,300 spawners; however, pre-dam spawning areas were estimated to accommodate ~15,000 adult Chinook salmon at 11.3 m^3/s (CDFG, 1991). USFWS (1997) called for a LMR fall-run Chinook salmon population target of 9,300. Average annual LMR salmon escapement has been monitored by video at Woodbridge Dam (1990-2007) as well as by seasonal carcass surveys over a longer period of time. Based on all available data and the latest analysis (Workman, 2007), the estimated adult Chinook salmon escapement has averaged 4,436 fish per year (min 250 max 16,128) since Camanche Dam completion (1964) and 8,162 (min 5,332, max 16,128) over the 10 years prior to this study. Most wild spawning occurs within 8 km below Camanche Dam, yielding typically ~800-1000 redds annually. The Mokelumne River Fish Hatchery uses the majority of up-migrating fish to produce 3–9 million juvenile Chinook salmon. The Federal Energy Regulatory Commission (FERC) ranked factors limiting salmonid production in the LMR and determined that salmon-spawning habitat quality and quantity were the most important factors (FERC, 1993).

3. METHODS

Rehabilitation planning, design, implementation, and long-term monitoring on the LMR

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have been guided by the Spawning Habitat Integrated Rehabilitation Approach (SHIRA). SHIRA (http://shira.lawr.ucdavis.edu) integrates concepts from hydrology, ecology, biology, geomorphology and engineering to design and evaluate alternative channel configurations for a degraded regulated river (Pasternack *et al.*, 2004; Wheaton *et al.*, 2004a,b). Two-dimensional (2-D) hydrodynamic models test the predictions of design hypotheses over 10^{-1}-10^{4} m scales (Pasternack *et al.*, 2006). 2-D models are used to evaluate design alternatives and final as-built project configurations down to the 0.1-1 m scale used by fish (evaluation methodology detailed in Wheaton *et al.* (2004b)). Monitoring is used to evaluate SHIRA predictions and drive adaptive management (Merz *et al.*, 2006; Elkins *et al.*, 2007). Although 2-D models and other tools used in SHIRA have uncertainty (MacWilliams *et al.*, 2006; Pasternack *et al.*, 2006) they help stakeholders understand the capabilities, complexities, and range of possible outcomes of rehabilitation projects. This helps to create realistic project goals.

SHIRA helped develop final grading plans for five different river rehabilitation sites (referenced by year in Figure 2). Cost-effective practices described in this study below were used to construct projects according to grading plans. Detailed topographic surveys were used to characterize and compare each site's pre-project and as-built condition, as well as to compare design plans with actual construction outcomes. The scientific and management foundations of each specific design are presented elsewhere (e.g. Wheaton and Pasternack, 2002; Wheaton *et al.*, 2004b; Pasternack *et al.*, 2006; Elkins *et al.*, 2007) and are not directly relevant to answering the scientific question posed in this study.

3.1 Grading Plans

To create the grading plan for each project, a baseline digital elevation model (DEM) was developed for the pre-project state of each site (Figs. 4-8, top panel). Next, alternative design

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scenarios were developed, evaluated and reduced to the final design based on various selection criteria (Wheaton *et al.*, 2004a,b; Elkins *et al.*, 2007). Finally, the selected design DEM was used to generate the grading plans for construction.

Topographic data was obtained using a Topcon GTS-802A or LEICA TPS1100 (or TPS1200) robotic total station. Surveying was conducted by wading with a prism pole and using a small rubber raft in un-wadable areas to obtain point densities of ~1-1.5 points/m^2 for each site. Key breaklines included bank toes, boulders, and slope breaks. Supplemental surveying of boulders and wood used a higher point density of ~10 points/m^2. Surveying accuracy was assessed using control network checks and was found to average ±0.0035 m horizontally and ±0.0039 m vertically.

Topographic data were imported into Autodesk Land Desktop 3 to create each baseline DEM. The four iterative stages of DEM development as described by French and Clifford (2000) were implemented: interpolation, visualization, editing, and augmentation. First, survey data were interpolated and a surface defined respecting breaklines. Next, the surface was visualized as a map and edited to remove obvious interpolation errors. The revised surface was visually verified in the field to check for poorly represented areas in the DEM. Further iteration was done as needed.

Final design scenario DEMs were developed using the pre-project DEM as a baseline. Points and contours were modified and augmented in Autodesk to describe the final design surface. The gravel volume of each design was determined by DEM differencing between design and pre-project DEMs. The design volume was converted each year to weight based on Merz *et al.* (2006), who determine an average dry bulk density of 1.645 ±0.054 metric tons per m^3 from bucket tests at a nearby quarry. Designs were iterated to yield estimated design weights corresponding to the contractual purchase weights of 907, 1906, 2087, 3554, and 3301 metric

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tons for each year chronologically 2001-2005.

Grading plans included laminated maps with corresponding markers placed at the construction site to provide reference points to the front loader operator and project workers. The set included contour maps of the (1) pre-project DEM, (2) final design DEM, (3) gravel-fill depth and (4) 2-D hydrodynamic model (FESWMS 3.1) predicted water depth for the discharge during construction. In addition, close-up views of final design features were provided on supplemental pages. In 2001-2004, bright markers on trees denoted approximate bed feature locations but not the upstream limits for feature construction. Visual inspection of depth was made by wading around the site with a stadia rod to check construction progress.

In 2005, a grid-based approach replaced the feature-based reference points and grade checking measures. A 6.1 x 6.1 m bed-elevation grid was extracted from the final design DEM and imported into a Leica TPS1200 total station. Labeled and brightly-painted wood stakes were posted on the banks in 6.1-m (20’) intervals down the channel as a visual aid for the front loader operator. These stakes were used to thoroughly check elevations in the grid during and after construction.

3.2 Construction Approach

Each year 2001-2005, a single geomorphic unit on the LMR was augmented with coarse sediment and re-contoured using a front loader according to the given grading plan for that year. Each year’s separate site is referenced in Figure 2. Coarse sediment used for each project varied depending upon available funding and project costs. The sediment consisted of washed 25-150 mm diameter river gravel (CDFG, 1991; Kondolf and Wolman, 1993) from an open floodplain quarry located 0.5 km from the active channel. Sediment was transported to each site in 15.3-m^3 (20-yd^3) dump trucks. To the extent possible sediment was poured directly into the channel to

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avoid losses on the floodplain or on roads, but some material was stockpiled at access points. Concurrent with sediment delivery, the front loader was used to re-contour the bed by scooping up a bucket full of material, transporting it to the desired location, and dropping it into place (Fig. 3). After the gravel bed was contoured, the front loader placed ~10-20 boulders (0.6-1.2 m diameter) and ~5-10 pieces of wood (trunks up to 0.6 m diameter) throughout each site to increase downwelling, channel complexity and cover for spawning salmonids (House, 1996; Geist and Dauble,1998; Merz, 2001). Boulders were free to adjust naturally. Wood was partially buried with placed sediment so that immediate transport would not occur. Depending on the amount of material placed and the number of dump trucks available to bring in the sediment, construction took 3-8 days.

Each project utilized a ~20 metric-ton, front loader with rubber tires and a 3.82-m^3 (5-yd^3) bucket capacity to construct instream design features (Fig. 3). Construction equipment specifications and phone correspondence with dealers were used to compile information about front loader capabilities (Table 1). Since front loaders were used during flows of 7-13 m^3/s, a primary concern was the maximum fording depth. Manufacturers recommend not fording past the wheel hub height; this generally coincides with the bottom of the oil pan on which the engine sits. Fording past this depth can suck water into the transfer cases and transmission resulting in expensive damage as experienced in 2003.

As-built bulk density may vary due to repetitive front loader traffic, particle size distribution, and gravel breakage. For each project year, the median grain size of the placed material was estimated using 3-5 instream pebble counts of >100 grains each after installation (Table 2). The footprint of compaction for each loader was calculated from construction photos of front loader wheels not submerged in water. On average, front loaders sank into the gravel half the radius of the wheel hub. From this approximation, the surface area in contact with

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gravel was calculated using tire dimensions. Finally, each loader's weight was divided by the four tires' total surface area to obtain stress on the gravel bed (Table 1). How the front loader affects bulk density is an important variable in determining erodibility and hyporheic water quality. Total gravel breakage was not quantified but may influence bulk density.

3.3 As-built DEM

Once construction was completed the site rested for 1-3 days to account for rapid settling (Merz *et al.*, 2006) before performing an as-built topographic survey. DEMs were generated for the as-built condition by the same method as the pre-project baseline (Figs. 4-8, bottom panel). The as-built DEM represents approximate spawning conditions at the site during the months immediately after construction. In situ bed porosity and bulk density were not monitored through time to quantify settling in this study, but were previously estimated to be a significant contributor to gravel deflation (Merz et al. 2006).

3.4 DEM Analysis

Using the DEM-differencing algorithm in Surfer 8 (Golden Software, Golden, CO), as-built DEMs were compared to design DEMs to determine the magnitude and spatial pattern of volume and elevation difference. Sets of DEMs for each site were imported into Surfer and used to generate identical high-resolution DEM grids. By overlaying the separate design and as-built gridded DEMs, Surfer calculated gross cut (in underfilled areas), gross fill (in overfilled areas), and net volume difference. Also, Surfer's Grid Math function subtracted design elevations from the as-built elevations to yield a DEM-difference map with areas of positive (overfilled) and negative (underfilled) as-built elevation deviations relative to the design surface. As-built DEMs were also differenced against pre-project DEMs to obtain actual as-built volume, enabling as-

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built dry bulk density calculations using the delivered gravel dry weight.

DEM difference error was evaluated on an elevation and volumetric basis to determine the amount of underfill or overfill representing significant deviation from the design. Topographic surveying error included vertical set-up accuracy of ~ ±0.004 m and prism-pole placement errors of ~ ±0.01 m. Given that bed particle size was in the 0.03-0.17 m range, vertical resolution was not limited by surveying accuracy, but by natural surface heterogeneity. Thus for this study, significant deviation was defined as more than a 0.15 m absolute difference from the design elevation. The direction of the deviation was either overfill (> +0.15 m) or underfill (< -0.15 m) relative to the design.

A volumetric error analysis to constrain deviations resulting from varying point densities and point locations between two DEMs of the same area on the LMR was performed by Merz *et al.* (2006). They reported an average error of +2 m^3 per 100 m^2 of channel surface area. Since project areas were ~2000-4000 m^2, volumetric errors were ±40-80 m^3. Thus, a volumetric difference between design and as-built surfaces exceeding ±80 m^3 indicated real surface variation.

In order to visualize volumetric differences between design and as-built topography, DEM difference maps were made using shades of red to denote underfill and blue to denote overfill. The darkest red shade corresponds to the lowest elevation (gravel deficit) and the darkest blue shade corresponds to the highest elevation (gravel excess). For each project year, this volumetric difference data was exported from Surfer and analyzed in Microsoft Excel. Histograms were used to determine the frequency of areas categorized into 0.15-m contour intervals as well as the percentage of occurrence of areas of overfill, underfill, and insignificant difference (Table 3).

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3.5 Construction Observations

Each significant elevation deviation from the design had an explanable cause. These were organized into broad categories: (1) gravel supply uncertainty, (2) construction operations and (3) gravel bulk-density differences. Determinations of gravel-supply uncertainty and bulk-density differences as causes of elevation error were based on comparing calculated design, purchased, and as-built gravel volumes for each project. Also, if the available gravel supply was depleted prior to design completion, then the cause of error associated with unfilled areas was attributed to gravel supply uncertainty.

For all projects, design crew members gave a qualitative interpretation for each significant error's source associated with construction operations. In each year, two lead scientists (authors Pasternack and Merz) provided consistent interpretation of methods. Staff scientists who had helped in the design process were present during construction each year. Also, front loader operators (one or two per project year) reported their experiences. While no formal construction appraisal process was available, all participants discussed construction constraints and developed a consensus for the problems encountered in each project. It was often agreed that individual areas of elevation error had multiple causes. Error sources were tabulated for each year and compared across years. Although this approach is qualitative, its repetition through five projects under guidance of the same individuals provided reasonable consistency.

4. RESULTS

The DEM difference plots show inaccuracy when constructing specified elevations to within ±0.15 m. Overall, 29% of as-built topography deviated from designs (Table 3). Deviations commonly occurred when gravel placement starting locations for riffle construction were too far upstream with a steep riffle entrance slope using too much gravel. This often left

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inadequate gravel to build the desired riffle exit slopes leaving them underfilled. In addition, complex bed features were generally built with excessive relief, yielding higher bar tops and lower chute troughs, a typical result of operator spatial disorientation and poor operator elevation and depth estimation. Detailed results for each project are presented to demonstrate these and other significant deviations. In all project years, the front loader created tire tracks 0.15-0.3 m deep. For each project, specific locations of significant deviation are numbered to simplify presentation in Figures 9-13. In this section, areas of significant deviation are reported as the absolute value of elevation difference: either >0.15 m underfilled or >0.15 m overfilled.

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4.1 The 2001 Project

The 2001 project design was specified to have an as-built volume of 1,147 m^3, corresponding to an estimated supply of 1,887 metric tons of gravel, with 980 metric tons of that planned to be salvaged from abandoned beds of adjacent hatchery channels at no cost (Table 2). The salvage operation only yielded 400 metric tons of usable gravel, making on-site design changes necessary to account for an overly ambitious design. Nevertheless, 81% of the 2001 as-built project area was within ±0.15 m of the design surface. Of the 19% of area with significant deviation, 83 % was >0.15 m underfilled and 17% was >0.15 m overfilled.

Design versus as-built DEM comparison yielded six areas of significant deviation (Fig. 9). The main sources of error were gravel deficits, operator spatial disorientation and poor operator elevation and depth estimation (Tables 4, 5). The *ad hoc* adjustments accounting for reduced gravel supply included eliminating gravel placement in areas 1 and 6 and reducing placement in areas 4 and 5 (Fig. 9). Operator’s spatial disorientation was responsible for overfilling areas 2 and 3. Operator’s poor elevation and depth estimation also accounted for underfilling areas 4 and 5. The purchased gravel volume equivalent of 1,307 metric tons was estimated to be 794 m^3 but the actual as-built volume was 649 m^3 (Table 2). As-built bulk density exceeded the quarry value by ~22%, yielding a higher density of 2.013 metric tons per m^3 as opposed to the bucket-test estimate of 1.645 ±0.054 metric tons per m^3.

4.2 The 2002 Project

The gravel shortage in 2001 prompted adapting the 2002 design to include gravel placements of varying priority depending on purchased gravel availability. The design specified an as-built volume of 1,448 m^3 assuming all features could be completed, and then 2,786 metric tons equaling an estimated 1,694 m^3 was purchased. Overall, 79% of the 2002 design versus as-built project area was within ±0.15 m of the design surface. Of the 21% of areas that deviated from the design, 43% of the as-built survey area elevations were >0.15 m overfilled, and 57% were >0.15 m underfilled.

The DEM comparison found eleven areas of significant deviation (Fig. 10). In 2002, several factors caused deviations: most were attributed to poor operator estimation of elevation/depth (31%) and fording depth limitations (25%) (Tables 4, 5). As shown in Fig. 10, design deviations in area 1 resulted from the loader constructing the riffle crest too far downstream and in area 5 from mistakenly filling a designed pool. Both deviations were related to operator spatial disorientation. Poor operator elevation estimation resulted in overfilling areas 2 and 6 and underfilling areas 3, 4, and 7. These elevation errors yielded less relief between the central bar and side channel. Area 8 was underfilled due to overfilling upstream. The operator did not place boulders at the exact designed locations, resulting in surveying errors around boulder clusters at area 9. The DEM difference between as-built and pre-project conditions yielded an as-built volume and bulk density of 1410 m^3 and 1.976 metric tons per m^3, respectively (Table 2). Once again, as-built bulk density exceeded the quarry value by ~20%.

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4.3 The 2003 Project

The 2003 project was the first phase of a 2-year scheme to rehabilitate the river's longitudinal profile and enhance its floodplain connectivity downstream of Camanche Dam. This project's adaptive design was not only spatially but also temporally sectioned so that deviations could be addressed in 2004. The 2003 section's final design required 2,020 m^3 of gravel but 3,217 metric tons estimated to yield 1,955 m^3 was purchased. In 2003, 64% of the total as-built project area was within ± 0.15 m of the design. Of the 36% total area significantly deviating from the design, 31% was >0.15 m overfilled and 69% was >0.15 m underfilled.

The design versus as-built comparison project results (Fig.11) showed eight significant deviations from the design starting from the upstream end of the project site. Design deviations in 2003 included: 55% from operator errors and 28% from channel conditions and/or vegetation obstructions limiting fording depth (Tables 4, 5). Operator spatial disorientation resulted because the channel was much wider at this site. Markers on trees were ineffective due to distance between markers and design features. Delivery trucks dumped gravel at area 3 which was overfilled. Poor operator estimation of depth in underfilled areas 4 and 6 yielded an oversized thalweg. Despite a 3.2% gravel deficit, this project had the highest observed as-built bulk density, 2.120 metric tons per m^3, for all project years (Table 2).

4.4 The 2004 Project

The 2004 project completed the two-phase design plan below Camanche Dam to rehabilitate downstream riffles and maintain high quality habitat. The design required 1,667 m^3 equivalent to an estimated 2,743 metric tons of gravel, and then 3,012 metric tons was provided. Overall, 68% of the 2004 total as-built project area was within ± 0.15 m of the design. Of the

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32% significantly deviating from the design, 58% was >0.15 m overfilled and 42% was >0.15 m underfilled.

Design versus as-built DEM analyses found eleven significant deviations (Fig.12); operator error caused half of these (Tables 4, 5). Areas 2 and 3 illustrate the tendency to overfill upstream sections of a project area, leaving downstream areas such as 6, 7, and 11 underfilled (Fig.12). This project's operator was only willing to work in very shallow water. For example, areas 3 and 8 were used as a safe pathway for gravel transport to the upstream section, but after construction this area was not re-graded down to the designed elevation. Area 8 received an extra 338 m^3 of fill due to spatial disorientation and proximity to a deep pool. Areas 5 and 9 illustrate minor DEM deviations due to boulder misplacement. Submerged wood and riparian shade trees played a role in limiting placement in areas 5, 6, 7, and 10. The as-built bulk density, 1.502 metric tons per m^3, was closest to the quarry estimated value (Table 2).

4.5 The 2005 Project

The 2005 project extended the rehabilitated longitudinal profile constructed in the 2003 and 2004 projects further downstream (Fig 2). The design required 1,950 m^3 (3,208 metric tons of gravel) and 3,384 metric tons was supplied (Table 2). Overall, 62% of the 2005 total as-built area was within ± 0.15 m elevation difference of the design. Of the 38% deviating from the design, 58% was >0.15 m overfilled, and 42% was >0.15 m underfilled. This greater percent of area with significant deviation relative to other years is explained by the relatively small project area and the greater fill depth associated with eliminating this unnatural pit.

Ten areas of significant deviation (Fig. 13) were found in the DEM comparison of design versus as-built topography for 2005. Intentional on-site design changes to accommodate wood placement caused an overfill in area 5. Area 8, the designed thalweg, was accidentally

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overfilled, which pushed it further toward the left bank than designed. The operator also filled ~15 m too far downstream past the designed project area, yielding area 9 with the largest volume of overfill for this year.

Operator gravel placement methods caused most of the 2005 site's errors. Like the 2004 project, there was a gravel surplus in 2005. However, unlike 2001-2004, the design of entrance and exit slopes for 2005 explicitly accounted for front-loader fording-depth capability and the unwillingness of the 2004 operator to risk damage to the front loader. As a result of this adjustment, it was easier to ascribe the relatively minor design deviations in areas 3, 4, 5 and 6 to poor elevation estimation by the operator , who turned out to be the same individual as from 2004. A surveyor periodically checked elevations referencing a grid with corresponding stakes at 6.1 m (20') intervals along the bank to aid the operator. The surveyor could guide the operator to improve grading but the front loader's tire tracks 0.15-0.3 m deep were unavoidable. Although tracks were observed in previous years, the 2005 project relied most heavily of all on having a surveyor guide the front-loader operator to ascertain if this would be an effective aid. Vegetation obstructions greatly hindered placement along the right-bank at area 7; thus, the operator overfilled the thalweg at area 8. Overfill in area 9 resulted from the following: (1) surplus gravel (2) right bank inaccessibility and (3) proximity to the front loader access point along the left bank. A deep downstream pool prevented shifting the gravel from area 9 to area 10. The as-built bulk density of the project was 1.434 metric tons per m^3; lower than the estimated quarry value. This enabled operators to fill an extra 409 m^3 of the site (Table 2).

5. DISCUSSION

The main goal of this study was to characterize as-built topography deviations from designs to aid adaptive management of geomorphic-unit rehabilitation construction methods.

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Another goal was to provide an example of an as-built assessment of design implementation, something that is lacking in the scientific literature. The National River Restoration Science Synthesis (NRRSS) found that only 10% of the ~37,000 river restoration projects nationwide recorded some form of assessment or monitoring (Bernhardt *et al.*, 2005). California has done somewhat better, where 22% of 4000 projects reviewed report monitoring (Kondolf *et al.*, 2007). River managers and stakeholders should continue to increase monitoring and post-project appraisals; however, insufficient funding and inconsistent agency mandates continue to inhibit the accomplishment of this collective goal (Wohl *et al.*, 2005). East Bay Municipal Utility District and the University of California at Davis have monitored LMR project sites for sediment budgets, channel hydraulics, inter-gravel permeability, dissolved oxygen concentrations, water temperature, macro-invertebrate diversity, and spawning patterns since 1998 (Pasternack, 2006).

The following subsections evaluate the overall practicability of design implementation by the aforementioned methods. Each design deviation source is assessed by category with recommendations for future projects. Then, these sources of error will help define criteria to assess successes and failures from ecological and geomorphic perspectives.

5.1 Sources of Errors in Design Implementation

5.1.1 Supply Uncertainties

The actual supply of gravel delivered for 2001 was deficient by 31%, but every year thereafter was within a few percent of the specified amount or in significant excess (Table 2). In 2001, the deficiency resulted from overestimation of salvageable gravel from an old hatchery channel. As a response to this uncertainty encountered in 2001, project planners in subsequent years designated low priority areas in which to abandon construction if contracted gravel was not delivered. Additionally, project planners continually sought funding for additional gravel to

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supplement guaranteed funding sources. Flexible designs and consistent effort to obtain gravel solved the supply deficit problem in project years 2002 to 2005. Another supply uncertainty may arise when the time between funding allocation and actual construction is delayed over several years, which occurred for a SHIRA project on the Trinity River below Lewiston Dam. During delays, gravel and diesel fuel prices may fluctuate and decrease the purchasing-power of allocated funding.

5.1.2 Construction Operations

Over all project years, the most common construction error was the operator's poor elevation/depth estimation, which accounted for 28% of all errors (Table 5). Operator spatial disorientation, wood obstructions, gravel deficits, and fording limitations had nearly equal occurrences each accounting for 13-18 % of errors (Table 5). Surveying errors, boulder placement deviations, and operator experience also contributed to problems with each project.

Combined factors influenced inaccurate riffle construction adjacent to deep pools. Adjacent banks lacked thorough markers to clearly identify upstream and downstream gravel placement limits of individual features. The operators repeatedly used excess gravel to construct riffle entrances leaving a deficit for riffle exits. However, this problem persisted even when those locations were clearly marked in 2005, because front loaders can only build steeply-sloped features. Equipment limitations prevented operators from creating the designed gentler riffle entrance and exit slopes. However, gravel tends to landslide down steep slopes so over time a gentler gradient will develop on its own. Alternately, an excavator located on the bank would eliminate error due to fording limitations but would have limited access to channels wider than its arm length (~4-7 m) and may damage the riparian corridor.

For front loader construction, project planners must design topography without gentle

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slopes. This simplified design approach was used in 2005 and proved highly practicable. Also, overhanging vegetation and dead wood obstructions (especially along the river-right bank) constrained accurate design implementation in all years in the locations where those features occurred (Fig. 3). Front loaders cannot easily place gravel beneath overhanging vegetation or around wood pieces near pools; thus, the project design should not include construction in these areas. As an alternative, placement of gravel upstream can promote eventual infilling around wood.

It was important to have in-depth conversations with the operators throughout the project to facilitate understanding between designers, managers, and operators. For instance, an on-site conversation with the 2004-2005 operator toward the end of the 2005 project increased the design team's understanding of the operator's gravel placement methodology. The operator suggested initially underfilling an area and then adding extra gravel to construct the designed grade, because initial overfill is difficult to reduce to the desired elevation. These statements are supported by net overfill in 2004 and 2005 (Table 3). These areas were not corrected because the operator and front loader were unable to back-scrape effectively. Given that projects are only built for a few days each year and that the participants change, a lack of time exists for developing highly effective integration and teamwork between all project participants.

Grid-based stakes were intended to be more effective than feature-based stakes. The feature-based method provided fewer markers and required more estimation by the operator who tended to misalign or accentuate features. Grid-based markers placed at ~6 m intervals along the bank did not significantly aid the operators' gravel placement accuracy and in-channel markers were not used. Additionally, surveyor elevation checks and flow path evaluations were used to help the operator improve grading, but once the bed was within 0.15-0.3 m it was difficult to improve due to tire tracks. Operator elevation checks using tire submergence were difficult on

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finer gravel because the front loader had difficulty gaining traction on deep, small gravels. Tire tracks ~0.1-0.2 m deep streaked the length of each project in 2001 and 2002. To test whether Chinook would use transverse tracks as proto redd dunes the front loader ran cross-channel at the end of construction in 2003-2005, but subsequent spawning showed no related pattern (Elkins *et al.*, 2007). Future gravel augmentation projects with front loaders should consider using in-channel markers and grid-based stakes placed at a finer resolution to measure gravel fill and water depth at key locations. A recent trial of feature-based, in-channel staking with color-coded labels to match fill depths was attempted during the 2007 project on the LMR. The project manager anecdotally reported the approach to be effective.

5.1.3 As-built Bulk Density

This study found that as-built bulk density of placed gravel in a river can vary significantly. Merz *et al.* (2006) studied bulk density effects at a single streambed-enhancement site within the same river reach as investigated in this study. They reported that bulk density of dry gravel measured in six, 19-L buckets at a nearby quarry was 1.645 ±0.054 metric tons per m^3. Averaging across all projects, the bulk density of the as-built projects was 1.809 metric tons per m^3, which is within 10% of the bucket-test value. However, the range of values was 1.434-2.120 metric tons per m^3, corresponding to 9-29% deviations from the estimated quarry value. Theoretically, bulk density is affected by the particle size distribution in each project and by compaction and breakage during the placement process (Merz *et al.*, 2006). The two least densely packed projects corresponded with the deliveries that had the two largest median grain sizes (Table 2). Similarly, the two most densely packed projects corresponded with the deliveries that had the two smallest median grain sizes. However, the data is too sparse and noisy to show a definitive relationship between as-built bulk density and particle size distribution.

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Front loader movement over the riverbed during construction causes gravel compaction to an unknown degree. During construction, a front loader enters the river at designated points to limit riparian damage and thus drives over built gravel paths many times en route to placement points. Due to repeated traffic, areas closest to the placement points may have a greater bulk density. The 2001-2003 sites were constructed using a single access point at the upstream end of each site, whereas the 2004 and 2005 sites were constructed using 2 access points each. Multiple access points reduce compaction due to loader traffic over placed material. Using multiple access points or placing material with an excavator instead of a front loader may result in a more predictable as-built bulk density. However, designs are made on a volumetric basis and gravel is purchased by weight. The design and construction process must use the best estimate of as-built bulk density so that contracted gravel supply volume will yield elevations of the designed channel morphology. This uncertainty requires further investigation.

In the case of optimal design compliance, only construction compaction or grain breakage would affect the channel bed elevation; however, this is not a realistic expectation. Through 2003, Merz *et al.* (2006) monitored the fate of gravel placement projects built on the Mokelumne in 1999, 2000, and 2001. At the end of the first year, each site had 14-20% volumetric loss. Subsequent annual losses were 3-10%. Although some of the losses were attributable to surficial scour, detailed analysis of a variety of mechanisms revealed that the majority of loss was attributable to deflation and compaction in this low-slope setting (Merz *et al.*, 2006). To address this, managers can build projects with vertical or overlapping layers phased over multiple years. Then gravel can self-adjust and adaptive design can respond to observed changes. This is also beneficial because it spreads funding needs over multiple years. Elkins *et al.* (2007) found no detrimental biological effects of phasing construction in this way during a 2003 to 2004 slope creation gravel augmentation project at the LMR.

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5.2 Ecological Implications of Geomorphic-unit Rehabilitation

This study determined that 70% of all as-built topography matched the designs. Before implementation, these project designs were evaluated using the SHIRA framework, based on ecological, geomorphic, and hydrologic processes. Collectively, these projects can be considered successful according to aforementioned project goals. Physical measurements taken pre- and post-gravel placement in 2000-2002 at one rehabilitated site showed increased water velocities, intergravel permeability, and dissolved oxygen as well as reduced depths and temperature differences between ambient and intergravel water (Merz and Setka, 2004). In addition, Merz and Ochikubo Chan (2005) found that clean gravels introduced into the LMR during 1996-2000 were colonized within 4 weeks by benthic macroinvertebrates of statistically equal density, biomass, and species richness as unenhanced spawning sites.

The 30% of rehabilitated channel area that deviated from designs did not affect predicted high quality habitat areas. Elkins *et al.* (2007) showed that high quality habitat (as defined by SHIRA) increased by 471% after the 2003 and 2004 combined projects. Also, predictions about preferential use of high quality spawning habitat by Chinook salmon in 2003 and 2004 were statistically confirmed by comparing them against actual observed spawner utilization at these sites (Elkins *et al.*, 2007). However, the presence of physical habitat is just one factor influencing salmonid populations. In California, watershed degradation, diversions, high precipitation variability, and predation interactions between introduced and wild stocks all influence salmonids (Moyle, 1994). The overall success of habitat rehabilitation is not completely dependent on habitat availability. Nevertheless, the use of SHIRA and related process-based methods appears to effectively eliminate habitat quality and quantity from the set of cummulative impacts hurting aquatic populations.

To account for expected construction uncertainty based on typical operator errors observed in this study, one approach would be to perform a pre-project modeling experiment determining the maximum allowable as-built depth deviation before a decline in high quality habitat would be expected to occur. Project designers could run 2-D hydrodynamic models of theoretical as-built topography with increased positive or negative elevation deviation at areas of concern. For example, a key test would check the impact of incorrect riffle crest elevation, which is highly sensitive and responsible for setting upstream backwater conditions (Clifford and French, 1998). Model outputs with various deviations could then be evaluated for their pattern of habitat quality for target species and life stages by coupling model results with habitat suitability curves (from Leclerc *et al.*, 1995). Though time consuming, this analysis would help project managers determine acceptable design deviations that still meet project goals.

5.3 Geomorphic Self-Sustainability as a Goal of Rehabilitation Projects

Currently, defining success or failure of river restoration projects depends on the stated goals of the individual project. Ecologists and geomorphologists are still developing acceptable process-based success criteria imperative to advancing river restoration, but the universality of such criteria for all rivers in all environments remains highly uncertain (Downs and Kondolf, 2002; Palmer *et al.* 2005). Depleted gravel supply and high transport capacity below persistent dams will affect the self-sustainability of gravel augmentation and it is doubtful that functional high-quality aquatic habitat can be maintained without on-going intervention (Pasternack, in press). Brooks *et al.* (2006) emphasize that regular intervention may not be a desirable management goal, but it is the reality of river rehabilitation in supply-limited systems, especially in the incipient stages of recovery.

Since Camanche Dam was built in 1964, the LMR has incised and degraded riffles into

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homogeneous glides. The main channel is disconnected from available sediment storage in historical side channels and island complexes. Thus, multiple gravel augmentations and habitat enhancement projects on the LMR are not indicative of individual projects lacking self-sustainability, but rather of a commitment to gradually mitigate a 40-year gravel deficit estimated as ~50,000 metric tons (Pasternack, 2006). According to the overall long-term management plan, the first phase of gravel augmentation and habitat rehabilitation 1999-2010 is expected to largely undo that long-term deficit. As of September 2007 a total of 29,873 metric tons have been placed. Once a baseline geomorphic balance has been restored to the system, then long-term self-sustainability will be promoted with small gravel injections at the dam to meet annual conveyance needs as estimated by Merz *et al.* (2006). Though the longevity of gravel augmentation projects is still unknown, long-term monitoring will facilitate adaptive management. The highly variable hydrology of the Californian Mediterranean climate may require a longer monitoring period to incorporate infrequent high flow events into project assessment (Kondolf *et al*., 2007) even in a regulated river such as the lower Mokelumne River.

6. CONCLUSION

In this investigation, the construction of detailed river rehabilitation designs emphasizing salmonid spawning habitat as the key ecological indicator was monitored and the sources of design deviations assessed. Overall, 70% of the 5 projects spatially replicated the designed topography. Construction with a front loader reasonably approximated the design features with more than 0.5 m relief. As evaluated in other studies (Wheaton *et al.*, 2004b, c; Merz *et al.*, 2006; Pasternack *et al.*, 2006; Elkins *et al.*, 2007), the construction yielded desired hydrologic and geomorphic processes for enhanced ecological productivity. Of the 30% of total as-built project area that deviated from the design surface, every project year showed regions of

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underfilling and overfilling. In the 2001, 2002, and 2003 projects, significant deviations were on average underfilled. In 2004 and 2005, the areas of significant deviation were overfilled.

Three major categories of deviations were found - gravel supply uncertainties, construction errors and as-built bulk density differences. Project management uncertainties made gravel supply deficits and as-built bulk density differences difficult to eliminate. We recommend developing spatially sectioned designs with an established prioritization for construction. Then gravel placement over multiple years can enable adaptive design and construction. Gravel supply deficits were consistently exacerbated by the operator's tendency to place too much gravel on riffle entrances. Operator spatial disorientation and front loader fording depth limitations prevented riffle entrance slope construction at the correct location. It is recommended to use fine resolution, on-bank and in-channel grid-based staking, frequent elevation checks and excavators for grading riffle entrance and exit slopes. There is a need to develop gravel placement methods where obstructions such as overhanging riparian vegetation or instream wood pieces exist. Designs should adapt to the abilities of available methods and equipment for the most accurate construction. Finally, project managers should provide on-site explanations of objectives and fundamental hydraulic processes to the construction crew to increase understanding and improve outcomes.

Using a front loader to build broad scale (> 0.5-m relief) design features based on geomorphic processes was reasonably effective. However, uncertainties attributed to human error and available methods inhibit detailed (< 0.5-m relief) rehabilitation. Despite uncertainties, limitations, and errors, following the recommendations reported in this study would improve as-built adherence to design specifications of future projects. This study exemplifies a post-project appraisal within the adaptive management loop in river restoration, but like most projects in the early stages of monitoring programs, spatial and temporal effectiveness over years to decades

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must still be considered.

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Table 1. Front loader specifications for LMR project sites by year

Year	Front loader model	Weight (kg)	Height to center of hub (m)	Tires	Footprint (kPa & (psi))
2001	Volvo 120E	20043	0.69	23.5R25	61.7 (8.95)
2002	Caterpillar 966G*	23752	0.86	26.5R25	61.2 (8.87)
2003	Caterpillar 966F*	23752	0.86	26.5R25	61.2 (8.87)
2004	Caterpillar 966F*	23752	0.86	26.5R25	61.2 (8.87)
2005	Caterpillar 950F*	18380	0.74	23.5-25-20PR	55.5 (8.05)
Reference	Komatsu WA400-5	18682	0.71	23.5-25-16PR	58.4 (8.47)

*Actual models used; specifications taken from newer 966H and 950H models.

Table 2. Design, purchased and as-built gravel metrics for each project year

Metric	2001	2002	2003	2004	2005
Design volume (m^3)	1147	1448	2020	1667	1950
Required supply (t)	1887	2382	3323	2743	3208
Purchased supply (t)	1307	2786	3217	3012	3384
Supply deviation (%)	-31	17	-3	10	5
Median grain size (mm)	55	64	59	82	71
Estimated density (t/m^3)	1.645	1.645	1.645	1.645	1.645
Purchased volume (m^3)	794	1694	1955	1831	2057
As-built volume (m^3)	649	1410	1517	2005	2359
As-built density (t/m^3)	2.013	1.976	2.120	1.502	1.434
Density deviation (%)	22	20	29	-9	-13

Table 3. Average areas of overfill, underfill and insignificant variation

Year	Percent of total area within ±0.15 m difference	Percent of total area of >±0.15 m difference	Percent of area overfilled*	Percent of area underfilled*
2001	81	19	17	83
2002	79	21	43	57
2003	64	36	31	69
2004	68	32	58	42
2005	62	38	58	42
Average	71	29	41	59

*Relative to area of > ±0.15 m difference.

Table 4. Potential sources for deviation in construction of a project design

	Area ID for each location of deviation from design				
Causes of error	2001	2002	2003	2004	2005
Gravel deficit	1,4,5,6	8,10,11	2,6,8		
Fording depth limitations		1,4,8,9	2,8	6,7	10
Operator's skill/experience/willingness			2,8		
Operator's spatial disorientation	2,3	1,5	1,2,6,5	1,8,11	8,9
Operator's poor elevation estimation	4,5	2,3,4,6,7	1,3,4,5	2,3,4,8	2,3,4,5,6
Overhanging vegetation		8	2,7,8	5,6,7,10	1,7
Gravel bulk density error					
Surveying errors/boulder placement		9		5,9	1,5,7

Table 5. Design deviation causes of error distributed by percentage for each year

Cause of error	2001	2002	2003	2004	2005	All years
Gravel deficit	50	19	17	0	0	14
Fording depth limitations	0	25	11	13	7	13
Operator's skill/experience/willingness	0	0	11	0	0	3
Operator's spatial disorientation	25	13	22	20	14	18
Operator's poor elevation estimation	25	31	22	27	36	28
Overhanging vegetation	0	6	17	27	21	15
Gravel bulk density error	0	0	0	0	0	0
Surveying errors/boulder placement	0	6	0	13	21	8

FIG. CAPTIONS

Figure 1. Map of the Mokelumne River basin showing locations of Salt Springs, Camanche and Pardee Reservoirs. The project sites were located in the gravel-bed reach downstream of Camanche Dam.

Figure 2. Clip of U.S. Geological Survey topographic map (Clements quadrangle, California) adapted to show the locations of each project site by year.

Figure 3. Construction with a rubber tire front loader (Caterpillar 966F) on river right of the 2003 project. Overhanging vegetation impedes access close to the bank.

Figure 4. Contour maps with 0.5 m intervals of the 2001 A) design and B) as-built topography for comparison of desired designed elevations to constructed elevations.

Figure 5. Contour maps with 0.5 m intervals of the 2002 A) design and B) as-built topography for comparison of desired designed elevations to constructed elevations.

Figure 6. Contour maps with 0.5 m intervals of the 2003 A) design and B) as-built topography for comparison of desired designed elevations to constructed elevations.

Figure 7. Contour maps with 0.5 m intervals of the 2004 A) design and B) as-built topography for comparison of desired designed elevations to constructed elevations.

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Figure 8. Contour maps with 0.5 m intervals of the 2005 A) design and B) as-built topography for comparison of desired designed elevations to constructed elevations.

Figure 9. Contour map with 0.15 m elevation change intervals between as-built and design for the 2001 project. Areas 1, 4, 5, and 6 were underfilled due to lack of gravel at the time of construction. See Table 4 for sources of error by area number.

Figure 10. Contour map with 0.15 m elevation change intervals between as-built and design for the 2002 project. Note that area 5 (side channel) and 6 (designed thalweg) were overfilled and area 7 (designed longitudinal bar) was underfilled. Visual observations and 2-D model simulations showed that the flow was divided, but not to the designed extent. Area 9 represents misplaced boulders and areas 10 and 11 were not filled due to gravel deficit. See Table 4 for sources of error by area number.

Figure 11. Contour map with 0.15 m elevation change intervals between as-built and design for the 2003 project. The riffle crest and chute elevation (areas 1 and 3) were overfilled, whereas the chute's length, area 4, was underfilled. This resulted in a much longer but shallower chute along the left bank. See Table 4 for sources of error by area number.

Figure 12. Contour map with 0.15 m elevation change intervals between as-built and design for the 2004 project. Note the overfilling of the upstream side channel at area 3 and at the pool tail at area 8 yielding a very steep slope transition. Also, note the underfilling at area 11, due to misplaced gravel used in other locations. See Table 4 for sources of error by area number.

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Figure 13. Contour map with 0.15 m elevation change intervals between as-built and design for the 2005 project. Note that deep areas along river right were underfilled due to vegetation obstructions (areas 2 and 7). Also, note the overfilled thalweg (area 8) and downstream end of the site (area 9). See Table 4 for sources of error by area number.

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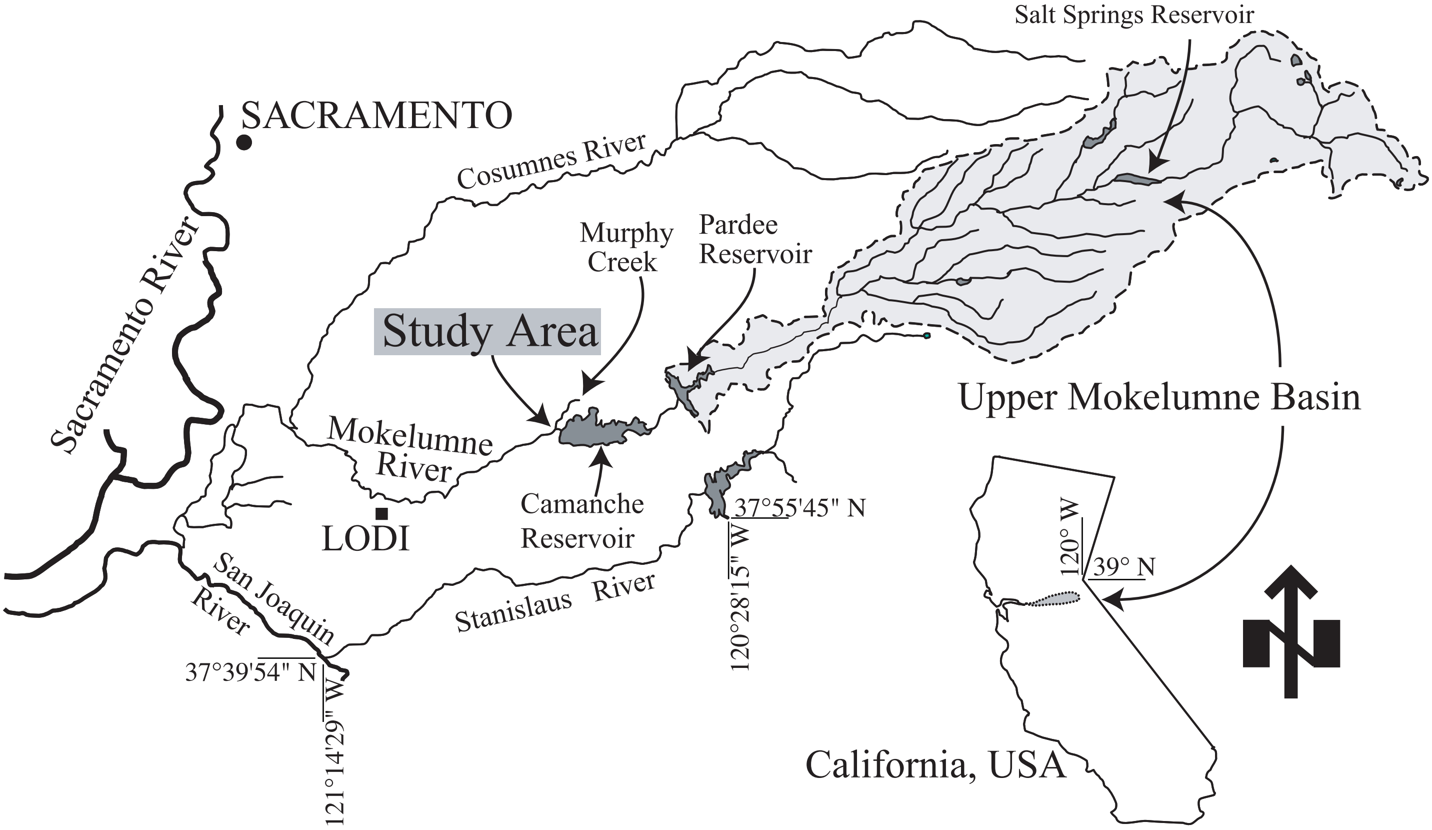
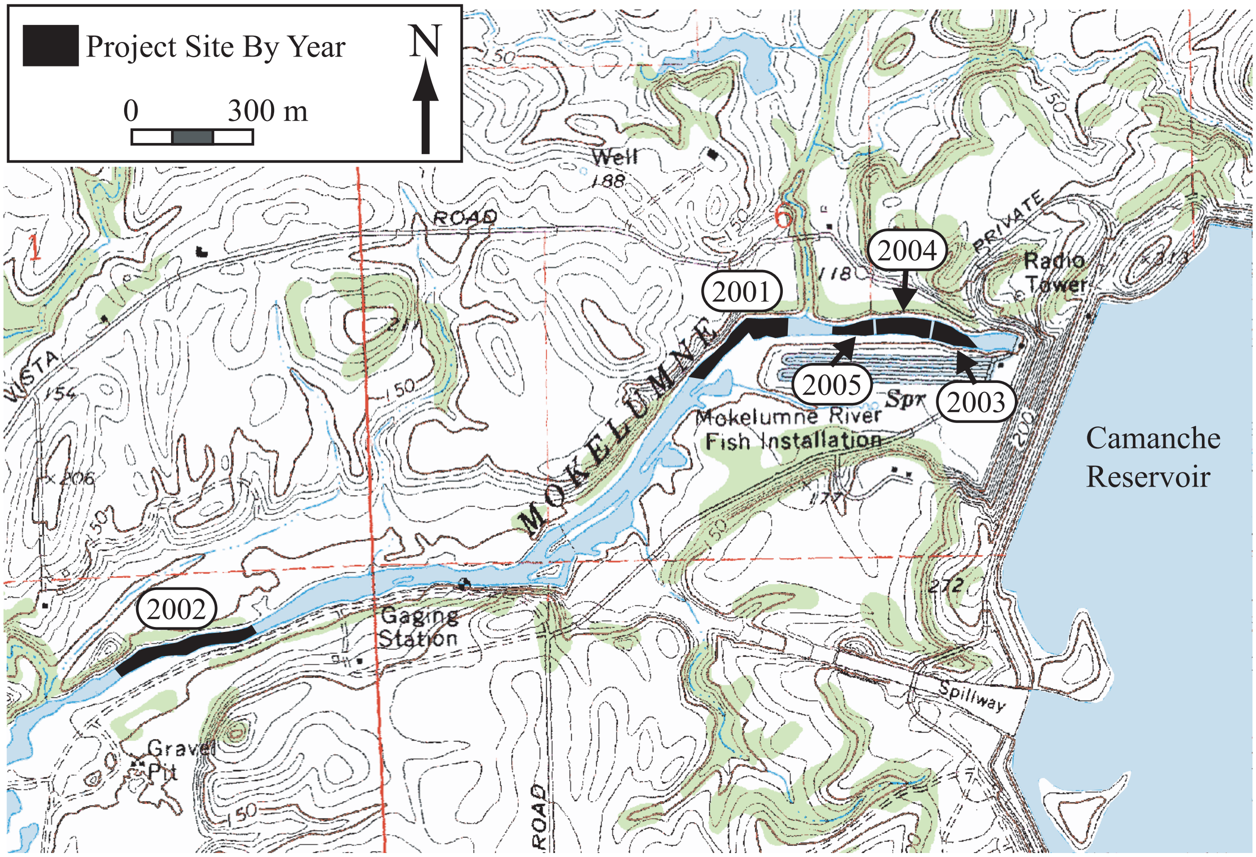
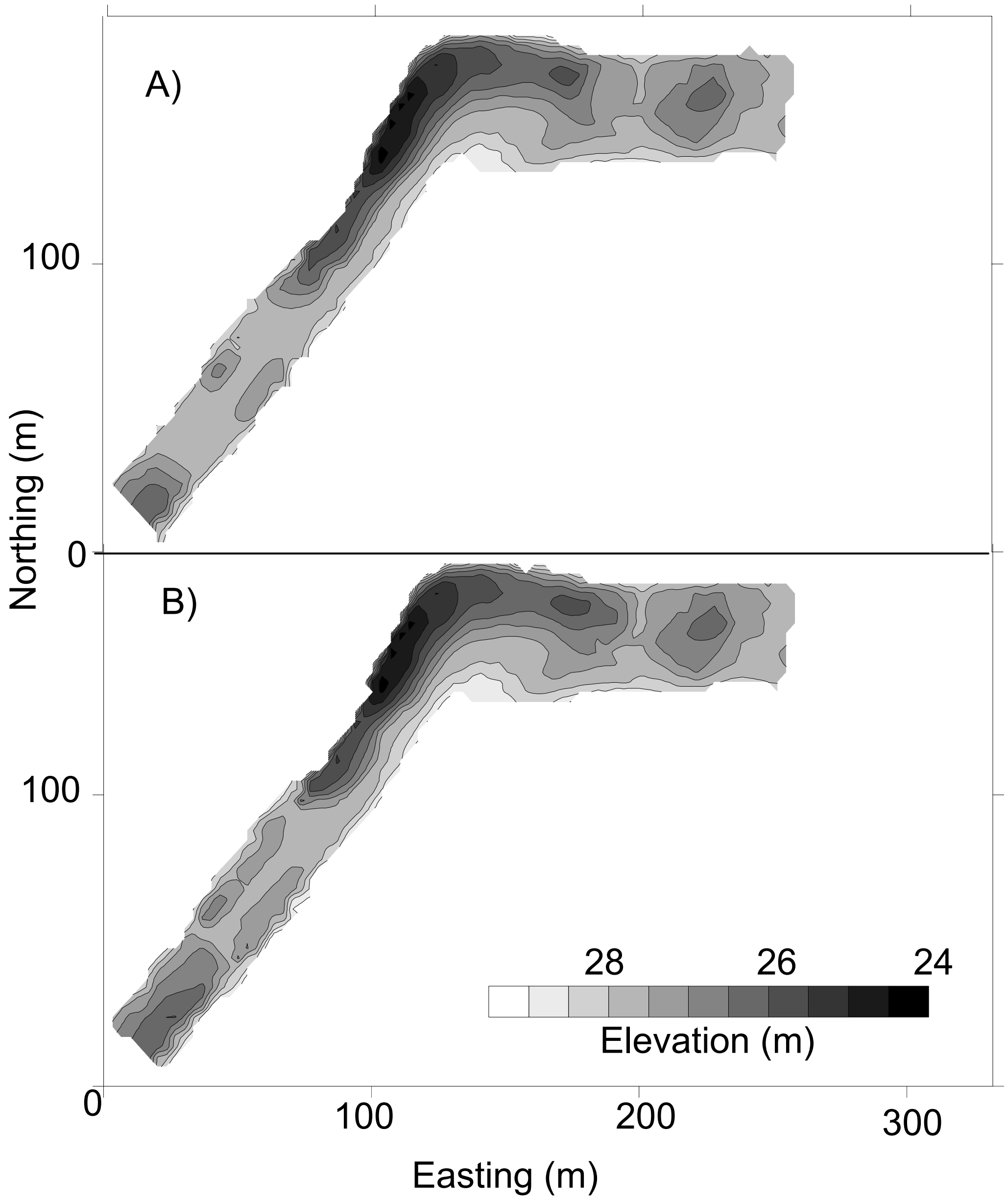

Salt Springs Reservoir
SACRAMENTO
Cosumnes River
Sacramento River
Murphy Creek
Pardee Reservoir
Study Area
Upper Mokelumne Basin
Mokelumne River
Camanche Reservoir
LODI
37°55'45" N
120°28'15" W
120° W
39° N
San Joaquin River
Stanislaus River
37°39'54" N
121°14'29" W
California, USA


Project Site By Year
0
300 m
N
2001
2002
2003
2004
2005
MOKELUMNE
Mokelumne River Fish Installation
Camanche Reservoir
Radio Tower
PRIVATE
ROAD
VISTA
Well
188
118
154
206
272
177
200
150
Spr
Gaging Station
Gravel Pit
Spillway
ROAD
1
6


918
SSCF
HOLT BROS
CAT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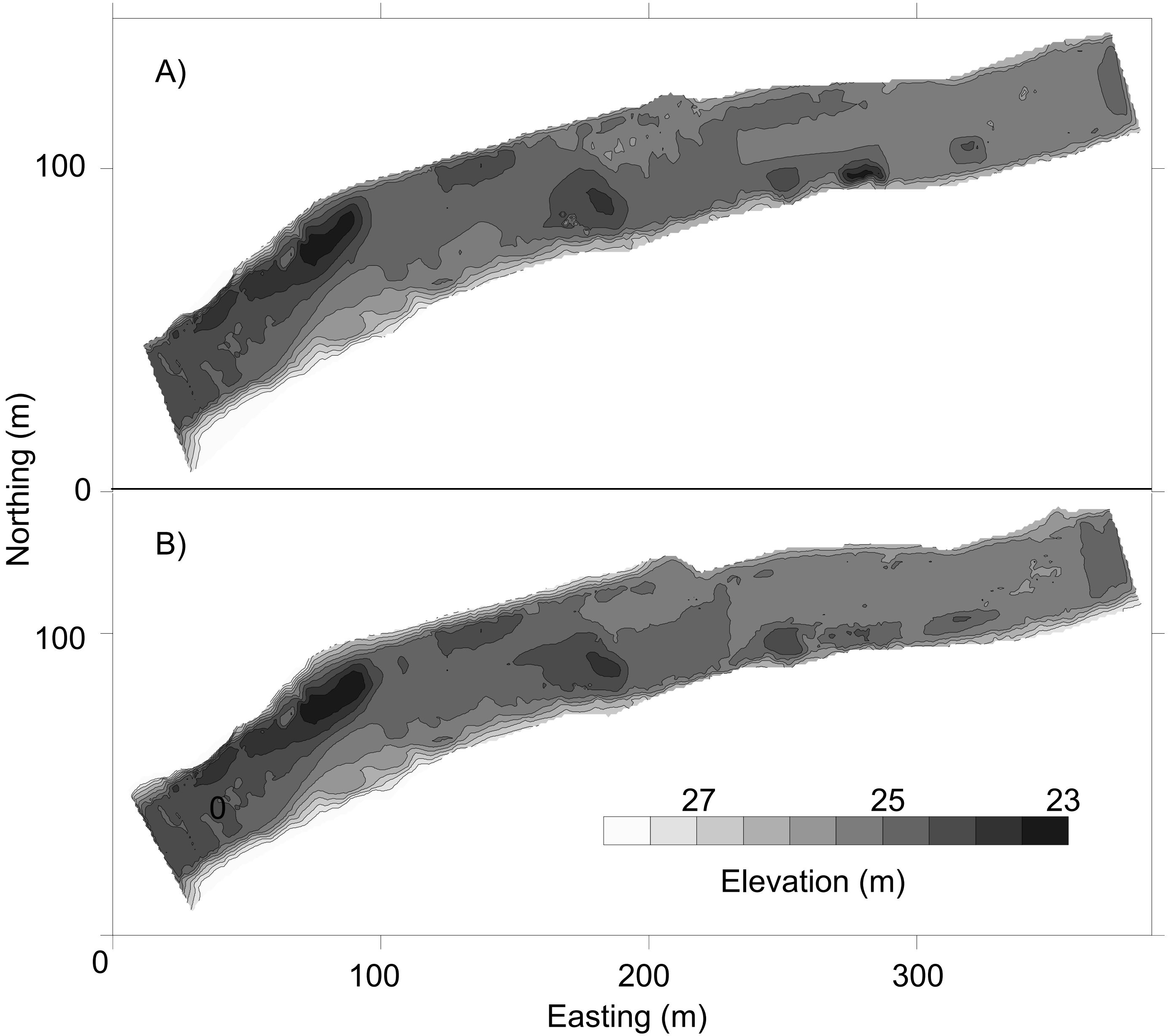
B)
Northing (m)
100
0
100
0
100
200
300
Easting (m)
28
26
24
Elevation (m)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B)
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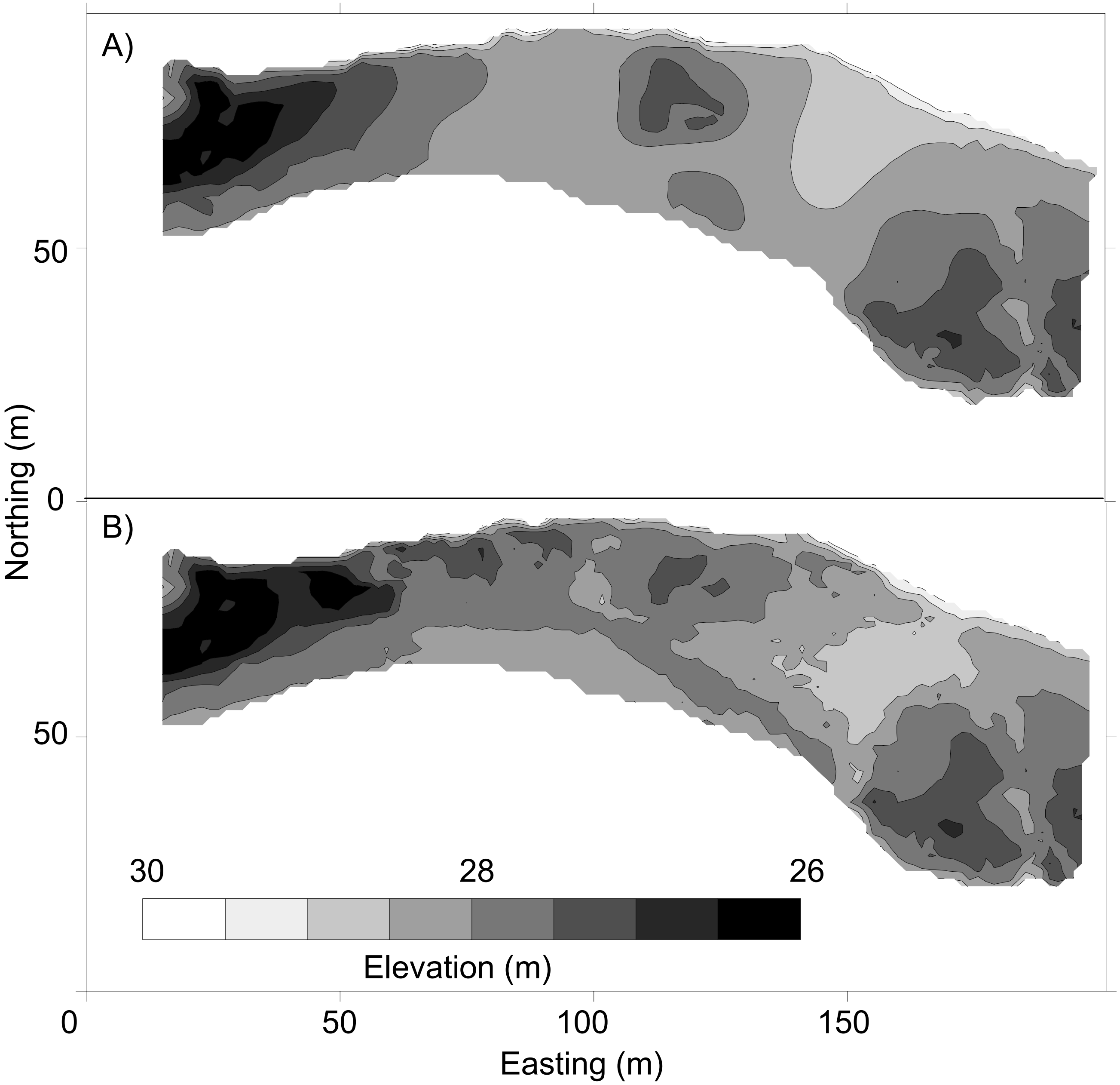
0
100
Northing (m)
0
0
100
200
300
Easting (m)
27
25
23
Elevation (m)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B)
Northing (m)
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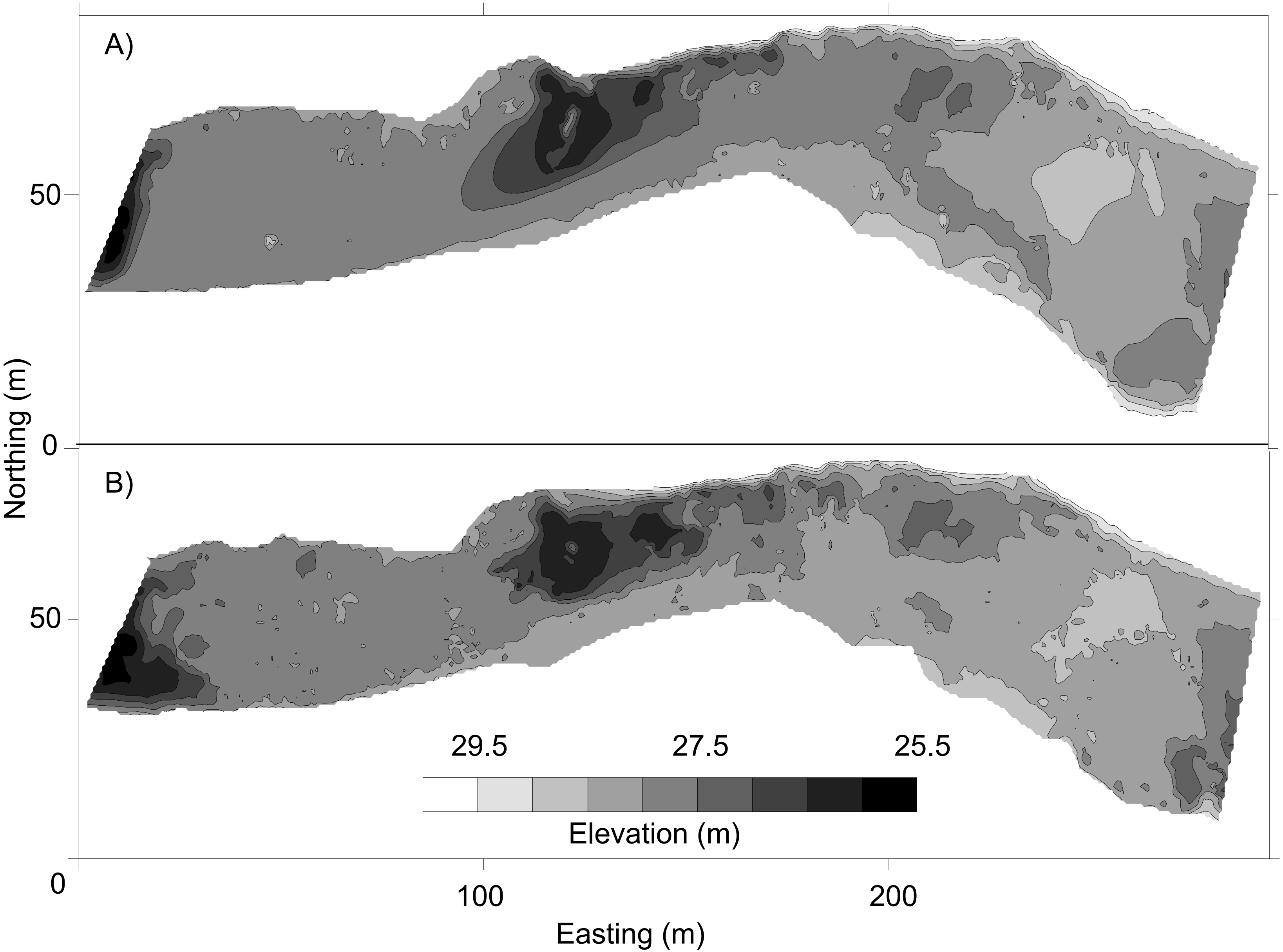
50
Easting (m)
0
50
100
150
30
28
26
Elevation (m)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B)
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200
Easting (m)
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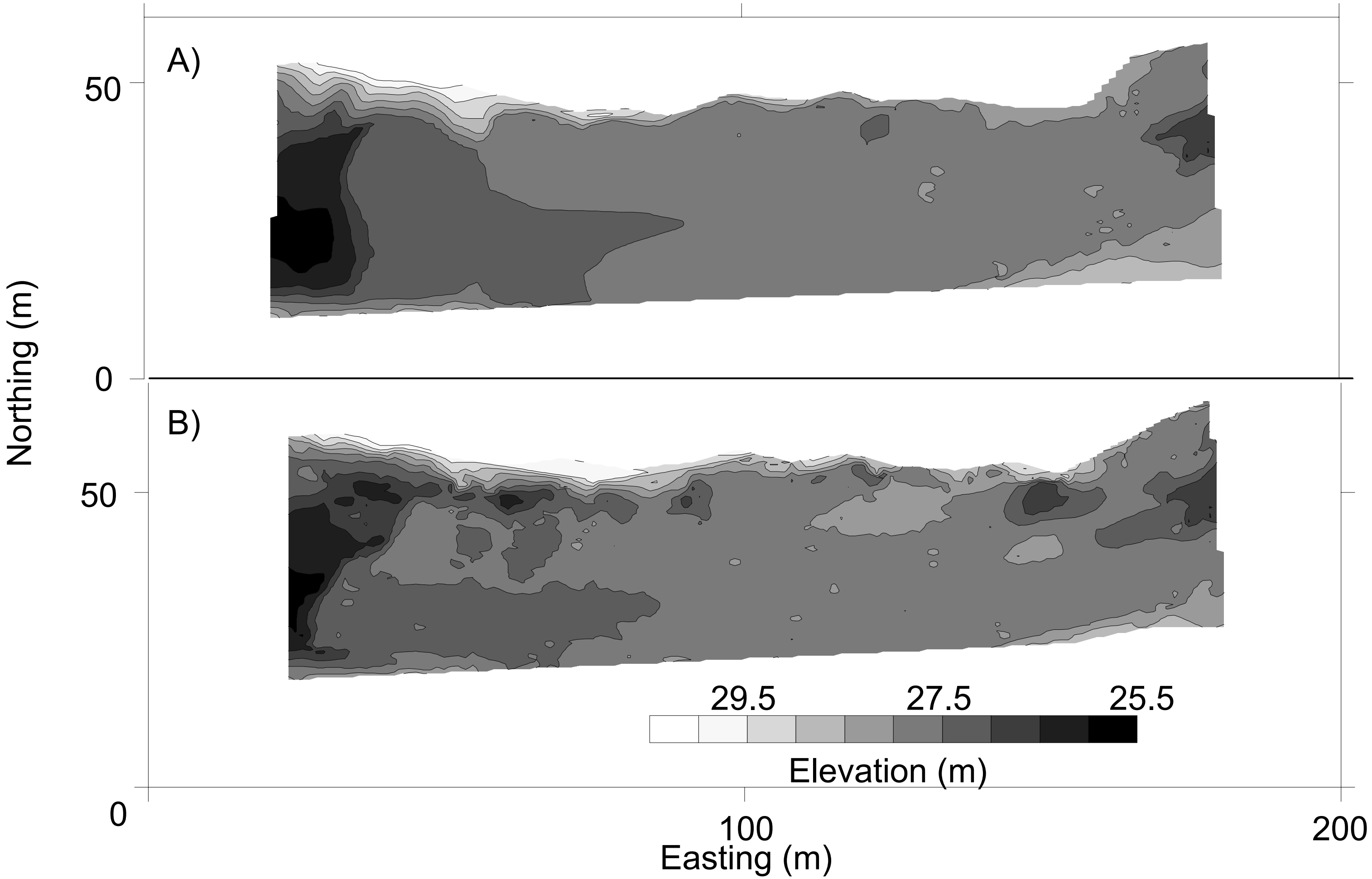
27.5
25.5
Elevation (m)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B)
Northing (m)
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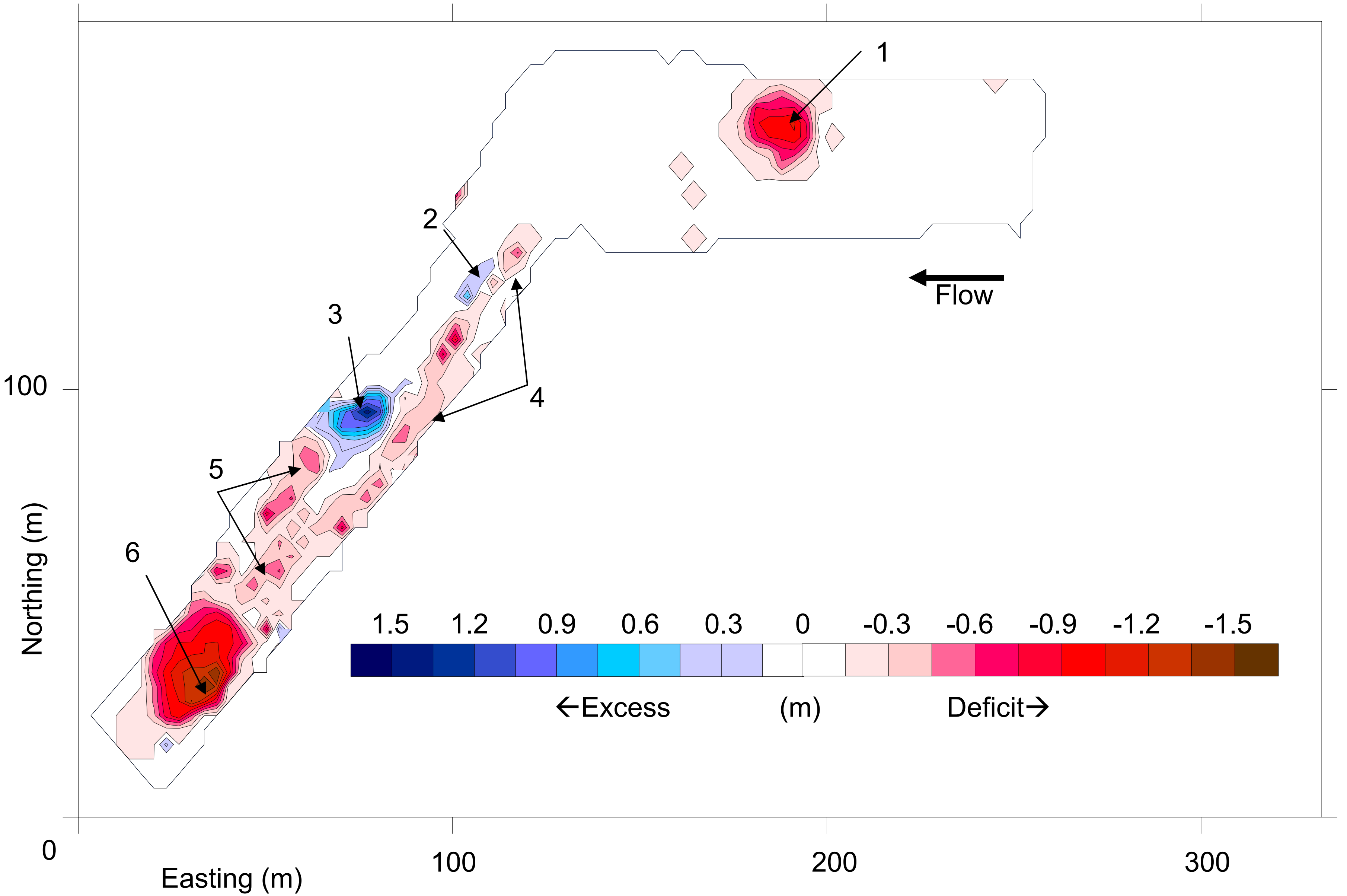
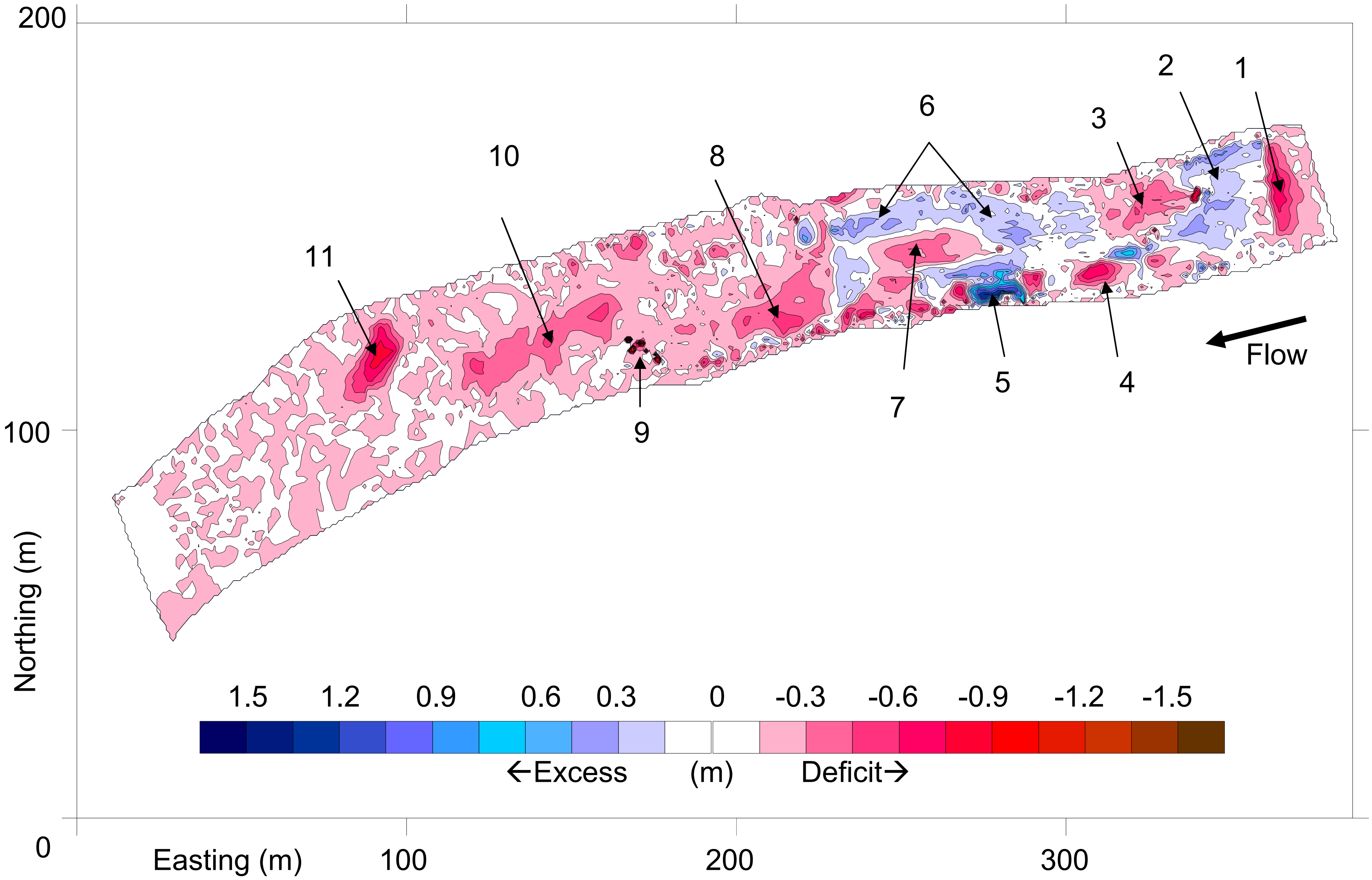
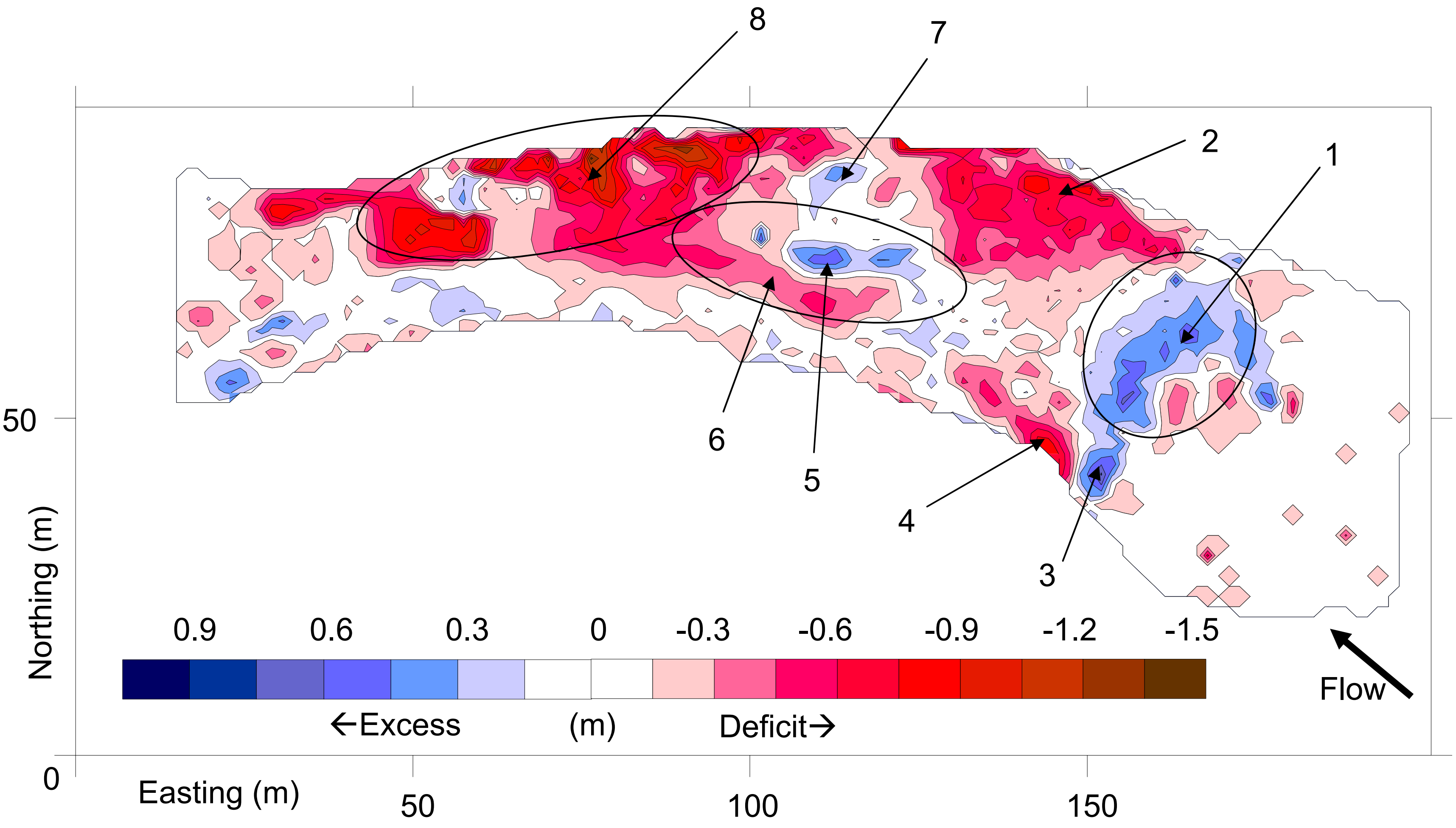
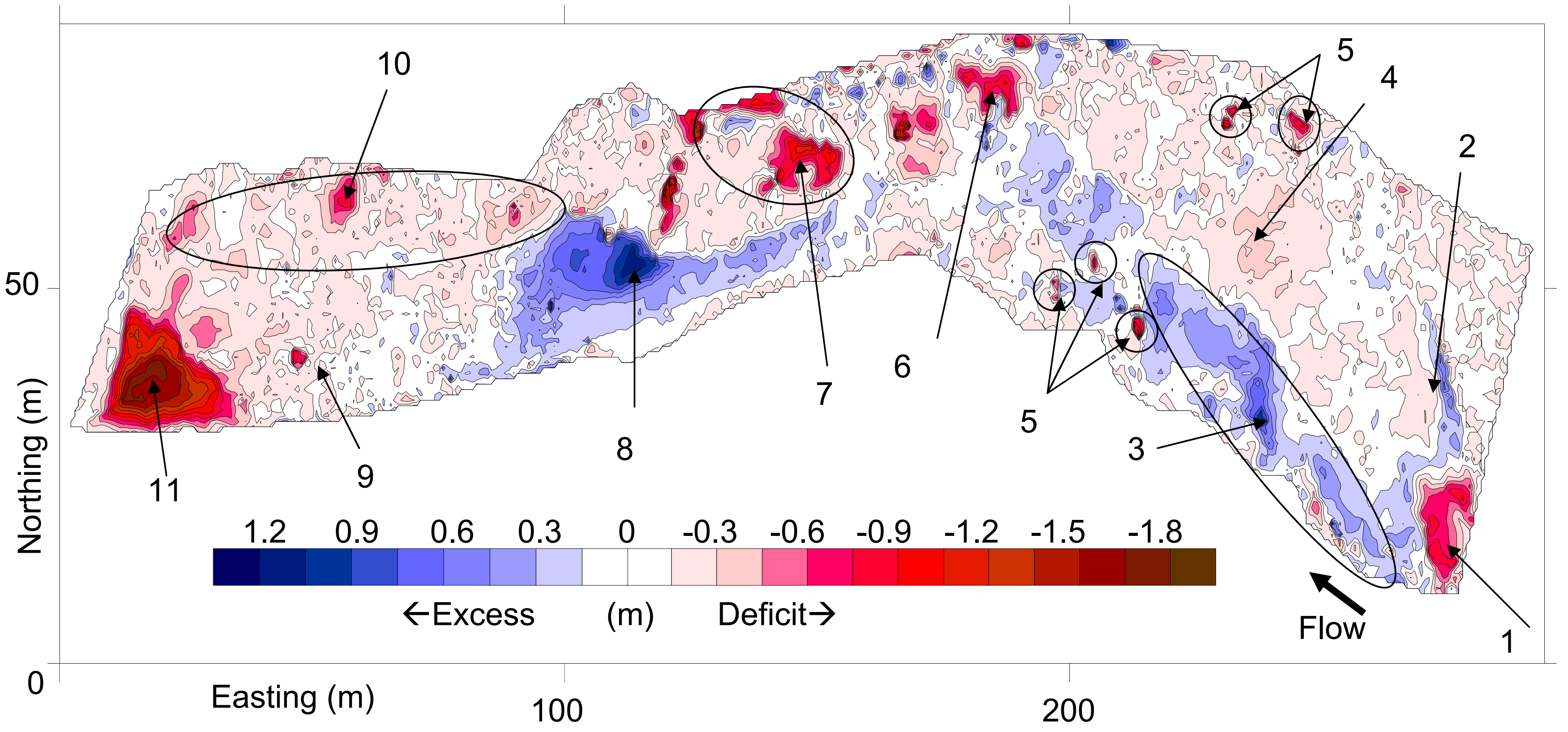
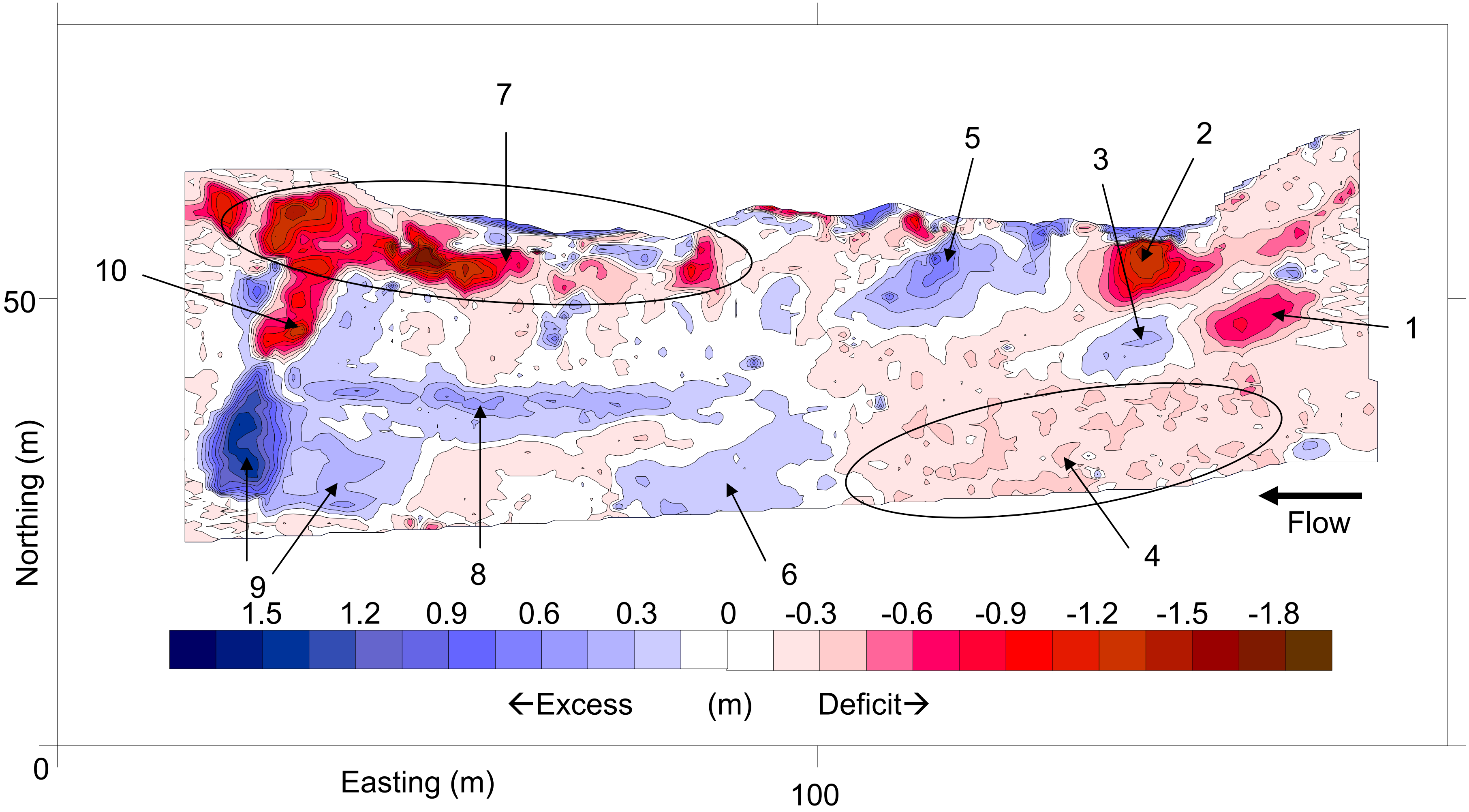
0
50
0
Easting (m)
100
200
29.5
27.5
25.5
Elevation (m)


1
2
3
4
5
6
Flow
100
0
100
200
300
Northing (m)
Easting (m)
1.5
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
←Excess
(m)
Deficit→


200
100
0
Northing (m)
Easting (m)
100
200
300
1
2
3
4
5
6
7
8
9
10
11
Flow
1.5
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
←Excess
(m)
Deficit→


8
7
2
1
6
5
4
3
50
0
Northing (m)
Easting (m)
50
100
150
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
←Excess
(m)
Deficit→
Flow


10
5
4
2
7
6
8
9
11
5
3
1
Flow
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
-1.8
←Excess
(m)
Deficit→
Northing (m)
50
0
Easting (m)
100
200


7
5
3
2
10
1
9
8
6
4
Flow
50
0
100
Northing (m)
Easting (m)
1.5
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
-1.8
←Excess
(m)
Deficit→