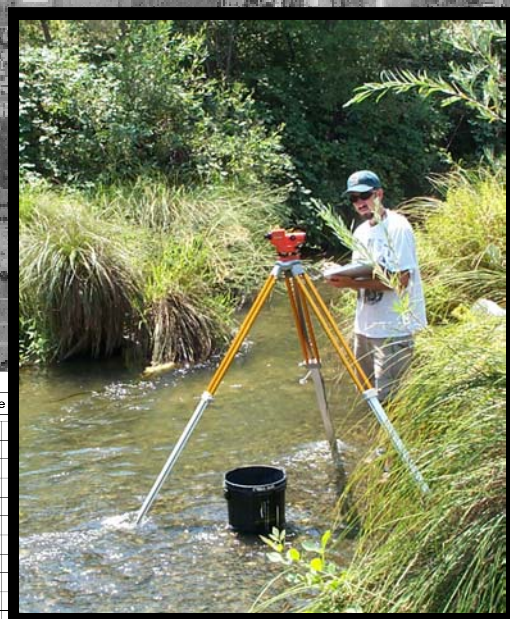
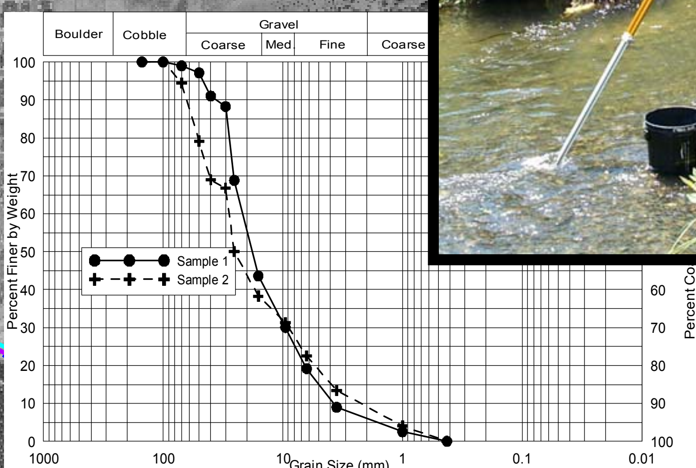
GRAVEL AND TEMPERATURE SURVEYS OF LOWER PUTAH CREEK





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Prepared for:
Lower Putah Creek Coordinating Committee
Vacaville, CA
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Gravel and Temperature Surveys of Lower Putah Creek

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EXECUTIVE SUMMARY

Major historical changes in the alignment, flow regime and sediment supply of lower Putah Creek have likely affected the quantity and distribution of streambed gravels suitable for fish spawning, but those effects have not previously been studied. The primary purpose of the present study is to document the distribution and texture of unconsolidated sediment along the bed of lower Putah Creek. In addition, this report documents historical changes in creek alignment and profile, describes sediment lithology, presents results of hydraulic simulations of bed shear stress, and characterizes changes in water temperatures resulting from removal of beaver dams by floods.

Lower Putah Creek is located in the southwestern corner of the Sacramento Valley and flows 26 miles across the valley floor from Putah Diversion Dam to the Toe Drain in the Yolo Bypass. Putah Diversion Dam is a reregulating reservoir below Monticello Dam, which controls runoff from 90 percent of the watershed. Both dams block the transport of coarse sediment along the creek. The lowermost 11 miles of the creek flow along an artificial alignment constructed over a century ago, which caused incision and steepening of the channel profile.

Preferred spawning site characteristics for trout and steelhead, chinook salmon, Pacific lamprey and resident native fish were tabulated from scientific literature review and interviews of experts. To the extent possible, the characteristics were expressed quantitatively in terms of flow depth, flow velocity, substrate texture and substrate thickness.

A canoe-based survey mapped hydraulic and substrate conditions along the entire length of lower Putah Creek, using GPS for location and steel probes, current meters and visual inspection to measure various channel, substrate and flow characteristics. The data were compiled into a digital database (geographic information system) as a one-dimensional linear map of the creek, with mapping segments as short as 9 feet. Segment attributes included flow width, depth and velocity, hydraulic category (pool, riffle, run), and substrate type (eight categories). The database was queried to determine the total number of river miles meeting the physical criteria for spawning habitat for each of the four groups of fish species. The resulting estimates of potentially suitable spawning habitat for trout/steelhead, salmon, lamprey and resident natives are 4.0, 1.9, 1.7 and 1.4 river miles, respectively.

Sixteen sites identified as potentially suitable spawning sites for salmon during the first survey were selected for detailed site investigations. Several transects across the creek were surveyed at each site, with water depth, water velocity, bed elevation and gravel thickness measured along each transect. These data were converted into maps and cross-sections for evaluation by fish biologists. The cross sections revealed that even at relatively good potential spawning sites, only one-fifth to one-third of the channel width strictly met the physical suitability criteria. Insufficient water depth was by far the most common limiting factor, although it would be less limiting during the winter-spring spawning season when flows are often higher.

Two gravel samples from each site were sieved to determine sediment texture. The results revealed that almost all of the substrate mapped as "gravel" during the canoe-based survey is considerably finer than the optimal size for spawning use by salmon, trout and steelhead. The median grain diameter was between 5 and 30 mm in almost all of the samples. The percentage of material smaller than 1 mm in diameter was generally acceptable (less than 12 percent of the sample weight), but the amount of material smaller than 10 mm commonly exceeded the preferred upper limit of about 40 percent by weight. A comparison of gravel lithology in Dry Creek and Putah Creek above and below their confluence failed to support a mixing-model approach to estimating the percentage of gravel in Putah Creek that derived from Dry Creek, which is the largest tributary downstream of Putah Diversion Dam.

Historical changes in channel alignment were investigated as an indicator of geomorphic dynamics and to determine whether the rates of meandering or avulsive channel realignment decreased following construction of Monticello Dam. U. S. Geological Survey topographic quadrangle maps from 1905 and 1947-1949 were scanned, georeferenced and imported into a geographic information system along with digital orthophotoquads from 1993. The alignments of Putah Creek, Dry Creek and several nearby ephemeral drainage ditches were digitized for each date. Fortuitously, the 1905 to 1947-1949 period represents four decades of pre-dam conditions, while the 1947-1949 to 1993 period represents approximately four decades of post-dam conditions. The analysis showed that channel alignment has been exceedingly stable between Winters and Mace Boulevard throughout the period of analysis. With one exception, the few changes in channel alignment above and below that reach occurred prior to construction of Monticello Dam. The one exception is at the confluence with Dry Creek, where sediment influx from that tributary has continued to push the channel of Putah Creek farther to the south.

Similar evaluations of changes in channel profile, width and depth since the mid-1940s did not reveal any trends with time. However, they did show that the cross-sectional area of the low-flow channel decreases in the downstream direction, consistent with a depositional environment on an alluvial fan, where high flows naturally tend to overflow the channel and spread out across the valley floor.

An existing flood hydraulics model of lower Putah Creek was extended into the Yolo Bypass reach of the creek using newly-available cross-section data, and the model was used to obtain longitudinal profiles of simulated bed shear stress at a range of flows. The Shields criterion was used to estimate the size of sediment grains likely to become mobile for a given shear stress. The results showed that shear stress varies tremendously over short distances and that it usually increases with increased flow, but that it decreases at some locations. This spatial-temporal heterogeneity presumably contributes to the uneven distribution of sediment along the channel. The mobility criterion indicated that perhaps one-third of the sediment textures obtained from the sieve analysis could be mobilized by fairly modest high-flow events (2,000 cfs).

Longitudinal temperature profiles along lower Putah Creek surveyed in 1993-1994 were compared with profiles in 1998-2002 to determine whether the removal of numerous beaver dams by high flows in the mid-1990s appreciably altered the thermal regime of the creek. Water released from Putah Diversion Dam is quite cold even in summer because it derives from deep within Lake Berryessa. It warms rapidly along the first 4 miles below the Diversion Dam. Removal of the beaver dams lowered the average low-flow stage of the creek by about 2 feet, with corresponding decreases in width, volume and residence time. It was hypothesized that the decrease in residence time would slow the rate of warming and allow cold water to reach farther downstream, thereby increasing habitat availability for native fish species, most of which prefer cold temperatures. Comparison of a small number of temperature profiles led to the tentative conclusions that the warming rate is most strongly affected by season (because of sun angle and associated shading of the creek surface) and only slightly affected by flow rate and maximum air temperature. Removal of the beaver dams seems to have had an intermediate effect, decreasing midday summer temperatures by about 2 EC along most of the reach below Winters.

Overall, gravel is not scarce along lower Putah Creek, but its texture is too fine for optimal spawning by some native fish, especially large salmonids. For more abundant fish, the number of river miles of gravel substrate might potentially limit reproduction. Of particular concern is whether the abundance of coarse sediment is decreasing with time because the largest historical source -- influx from upstream -- has been eliminated by dams.

The principal recommendation in this report is that its contents be evaluated by fish biologists to assess the adequacy of existing streambed gravels to support present or future fish populations. The remaining recommendations describe additional technical investigations of sediment source and transport rate. These investigations could include comparison of data in this report with historical texture data (if available) and sediment texture upstream of Lake Berryessa and along the interdam reach. Marked-pebble studies and measurement of suspended and bedload sediment discharge at various flow magnitudes could be used with flow-regime information to estimate average sediment discharge rates. The existing flood hydraulics model could be enhanced to include sediment transport, using some of the measured sediment flux data to estimate model parameters. A survey of subarial gravel bars adjacent to the low-flow channel could quantify the amount of coarse sediment the creek could potentially entrain from that source. Finally, a gravel-replenishment pilot project would go to the heart of the matter and reveal whether introduction of optimal spawning gravel at selected locations attracts an increased number of spawning fish.

INTRODUCTION

Background

The alignment, flow regime and sediment budget of lower Putah Creek have been substantially altered by human activities over the past 130 years, but the effects of those changes on the quantity and texture of in-channel sediment have not been studied. The resulting impact on spawning opportunities for fish is similarly unknown. The possibility that a long-term deficit of coarse sediment might be limiting the availability of spawning habitat became apparent in the late 1990s, when a landowner discovered numerous Pacific lamprey fry emerging from an artificial gravel ford constructed to allow vehicle access across the creek. This observation underscored the dearth of knowledge regarding channel substrate and sediment transport conditions along lower Putah Creek and eventually led to the present study.

Putah Creek is the southernmost major drainage entering the Sacramento Valley from the west. Its watershed encompasses 633 square miles of mountainous terrain in the southern Coast Ranges, of which about 90% is upstream of Monticello Dam and Lake Berryessa (Figure 1). Water released from the dam flows 7 miles down the creek to Putah Diversion Dam – 3 miles west of Winters – where most of the water is diverted into Putah South Canal for agricultural and municipal use. Some of the released water as well as spills from Lake Berryessa and unregulated runoff from the interdam reach continue past Putah Diversion Dam and down the 26-mile length of lower Putah Creek -- past the City of Davis -- to the Toe Drain of the Yolo Bypass. The Toe Drain flows to the Delta via Prospect Slough, Cache Slough and the Sacramento River near Rio Vista.

Flow in lower Putah Creek is highly regulated because Monticello Dam controls a large percentage of the watershed and because the capacity of Lake Berryessa is four times larger than the average annual runoff from the watershed. In particular, high flows that formerly sustained much of the geomorphic processes along the creek have been greatly decreased. For example, the estimated 100-year peak flow in lower Putah Creek is now only about one-third of its pre-project magnitude (USACE 1995).

Sediment transport has been affected even more than flow, because Monticello Dam traps all of the sediment from the upper watershed, and Putah Diversion Dam traps all sediment coarser than sand (Northwest Hydraulic Consultants 1998). Consequently, the supply of gravel and cobbles to lower Putah Creek has been decreased to less than one-tenth of its pre-project level. The expected geomorphological response of the creek to decreased sediment influx would be to entrain additional sediment downstream of Putah Diversion Dam by incision and bank scour. However, these responses have been slowed by the decrease in high flows that accompanied the decrease in sediment influx. No systematic monitoring of channel geometry, profile, or sediment flux has been implemented during the 45 years since Monticello Dam was constructed.

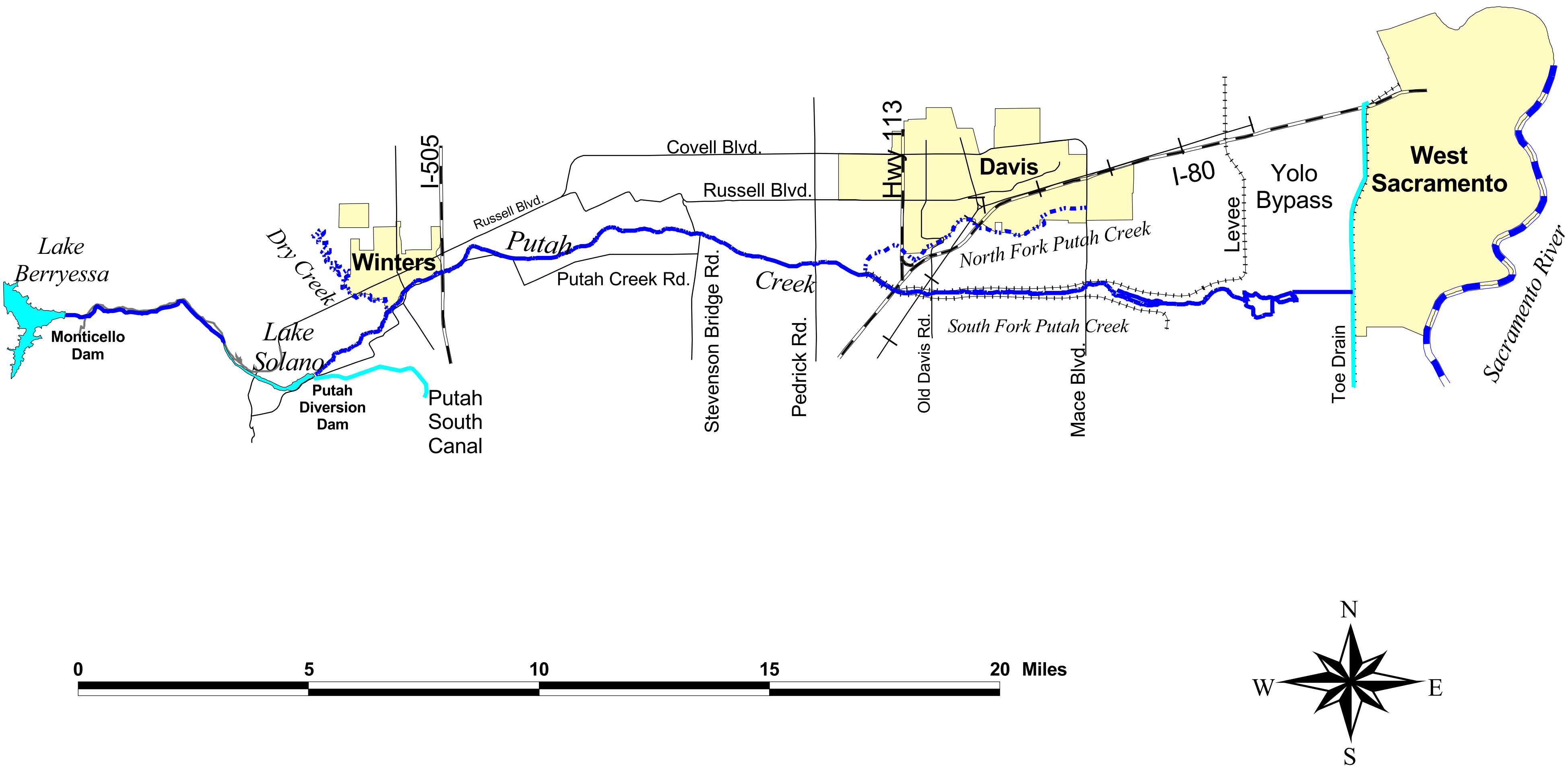


Figure 1. Location of Lower Putah Creek

Purpose

The principal goal of this investigation was to map the locations of potential spawning areas for anadromous and resident native fish species along the length of lower Putah Creek. Specifically, surveys of channel substrate and hydraulic conditions were needed in order for fish biologists to determine whether lack of suitable spawning habitat might be limiting the populations of native fishes. This goal was expanded during the course of the study to encompass a broader evaluation of sediment supply and geomorphic dynamics. A second goal of the project was to compare the thermal regime of the creek before and after the mid-1990s, when high flows washed out numerous beaver dams and appeared to decrease the average depth and hydraulic residence time of the channel. It was hypothesized that this change in hydraulics would be associated with a decreased warming rate downstream of Putah Diversion Dam and a longer cold-water reach, which would be beneficial for native fish species.

Scope

A variety of approaches were used to address the issues of sediment distribution, hydraulic patterns, sediment supply, thermal regime, and geomorphic dynamics. The field work and data analysis tasks included the following:

- A literature review of the substrate and hydraulic characteristics of spawning sites used by native fish species found in lower Putah Creek.

- A reconnaissance survey of hydraulic type (pool-riffle-run) and sediment texture (eight categories ranging from gravel to consolidated clay-silt) by canoe along the entire 26-mile length of lower Putah Creek during summer 2002.

- Detailed surveys of 16 sites identified from the reconnaissance survey as having relatively good conditions for spawning. The surveys measured bedform topography, water depth and velocity, gravel texture and gravel thickness. The sites were also photographed and marked with monuments for possible future resurveys.

- A detailed description of sediment lithology for Dry Creek and Putah Creek upstream and downstream of Dry Creek to estimate the source of sediment using a mixing-model approach.
- Compilation of historical temperature data from 1993-2000 and completion of two additional canoe-based temperature surveys in 2002 to compare the warming rates of the creek downstream of Putah Diversion Dam under various flow and weather conditions.

- Compilation of historical surveys of the creek channel to estimate rates and dates of incision and identify any changes in slope.

- Digitizing the creek alignment from historical maps to determine which reaches of the creek have experienced realignment and whether realignment continued after construction of Monticello Dam.

- Simulation of flow hydraulics along lower Putah Creek using a HEC-RAS model to identify the distribution of bed shear stress and the potential mobility of sediment grains of various sizes under the existing flow regime.

The methods and results for each of these investigative steps are described in detail in the remaining chapters of this report. Field work for the project was completed during summer 2002.

Although the scope of the sediment survey was expanded to include an analysis of historical geomorphic dynamics and an indirect estimate of sediment mobility using modeling, sediment transport rates were not measured or estimated. Some tentative inferences regarding sediment supply and transport are presented in the conclusions, and additional work needed to directly address these questions are described in recommendations section.

Acknowledgements

This project was funded by CALFED through a grant to the Lower Putah Creek Coordinating Committee (LPCCC). Solano County Water Agency (SCWA) and the Department of Wildlife and Fisheries Conservation Biology at the University of California at Davis (UCD) administered the contract and provided greatly-appreciated backup field equipment. The Putah Creek Streamkeeper, Rich Marovich, maintained good landowner relationships during field activities. Peter Moyle and Eric Larsen of UCD contributed information and suggestions regarding spawning habitat criteria and geomorphic processes. Botanist Rob Preston identified several samples of benthic algae collected from the creek.

SPAWNING HABITAT REQUIREMENTS FOR NATIVE FISH

Annual fish surveys over the past two decades have documented the occurrence of at least nine species of native fishes in lower Putah Creek (Moyle 1992; Trihey & Associates 1996; Moyle pers. comm.). For the purposes of this investigation, the species were grouped into several categories based on known or suspected similarites in spawning requirements and the lack of detailed information for some of the species. Table 1 shows the best available information characterizing the spawning habitat requirements of these fishes, as compiled by Moyle (2002). In general, much more information is available for salmonids than for other native fish. Native salmonid species include fall run chinook salmon, rainbow trout, and probably steelhead (anecdotally present but not confirmed). Gravel texture and redd size for these fishes varies somewhate based on fish size. Salmon and steelhead are anadromous, as is Pacific lamprey, a non-salmonid native anadromous fish that also spawns in lower Putah Creek. The remaining native species are primarily cyprinids (Sacramento blackfish, hitch, Sacramento squawfish, and Sacramento

Table 1. Spawning Site Criteria for Native Fish in Lower Putah Creek

Fish	Hydraulic Conditions: Type	Depth (ft)	Velocity (ft/s)	Substrate Conditions: Gravel Texture	Gravel Thickness	Redd
Rainbow trout Steelhead Chinook salmon	Riffles or pool tailouts preferred	0.3-4.9 (trout and steelhead) 0.8-3.3 (salmon)	0.6-5.1 (trout and steelhead) 1.0-2.6 (salmon)	Fines <1 mm less than 14% by weight Fines <10 mm 12-40% by weight D_{50} less than 10% of fish length (less than 4% of length preferred) 25-250 mm typical grain size (large 10-130 mm typical grain size (small	>12 inches (?) Perceptible flow through gravel	Redds dug by agitating gravel to create a depression and decrease percentage of fines Preferred gravel size related to adult fish size.
Pacific lamprey	Riffles or pool tailouts preferred	1.0-2.7	0.4-2.8	Similar to salmon, but not as fussy	Unknown	Redds dug by individually moving larger stones to downstream edge of depression
Sacramento blackfish	Pool edges	>2	Slow	Unimportant	Unimportant	Sticky eggs deposited on roots and vegetation
Sacramento pikeminnow	Riffles	>1	1.0-2.5 (?)	10-50 mm dominant size	Unimportant	Clean off surface and lay sticky eggs
Hitch	Riffles	>1	1.0-2.5 (?)	Clean, fine-to-medium gravel (10-50 mm dominant size)	Unknown	Eggs not adhesive but sink into gravel
Sacramento sucker	Riffles	>1	1.0-2.5 (?)	10-50 mm dominant size	Unimportant	Sticky eggs adhere to gravel or debris
Threespine stickleback	Pools and backwaters	0.7-3	Slow	Soft or mixed bottom material	Unimportant	Build nests of vegetation

Sources: Moyle (2002), Kondolf (2000), Moyle (pers. comm.)

pikeminnow), catstomids (Sacramento sucker), gasterostids (threespine stickleback), and embiotocids (tule perch). Tule perch bear live young, and blackfish and sticklebacks spawn on vegetation. Sediment texture is consequently unimportant for these species, although suitable hydraulic conditions must still be present.

In general, these native fish species appear to be less particular about water depth than about flow and substrate. Also, the fish are likely to spawn in any case, using the best available site even if it is less than optimal.

For the fish species that spawn on gravels with moderate flow velocity, the preferred gravel texture ranges from 10-50 mm for pikeminnows, suckers and hitch to 25-250 mm for salmon and steelhead. All species prefer fairly clean gravel. Studies of salmonid spawning in other areas have found that it is preferable to have no more than 10% of the gravel (by weight) be less than 1 mm to ensure adequate flow and oxygen delivery through the gravels. Fine material less than about 10 mm can also block the emergence of fry from the gravels, especially if it is deposited after spawning has occurred. A few observations of natural gravels used by salmon to build redds indicate that material smaller than 10 mm typically comprises about 14-40% of the material (Kondolf 2000).

HISTORICAL MODIFICATIONS OF PUTAH CREEK FLOW AND GEOMORPHOLOGY

The sequence of major historical alterations of the channel and flow regime along lower Putah Creek and their probable effects on geomorphic processes are described below.

South Fork Channel

In response to frequent flooding near Davisville (now Davis), residents began excavating a new channel (the South Fork) in 1871 using horse-drawn equipment. The channel split off from the original channel near what is now River Mile 8.0, about 4,000 feet upstream of I-80, and followed a relatively straight easterly course to the Yolo Bypass (Figure 1). The original channel is now referred to as the North Fork of Putah Creek. The channel was largely completed by the beginning of the 20th century, but excavation continued until the 1940's (Larkey 1969). Some downcutting of the channel occurred following construction of the South Fork, some of it by erosion during floods and possibly some by excavation. By 1950, the bottom of the creek channel at the split was about 18 feet below the former invert elevation at that location. The creek at that time was incised 35-40 feet below the surrounding valley flats from Winters to the North Fork split, decreasing to 20 feet at Mace Boulevard (Thomasson et al. 1960). However, the North Fork was incised nearly as much at Davis prior to construction of the South Fork. A description of the ditch pump used by Jerome Davis to irrigate his dairy pastures appeared in the 1858 edition of the *Transactions of the State Agricultural Library* (Larkey 1969). The vertical distance from the creek up to the valley flats was reportedly 20 feet at that time.

Flood Control Levees

In the late 1940s, the U. S. Army Corps of Engineers (USACE) constructed flood control levees along the north and south banks of Putah Creek from the North Fork split (River Mile 8) to the Yolo Bypass as part of the Sacramento River Flood Control Project. The levee sealed off the North Fork so that it no longer received flow during flood events. The levees rise 7-12 feet above the valley flats and are spaced 500 feet apart at the upstream end, gradually increasing to 2,000 feet apart at the Bypass (Jones & Stokes Associates, Inc.1992). By confining flood flows to a relatively narrow channel, the levees presumably increase the depth and velocity of flow, increase the shear stress and the ability of the creek to convey sediment. There does not appear to have been widespread downcutting or channel enlargement since then, however.

The levees were constructed from earth excavated from terraces along the low-flow channel. The cut areas are indicated in the as-built cross-sections. These blueprints do not state the total volume of excavated material, but it can be estimated from the levee dimensions. The combined length of the north and south side levees is 15.4 miles, and the average height above the previous ground surface is about 10 feet. With a 20-foot crown width and 2:1 and 3:1 side slopes on the outboard and inboard sides, respectively, the total volume of levee material is 1,355,000 cubic yards. This is a large volume relative to recent sediment transport rates along lower Putah Creek. For example, it is 242 times greater than the average annual sediment accumulation rate in Lake Solano (Northwest Hydraulic Consultants, 1998). This suggests that the levee project could have created a new or enlarged depositional zone along the leveed reach by widening the low terraces adjacent to the low-flow channel. If so, this could function as a sink for sediment that would otherwise enter the Yolo Bypass reach of Putah Creek.

Solano Project

The U. S. Bureau of Reclamation built the Solano Project on Putah Creek in the 1950s. The main facility of this major water-supply project is Monticello Dam, located about 10 miles upstream of Winters and completed in 1957. The reservoir impounded by the dam (Lake Berryessa) has a capacity of 1.6 million acre-feet, or about four times the average annual runoff in the creek. Water released from the dam flows 7 miles down Putah Creek to Putah Diversion Dam, where most of it is diverted into Putah South Canal for agricultural and municipal use in Solano County.

Because the capacity of Lake Berryessa is very large relative to average annual runoff, most high flows are captured entirely. A reservoir operations analysis showed that up to 25 years can elapse between spills (Conwell 1975). When spills do occur, peak flows are greatly diminished by storage effects as the reservoir surcharges above the spillway elevation. The 100-year pre-project peak flow of nearly 90,000 cubic feet per second (cfs) has been decreased to 32,300 cfs (USACE 1995). Flow in lower Putah Creek below the Putah Diversion Dam consists of releases required under the Putah Creek Instream Flow Settlement Agreement, Berryessa spills, and unregulated runoff below Monticello Dam. The average annual discharge is now approximately 90,000 acre-feet, or about one-fourth the preproject amount.

The large decreases in peak flows and annual discharge have greatly decreased the sediment transport capacity of lower Putah Creek. Furthermore, 90% of the 633-square-mile watershed is upstream of Monticello Dam, which intercepts all of the sediment yield from the upper watershed. Thus, sediment influx and the capacity to transport sediment were simultaneously greatly decreased. The expected result from this combination of changes would be a relatively stable system with little geomorphic change. However, the present flow regime is still capable of transporting a significant amount of sediment and may be outpacing the sediment supply. This could explain the lack of unconsolidated bed material (sand and gravel) in many areas along the creek, where the creek bed consists of dense clayey silt.

Putah Diversion Dam also traps sediment derived from tributaries along the interdam reach, but not as completely as Monticello Dam traps sediment from the upper watershed. The lake formed by the Diversion Dam (Lake Solano) was completed in 1959 and was largely filled with sediment by the 1990s. A comprehensive investigation of sediment texture and accumulation rate at Lake Solano conducted in 1998 found that there has been a long-term average sediment accumulation rate of about 5,600 cubic yards per year, but also that some of the sediment accumulated in dry years is flushed out in subsequent wet years (Northwest Hydraulic Consultants, 1998). As would be expected where a creek enters a lake, sediment deposited at the upstream end of the lake was generally coarser (sands and gravels) than sediments near the dam (fine sand and silt). The sediment flushed out through the gates of the dam would consist primarily of the more easily suspendable fine material. Thus, the dam probably traps coarse sediment fairly completely and fine sediment only partially. This texture filtering may degrade the quality of spawning gravels along lower Putah Creek by mixing additional fine material in with coarser material from local sources.

Gravel Mining

Extensive gravel mining occurred along a 2-mile reach of Putah Creek immediately downstream of Putah Diversion Dam during the late 1950s and 1960s. Aerial photographs taken in 1966 show a broad swath of exposed gravel and little vegetation along this reach. Mining in this area was discontinued in 1969 as a result of environmental concerns (Jones & Stokes Associates, Inc., 1992). The University of California at Davis also mined gravel from the creekbed near Pedrick Road until the late 1970s. Vegetation recovered quickly in both locations following the cessation of mining. Records indicating the volume of material mined were not obtained for this study, but the likely geomorphic effect of the mining would be scour and downcutting immediately upstream of the excavated area and a tendency for the excavation to function as a sediment trap. In other words, the mining activities could have caused a lasting decrease in the amount of sediment reaching downstream parts of the creek.

LONGITUDINAL MAPPING OF SUBSTRATE AND FLOW HYDRAULICS

The spatial distribution of bed material in lower Putah Creek is complex and varies significantly over distances of only a few feet along the length and width of the creek. This complexity reflects local variations in hydraulic conditions as they affect sediment transport. Most studies of spawning gravels consist of detailed measurements of short reaches preselected by the investigator and known to contain suitable material for spawning. The objective of the present study was to map the distribution of bed material along 26 miles of stream channel. This objective was achieved by dividing the survey into two phases: a reconnaissance-level survey along the entire length of the creek using simple sampling methods (described in this section), followed by detailed measurements and sampling of the best potential spawning sites (described in the subsequent section).

Methods

The 26 miles of Putah Creek between the Putah Diversion Dam and the California Department of Fish and Game/Los Rios Farms check dam in the Yolo Bypass were surveyed by canoe between June 25 and July 18, 2002. Measurements of flow hydraulic conditions and channel substrate were made along the centerline of the creek, and positions were recorded using a Magellan Meridian Platinum model global positioning system (GPS) receiver. The GPS locations were generally accurate to within about 40 feet (all points plotted within the open-water area of the creek on georeferenced orthophotoquads). The lengths of segments shorter than about 80 feet were measured manually and entered as additional waypoints during data postprocessing.

Channel hydraulics were characterized as “pool”, “riffle” or “run” using the following qualitative definitions:

> **Pool.** A portion of a stream where water velocity is slow and the depth is greater than a riffle or run. Pools often contain eddies with varying directions of flow compared to riffles or runs, where flow is nearly exclusively downstream.
>
> **Riffle.** A shallow portion of a stream extending across a stream bed characterized by relatively fast moving turbulent water. The water column in a riffle is usually constricted, and water velocity is fast due to a change in surface gradient. A rushing sound is audible.
>
> **Run.** A relatively shallow portion of a stream characterized by moderate velocities, a fairly smooth surface and generally laminar flow. A run is ususually too deep to be considered a riffle and too shallow and fast to be considered a pool.

An attempt was made to convert these qualitative definitions into quantitative values of depth, velocity and turbulence appropriate for lower Putah Creek, but several proposed schemes were not favorably received by local fish biologists (Moyle, Sommer, Shaul pers. comms.). This dilemma was overcome by recording the average depth, width and velocity of each stream segment in addition to assigning it to a pool-riffle-run category. This enabled quantitative analysis to be completed for the present study and allows future investigators to apply their own quantitative definitions of pool, riffle and run. Flow width was estimated by eye with periodic tape-measure confirmation. Depth was measured by a stadia rod, and velocity at six-tenths of the flow depth was measured using a Global Water Flow-Probe (horizontal-axis propeller-type meter).

Channel substrate was sampled on the basis of the sound and feel experienced when probing the creekbed with a 3/8-inch diameter steel rod. Along most of the length of lower Putah Creek, the bed consists of a dense clay-silt material over which sand and gravel is transported. The clay-silt makes a dull “thunk” sound and grabs the end of the rod. Sand makes a “swish” sound and is fairly easy to penetrate. The rod bounces off of gravel and makes a loud “clank”. Mixtures of sand and gravel could be fairly readily identified. In a few locations, the bed consisted of soft organic muck, which was silent and offered little resistance to the probe. In many locations, sand and gravel occurred as patches on exposed clay-silt, and patchy areas were mapped as a separate category. The creek water was too turbid to visually characterize bottom sediment in water depths greater than about 2 feet. At the beginning of the study, the probe method was calibrated by retrieving bed samples when a new sound or feel was encountered. In all, eight substrate categories were mapped using this method.

A new channel segment was defined and mapped whenever the hydraulic condition or substrate changed from one type to another. These transitions were identified visually by the canoe crew, with segment lengths generally no shorter than two channel widths. Some shorter riffles were mapped as separate segments.

Measurements of substrate, depth and velocity were limited to the centerline of the creek. This effectively decreased the mapping exercise from two-dimensions to one. Depth and velocity vary somewhat predictably from the centerline to the bank, allowing some inferences to be made about the additional diversity of habitat available in the widthwise direction. Putah Creek has a fairly rectangular channel cross section in most locations because of the cohesiveness of the clay-silt into which the channel is incised. The bank typically drops steeply to 2-3 feet below the low-flow water surface, whereupon it abruptly flattens to a nearly level surface across the remaining width of the creek.

The geographic coordinates of the endpoint of each stream segment were recorded and these were entered as points in a geographic information system (GIS) using ArcView 3.2 software. The points were projected to UTM zone 10, NAD83, in meters and overlain on orthophotoquadrangle images developed by the U. S. Geological Survey from aerial photography in 1993. A line theme of stream segments was created by digitizing between the points at a screen scale of 1:12,000, following the low-flow creek channel visible on the orthophotoquads. The attributes entered for each segment were the endpoint latitude and longitude, waypoint number (from the original GPS readings), segment number in downstream order, average width in feet, average depth in feet, average velocity in feet per second, hydraulic type (pool, riffle, run), point type (if the segment ended at a point feature such as a beaver dam, channel split or debris jam), remarks about the reach, reach length (meters and feet), and river mile. Consistent with historical convention, river mile 0.0 is where the projected southward alignment of the west Yolo Byass levee intersects the creek, corresponding to the downstream end of segment 320 in this survey. The river mile is the cumulative distance along the segments upstream or downstream of river mile 0.0. A total of 330 segments were mapped, ranging in length from 9 to 3,100 feet.

Results

The GIS can produce one-dimensional maps of lower Putah Creek showing selected values or ranges for any attribute or combinations of attributes. This section presents and evaluates maps of hydraulic condition, substrate type, and spawning habitat along the creek. Spawning habitat is defined by ranges of depth, velocity and substrate type for four categories of fish.

Hydraulics

Figure 2 shows the distribution of low-flow hydraulic conditions along the creek. Using Pedrick Road as the dividing line, the map is divided into two sements, with the reach from Putah Diversion Dam to Pedrick Road shown in the upper panel, and the reach from Pedrick Road to the Yolo Bypass shown in the lower panel. Note that some of the shortest segments may not be visible at the scale of the figure. The map reveals that pools occupy the largest percentage of the creek's length. Riffles are relatively short but are scattered throughout the reach between Putah Diversion Dam and I-80. They are scarce downstream of I-80. Runs are quite variable in length and not consistently sequenced with pools or riffles. Table 2 shows the cumulative river miles occupied by pool (72%), riffle (5%) and run (23%) conditions.

Hydraulic conditions change with increasing flow. The canoe surveys were completed in summer when flow was supplied by steady releases from Putah Diversion Dam and was 20-43 cfs, depending on month and location. Flows during the spawning season (generally winter through spring) are often higher, with correspondingly greater width, depth and velocity. Rainstorms can produce flows reaching thousands of cubic feet per second, but the duration of runoff is short. Spills from Lake Berryessa can produce flows over 1,000 cfs that persist for weeks to months. These flows cannot be relied upon to sustain local fish populations, however, because several decades can elapse between spills. The most reliable occurrence of persistent elevated flow results from one of the elements of the Putah Creek Instream Flow Settlement Agreement: a flow requirement of 50 cfs for 30 days during March-April. The relative proportions of increase in width, depth and velocity depend on channel geometry at a given site. Rating curves relating each of these variables to flow have been developed for 12 sites by SCWA and reveal general patterns. These sites are almost all located in runs where flow is relatively narrow, neither deep nor shallow, and swift but not turbulent. These characteristics fit the spawning site suitability criteria for most of the fish species and the flow-depth-velocity relationships at the gages sites are thus fairly representative of conditions present at many of the potential spawning sites. Power functions that fit the cluster of data for depth-versus-flow and velocity-versus-flow for all 12 gaged locations in the 0-70 cfs range are as follows:

$$D = 0.14\ Q^{0.5} + 0.1 \qquad \text{(Eq. 1)}$$

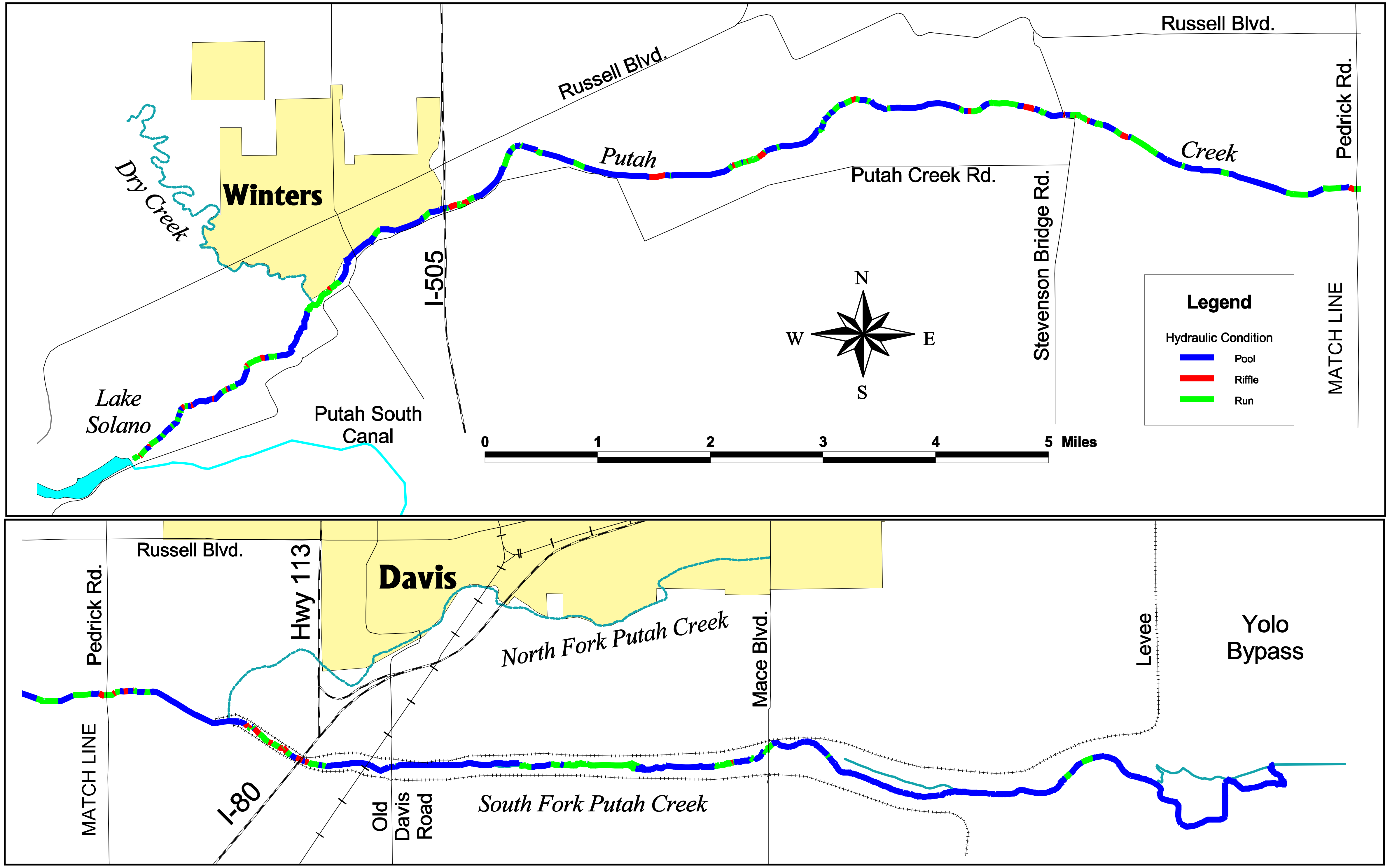


Figure 2. Distribution of Low-Flow Hydraulic Condition along Lower Putah Creek

Table 2. Cumulative Length of Combinations of Hydraulic Condition and Substrate along Lower Putah Creek, in Miles

	Hydraulic Type			
Substrate Type	Pool	Riffle	Run	Total
Clay-silt ("claypan")	4.09	0.27	0.55	4.91
Gravel	3.76	1.01	3.28	8.06
Sand and gravel	2.97	0.00	1.12	4.09
Sand	1.57	0.00	0.14	1.71
Mud	1.13	0.00	0.00	1.13
Patchy gravel	3.28	0.04	0.72	4.05
Patchy sand and gravel	0.55	0.00	0.10	0.65
Patchy sand	0.71	0.00	0.00	0.71
Total	18.07	1.33	5.91	25.30

Table 3. Cumulative Length of Potentially Suitable Spawning Habitat along Lower Putah Creek

	Miles of Spawning Habitat			
Substrate Type	Pool	Riffle	Run	Total
Chinook salmon	0.00	0.19	1.67	1.86
Rainbow trout/Steelhead	0.24	0.83	2.91	3.98
Pacific lamprey	0.06	0.19	1.42	1.67
Hitch, Sacramento sucker, Sacramento pikeminnow	0.00	0.11	1.31	1.42
Total	0.30	1.32	7.31	8.93

$$V = 0.22\ Q^{0.6} \qquad \text{(Eq. 2)}$$

where D equals mean cross-section depth in feet, Q equals flow in cubic feet per second, and V equals velocity in feet per second. For example, an increase in flow from 20 to 50 cfs increases mean depth by about 0.4 foot and mean velocity by about 1.0 feet per second (ft/s). These formulas can be used to adjust the indicated depths and velocities for runs and – with less accuracy – riffles in the GIS attribute table to estimate hydraulic conditions over a small range of flows. Increased flow within a relatively low range (e.g. 20-70 cfs) would have only a minor effect on cumulative lengths of each of the three hydraulic types. That is, a slight increase in flow would not convert pools to riffles or runs. Some riffles might convert to runs because of increased depth of inundation, but these situations might be offset by runs that convert to turbulent riffles as a result of increased flow velocity.

Substrate

Figure 3 shows the distribution of channel substrate material along the length of lower Putah Creek. Although dense clay-silt ("claypan") is probably the underlying bed material in most locations, the map reveals that it is ovelain by unconsolidated sand and gravel along most of the length of the creek. There are noticeable local variations in the texture and amount of unconsolidated material, and the creek can be divided into several reaches with different substrate patterns. Between Putah Diversion Dam and I-505 very little claypan is exposed, and the unconslidated material consists largely of gravel or a mixture of sand and gravel. From I-505 to Stevenson Bridge, the substrate texture is gravelly with little sand mixed in. However, the gravel is patchy along about half of this reach, with exposed claypan between the gravel patches. From Stevenson Bridge to the North Fork split (about 1 mile upstream of I-80), the dominant texture is a mixture of sand and gravel, and coverage is fairly continuous. From the North Fork split to Mace Boulevard, the substrate is heterogeneous and includes all eight of the texture categories. Below Mace Boulevard there is a noticeable increase in the amount of exposed claypan. The unconsolidated material is predominantly a mixture of sand and gravel, and this material occurs mainly in patches.

The distribution of sediment textures cannot be explained as a simple result of one or two sediment transport concepts. For example, the absence of fine material in the reach between I-505 and Stevenson Bridge is peculiar, given that sand is mixed with the gravels upstream and downstream of that reach. Velocities are not uniformly high along that reach (pools are common), which would otherwise be a plausible explanation. Nor is there a consistent fining of sediment size in the downstream direction, which is the usual large-scale pattern along rivers. Sand is present at locations close to Putah Diversion Dam, and gravel is present as far downstream as the Yolo Bypass. Local variability in sediment texture could be the result of localized variations in hydraulic conditions that favor deposition of one grain size range or another. That is, given a uniform initial mix of grain sizes, a stream will create localized deposits of differing textures, as commonly occurs with glacial outwash deposits, for example. An alternative and also plausible explanation of the texture variation is that the creek might entrain sediment from in-channel bars or localized exposures

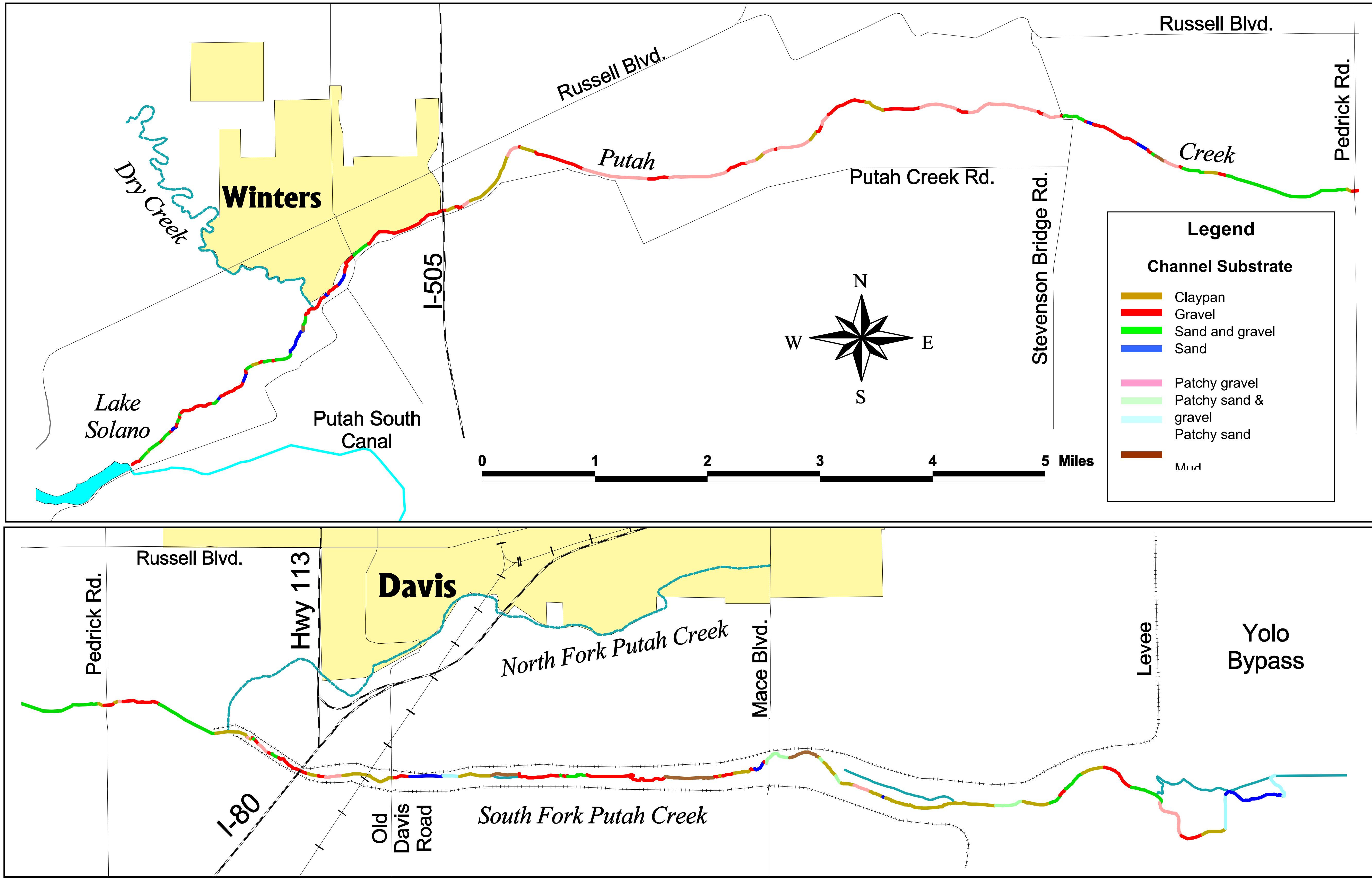


Figure 3. Distribution of Channel Substrate Type along Lower Putah Creek

of gravel strata in the largely fine-grained geologic deposits over which it flows. In-channel bars are present in many locations. They were not mapped in detail, and thick growth of vegetation appears to have stabilized most of them, at least at low flows. The volume of material in these bars is potentially large relative to present transport rates, however, and scour marks as well as historical aerial photographs suggest that material from the bars is recruited into the active low-flow channel during flood events. It is possible that this source of coarse sediment supply has been larger than the influx from Dry Creek during the four decades since Putah Diversion Dam was constructed and has slowed the long-term rate of sediment depletion from the creek channel.

It is clear that currents at high flows are capable of transporting sediment across bare exposures of claypan and from bar to bar across pools. This is demonstrated by the presence of patches of sand and gravel along some stretches of claypan and the resumption of continuous sand and gravel substrate downstream of the exposed claypan reaches. This pattern could be associated with so-called velocity reversals that occur at high flows. This phenomenon was first identified in a master's thesis study of Dry Creek and refers to the relative velocity over bars (riffles) and pools (Keller 1969). At low flow, mean velocity is lower in pools, but at high flows this relationship can reverse. The greater depth of pools can also increase shear stress at the bed, thereby increasing transport capacity relative to shallow areas over bars. Velocity reversals likely occur only at certain locations, depending on channel geometry, but they could be the cause of some of the bare claypan reaches.

Spawning Habitat

The locations of reaches potentially suitable for spawning by the four categories of native fishes were identified by selecting the segments that met the substrate, depth and velocity criteria identified in Table 1. This was achieved by means of boolean queries of the channel segment attribute table in ArcView. These potentially suitable areas were subsequently sampled to determine whether gravel texture was also suitable for spawning (see "Site Surveys" below). The cumulative length of suitable channel for each fish category is shown in Table 3, subtotaled by type of hydraulic condition. Overall, 35% of the length of lower Putah Creek appears to be potentially suitable for spawning by at least one category of fish. The great majority (82%) of suitable sites were in reaches classified as runs, and almost none were in pools.

The locations of channel segments that meet the criteria for trout and steelhead are shown in Figure 4. The criteria were a depth between 0.4 and 5.0 feet, a velocity between 0.6 and 4.9 feet/sec and a substrate of gravel. These segments total 3.98 miles of creek channel and are distributed as short segments dispersed along the reach from Putah Diversion Dam to Mace Boulevard. The total length of potentially suitable spawning reaches was more than double the total length for the other fish categories because of the broader depth and velocity tolerances for trout and steelhead.

The distribution of potentially suitable spawning habitat for salmon is shown in Figure 5. The combined length of these segments (1.86 miles) is only about half of the total length for trout

Figure 4

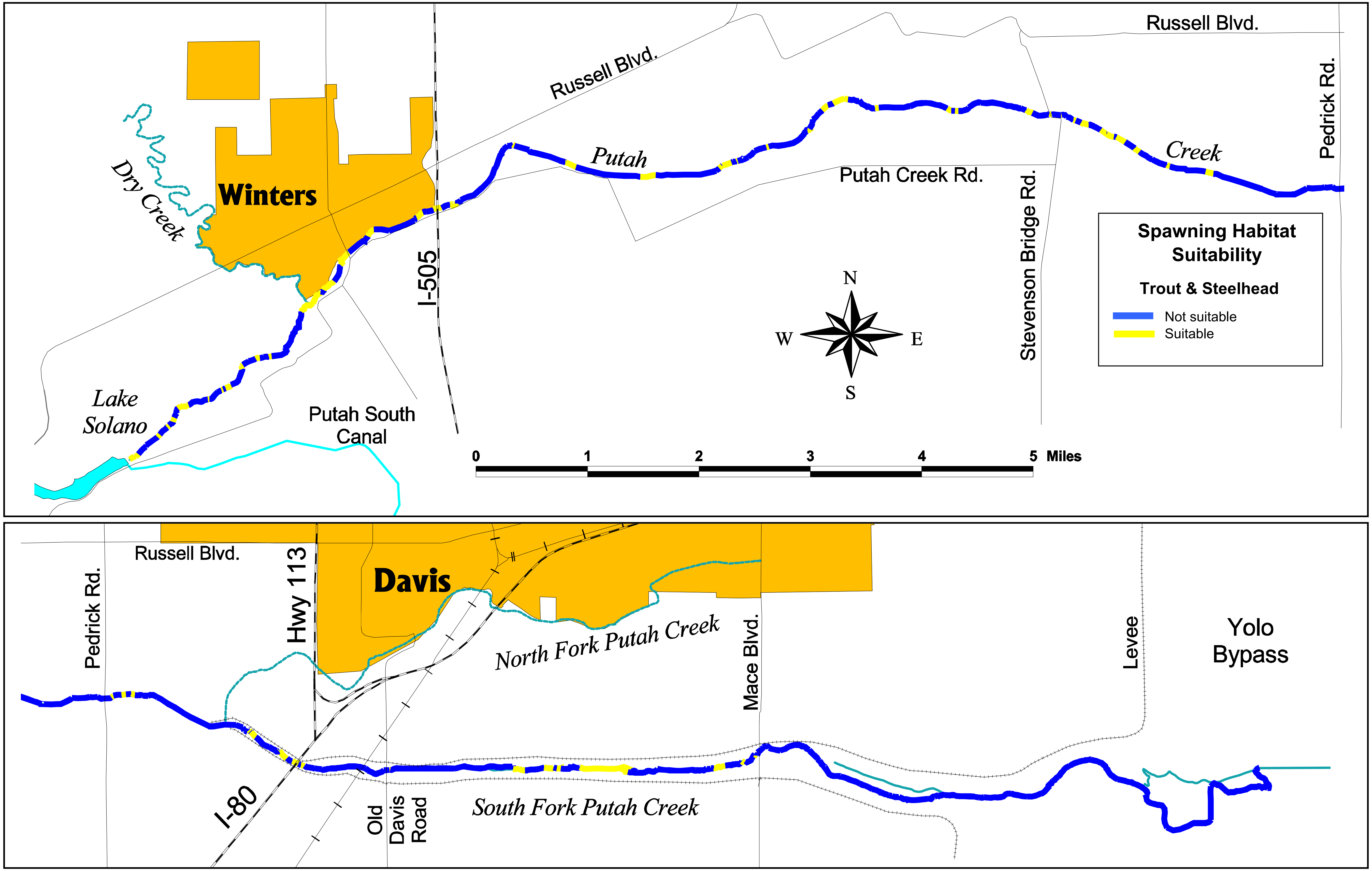


Figure 4. Distribution of Suitable Spawning Habitat for Trout and Steelhead along Lower Putah Creek

and steelhead. The depth and velocity ranges for salmon are entirely contained within the ranges for trout and steelhead, and the substrate criteria are the same, so the suitable segments are a subset of those for trout and steelhead. The suitable segments for salmon are also distributed throughout the reach from Putah Diversion Dam to Mace Boulevard. The segments identified as potentially suitable include the location 0.5 mile below Stevenson Bridge where salmon were seen spawning in 1998 (Sherwin 1998).

Segments of potentially suitable spawning habitat for lamprey are shown in Figure 6. The depth and velocity ranges are also basically a subset of the ranges for trout and steelhead. Unlike the salmonids, however, lamprey were assumed to be willing to use patchy gravel substrate, as confirmed by their use of an artificial road crossing midway between I-505 and Stevenson Bridge. The total river miles of potentially suitable spawning habitat (1.67 miles) was similar to the total for salmon. Slightly more than half of the individual stream segments suitable for lamprey were also suitable for salmon. The lamprey segments were also scattered throughout the reach from Putah Diversion Dam to Mace Boulevard.

The locations of creek segments potentially suitable for spawning by pikeminnow, hitch and suckers are shown in Figure 7. The criteria for these species are fairly close to the criteria for lamprey, and the combined length of suitable segments (1.42 miles) was similar. About 80% of the suitable segments for these species were also identified as suitable for lamprey.

The selection criteria used to identify potentially suitable spawning segments are approximate. Fortunately, database queries are easy to implement, and future investigators can apply their own estimates of suitability ranges for depth, velocity, substrate and hydraulic condition.

SITE SURVEYS OF MOST LIKELY SPAWNING LOCATIONS

The reconnaissance survey of channel substrate and hydraulic condition was followed by detailed surveys at selected sites to further characterize their suitability for spawning. Sixteen sites were selected from among the segments mapped as potentially suitable for salmon, trout or steelhead. The site locations are shown in Figure 8 and were deliberately distributed throughout the reach between Putah Diversion Dam and Mace Boulevard. The selected sites were ones that appeared to offer relatively optimal conditions: a riffle or run with an extensive deposit of fairly coarse gravel, a water depth of 1-2 feet, and a water velocity of about 2 ft/s. The focus of the site surveys was to document gravel texture, gravel thickness, and localized variations in depth and velocity across the channel.

Methods

A Lietz automatic level and stadia rod were used to survey about 20-30 points on the creekbed grouped into several cross-section alignments spread out along approximately 100 feet of channel length. Information recorded at each point included bed elevation, water depth, gravel

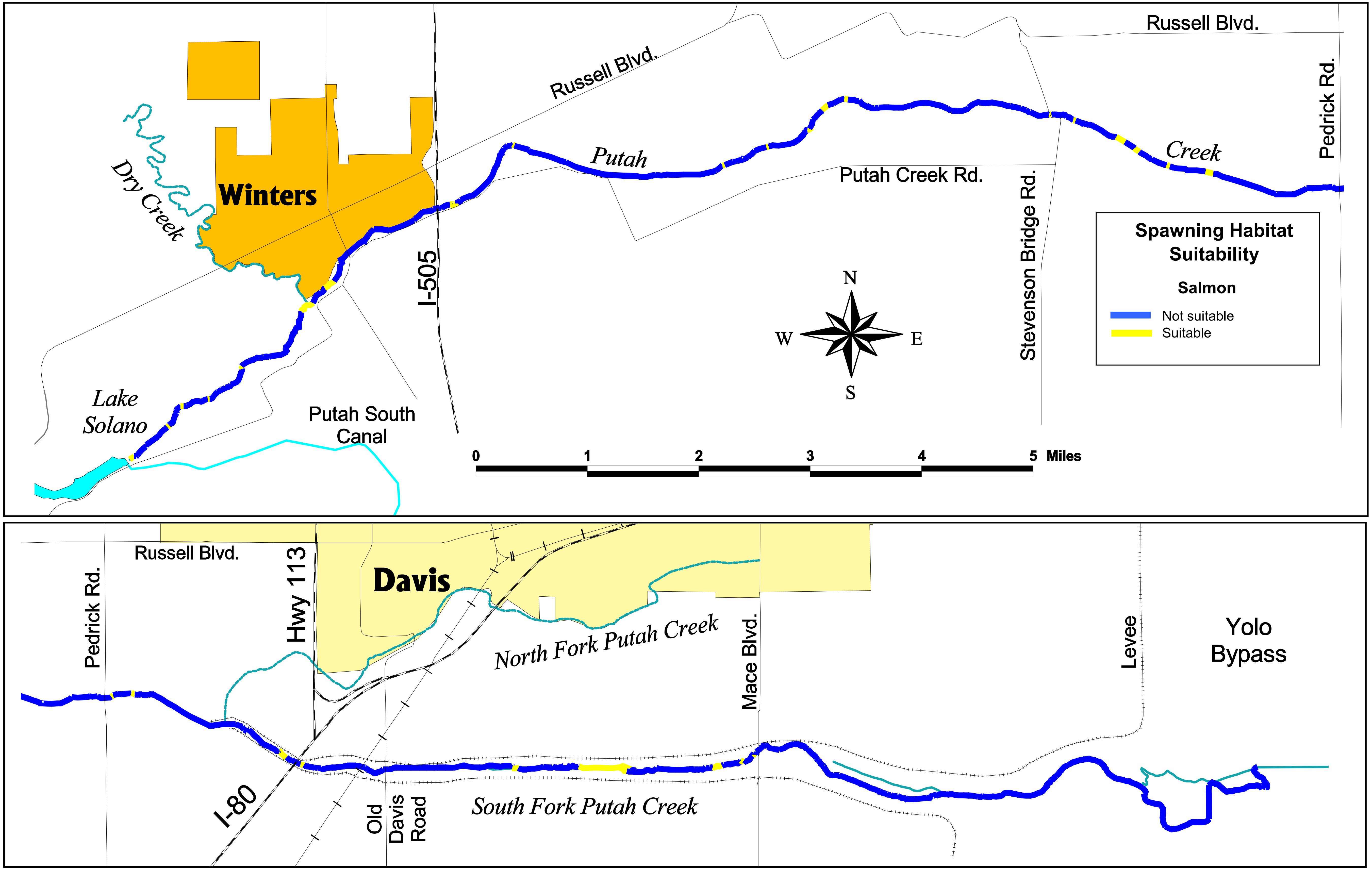


Figure 5. Distribution of Suitable Spawning Habitat for Salmon along Lower Putah Creek

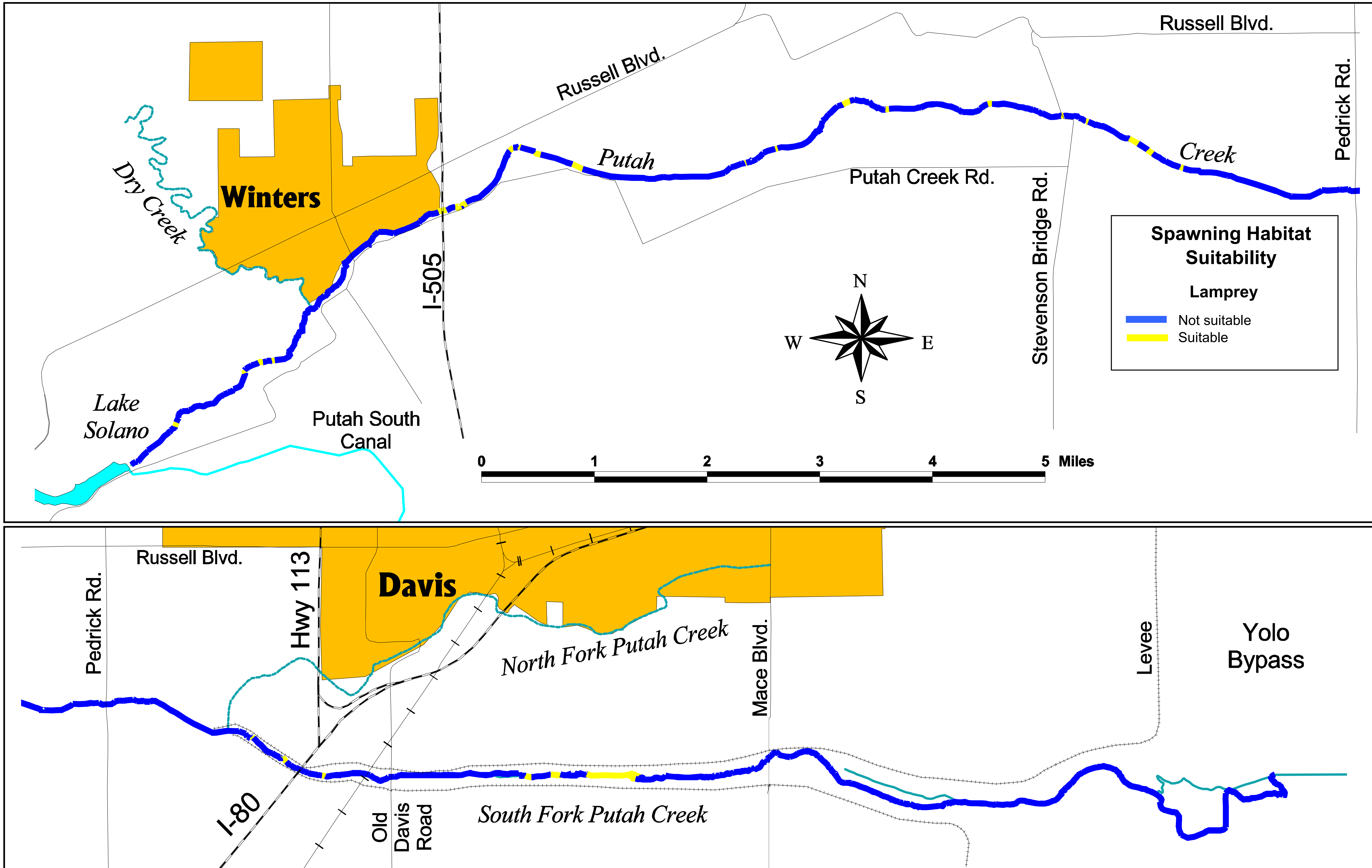


Figure 6. Distribution of Suitable Spawning Habitat for Lamprey along Lower Putah Creek

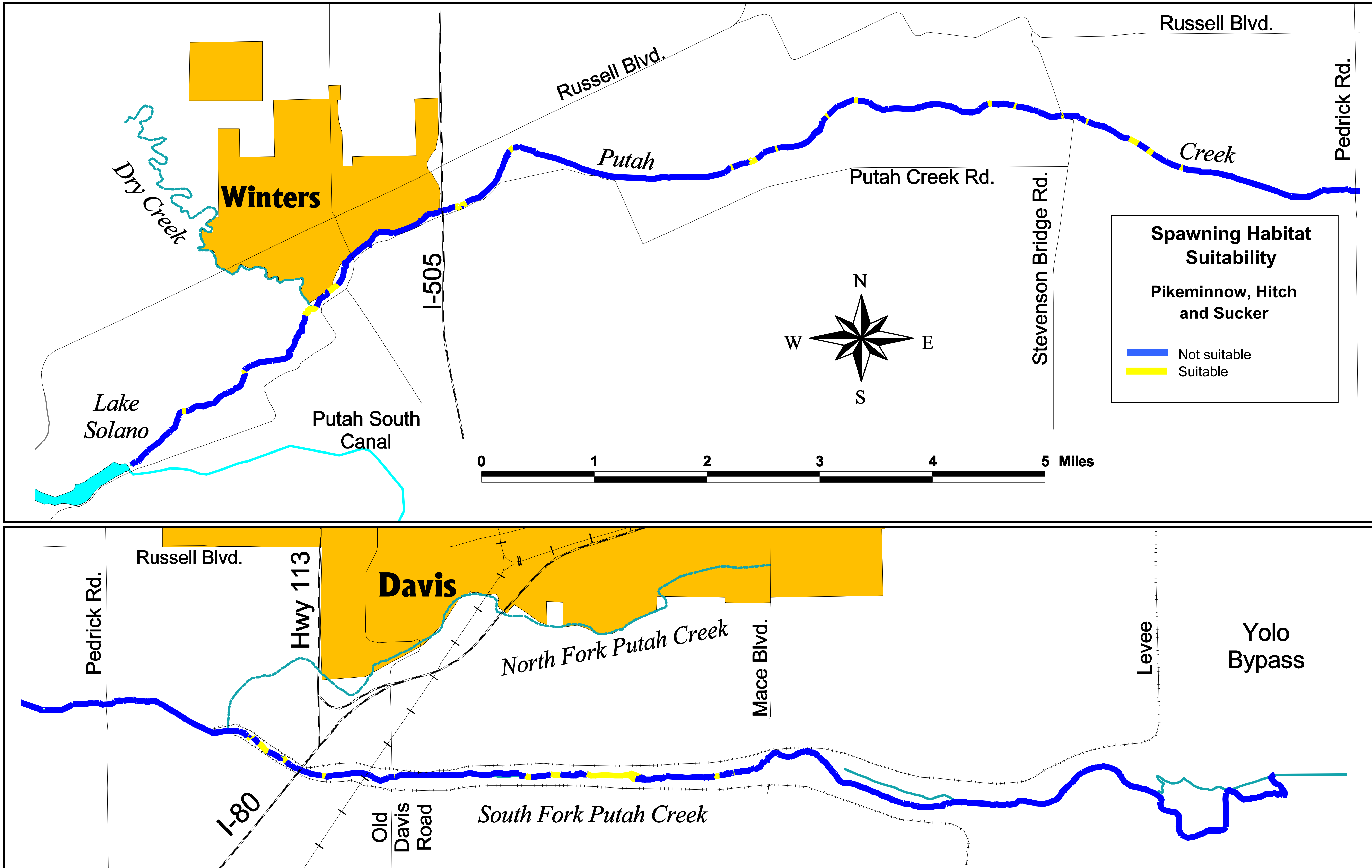


Figure 7. Distribution of Suitable Spawning Habitat for Pikeminnow, Hitch and Suckers along Lower Putah Creek

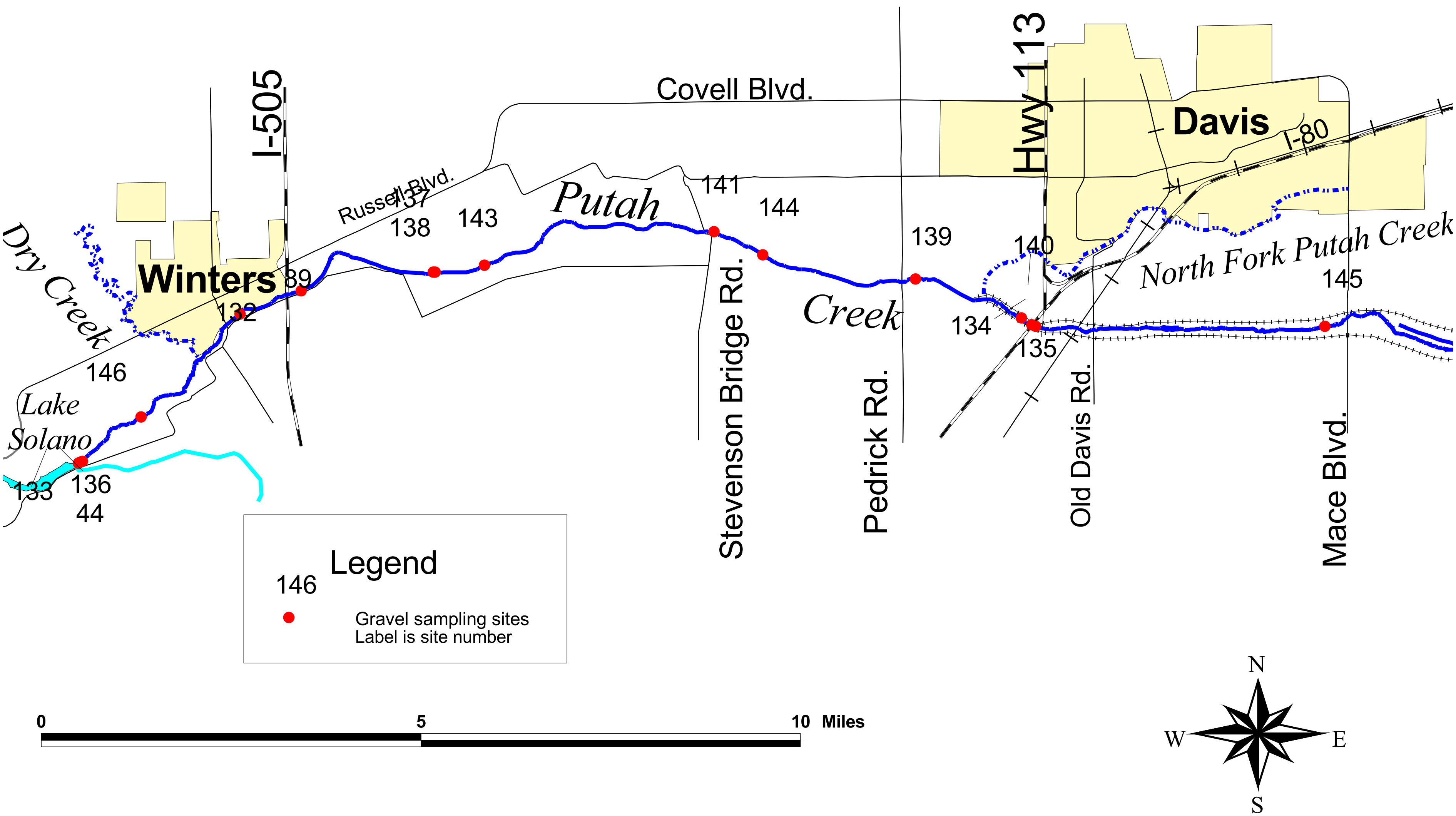


Figure 8. Locations of Gravel Sampling Sites along Lower Putah Creek

thickness, substrate type, and average water velocity (at six-tenths of the distance from the water surface to the creekbed). Presence or absence of algae was also noted.

To facilitate future resurveys, a monument was constructed at the instrument location at each site. Each monument consisted of a 3-foot steel fencepost driven fully into the ground and one or two bright white quartz decorative rocks each weighing 3-5 pounds placed on the ground over the top of the fencepost. The instrument stations were generally on the bank of the low-flow channel. The bearing, distance and elevation to a second (backup) monument higher on the bank (a distinctive tree or second fencepost) were also recorded. At a few sites, the instrument was set up in the channel, in which case the monument was constructed at the backup stake. The height of the instrument was recorded, and all site elevations are relative to the top of the fencepost. An approximate (probably +/- 5 feet) estimate of the elevation of the top of the fencepost was backcalculated from the profile of channel invert elevation in the USACE HEC-RAS model, which was based on a 1994 aerial topographic survey (see “Channel Geomorphology” below). The instrument location was also recorded using GPS, and photographs were taken of the creek from the monument location in the upstream, transverse and downstream directions. The survey data were entered into Excel spreadsheets, printouts of which are included in Appendix A. The site photographs are also included in the appendix.

The survey data were processed to create maps of the instrument and point locations at each site and to develop cross sections showing water depth, mean velocity, bed elevation and gravel thickness across the channel. Site maps and cross sections are included in Appendix A.

Two gravel samples were collected at each site from locations that appeared representative of typical conditions at that site. The samples were collected by inserting a 12-inch diameter plastic cylinder (“bottomless” 5-gallon bucket) approximately 6 inches into the creekbed and scooping out the enclosed core of material. Total core penetration was somewhat variable, and sample sizes ranged from 5-10 kg. The samples were wet-sieved on-site using standard 8-inch sieves with sieve openings of 25.4, 16, 9.5, 6.3 and 3.55 mm. Tests verified that water was a negligible percentage of total sample weight for these size fractions and did not interfere with sieving. Material finer than 3.55 mm was found to contain a significant percentage of water, and surface tension effects prevented accurate sieving while wet. This fine material was subsequently dried and dry-sieved to size fractions of 1.0, 0.425 and <0.425 mm in the laboratory. All stones retained on the 25.4 mm sieve were measured by hand (intermediate axis) and divided into the following class intervals: 25.4-30, 30-40, 40-50, 50-70, 70-100, 100-150 and >150 mm. Each class interval was weighed, so that the results were the same as if the entire sample had been dry sieved into 15 size categories.

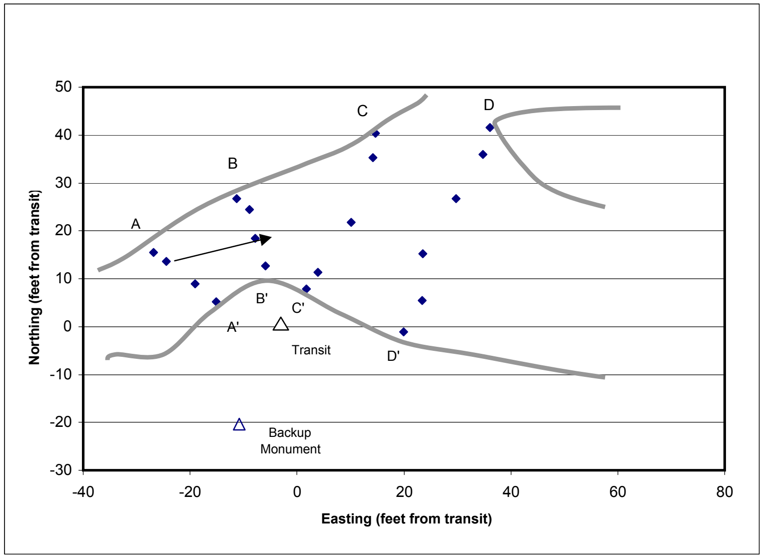
This gravel sampling method did not strictly conform to recommended sampling procedures but was considered reasonable and perhaps preferable for a survey covering many miles of creekbed. The gravel texture was slightly too fine to obtain accurate results using the pebble-count method, which lumps all grains smaller than about 4 mm into a single size category (Kondolf 1997). That size interval comprised 19% of the Putah Creek samples, on average, which is a large percentage to lump together. It also precludes a calculation of the percentage of material smaller than 1 mm, which is one of the criteria for spawning site suitability. Also, pebble counts measure only the surface texture, whereas the core method includes surface and subsurface material that would actually be encountered by a fish constructing a redd. Surface armoring was not apparent at any of the sites. Accurate grain-size analysis by sieving, on the other hand, requires large sample sizes -- 200 kg for samples containing stones as large as 100 mm in diameter, according to some researchers (Church and others 1987). By this standard, the Putah Creek samples were approximately 25 times smaller than the recommended sample size. The smaller sample size used in this study equaled the maximum amount of material that could be loaded into the sieve set at one time and was selected purely for expedience. However, given the limited total effort available for sieving and the expected large degree of spatial variation in gravel texture, processing small samples at 25 locations provides a better picture of spawning gravel distribution and quality along the creek than processing a single sample 25 times larger.

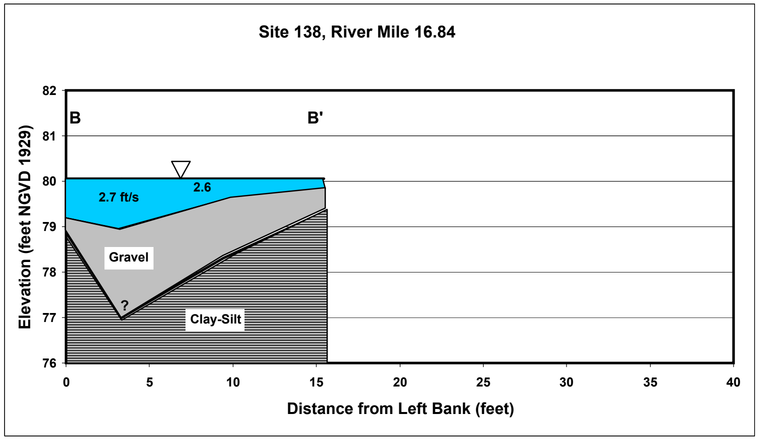
Results

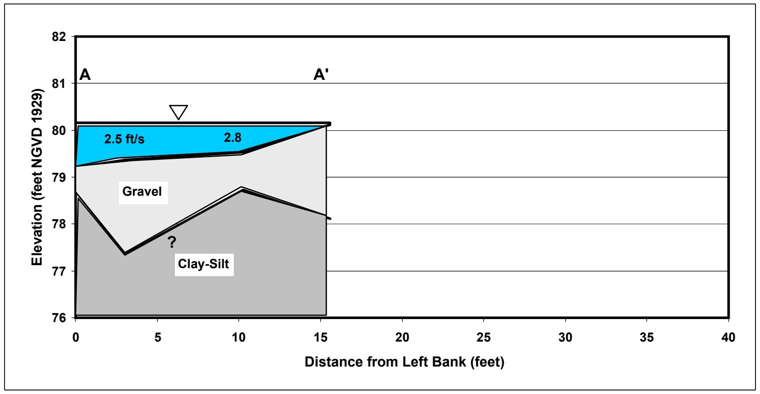
Cross-Sections

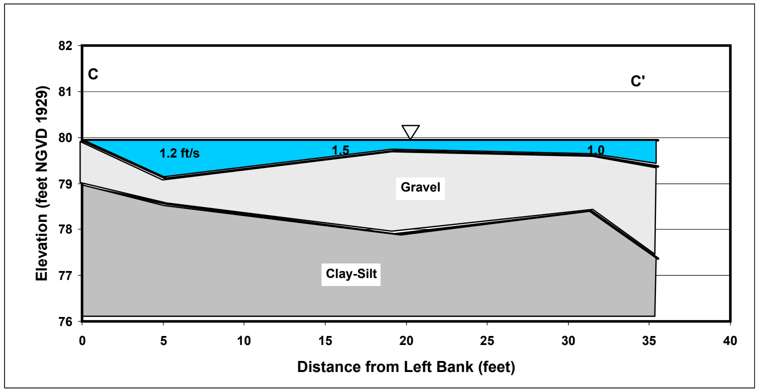
Three to five cross sections at each of the sampled potential spawning sites are included in Appendix A, and the cross sections for site 138 are shown in Figure 9 as an example. Flow width, depth and velocity as well as gravel thickness and texture are quite variable among cross-sections and even along and between individual cross-sections at the same site. In general, conditions at the sites consisted of a thin veneer of gravel (0.3-2.0 feet thick) over a dense clay-silt layer, moderate water velocities and shallow water depths (mostly less than 1.5 feet deep).

Each of the surveyed cross-sections was evaluated with respect to the four physical criteria for spawning habitat suitability listed in Table 1: water depth, flow velocity, substrate texture, and substrate thickness. The fraction of total channel width that met the criteria for each of the four fish species groups was recorded. These estimates were approximate because the variables were measured at only a few points along each cross section and were assumed to vary linearly between those points. Also, some criteria for some species are unknown (e.g. minimum gravel thickness for lamprey spawning, which was assumed to be 0.5 foot if all other criteria were met). The suitability was tabulated along 65 cross sections at 16 prospective spawning site locations, representing a total of 1,771 linear feet of cross section. The results for each cross section are shown in Table A-1 in Appendix A, and a summary for all of the cross sections is shown below in Table 4.









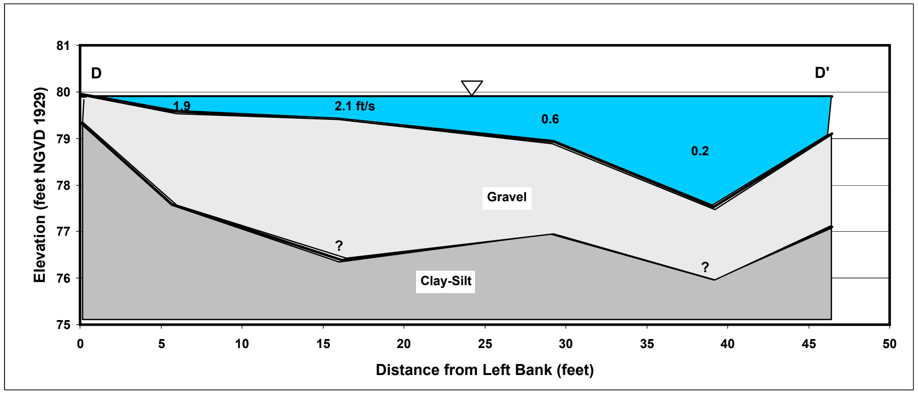


Figure 9. Channel Cross-Sections at Potential Spawning Site 138

Table 4. Average Percent of Channel Width that Meets Spawning Site Criteria for Each Species Group

Species Group	Percent of Width Suitable
Chinook salmon	19
Rainbow trout/Steelhead	33
Pacific lamprey	19
Hitch, Sacramento pikeminnow and Sacramento sucker	21

The cross-section analysis revealed that even in locations that appeared visually to have high potential for spawning suitability, only one-fifth to one-third of the channel width strictly met the physical criteria specified in Table 1. Insufficient flow depth was by far the most common limitation, especially for lamprey and the resident natives, which prefer depths greater than 1 foot. Insufficient gravel thickness was the next most common limitation for salmon, trout/steelhead and lamprey (no minimum was specified for the resident natives). Low velocity was nearly as common a limitation as inadequate gravel thickness, but high velocity was rarely a limitation. A few cross-sections had mud or sand near the banks, which eliminated those areas from suitability. All sediment mapped as "gravel" during the cross-section surveys was considered suitable for spawning, although subsequent sieve analysis demonstrated that much of the gravel may be too fine, especially for salmon.

The larger percentage of width suitable for trout/steelhead than for salmon stems entirely from the smaller minimum acceptable depth (0.3 versus 0.8 foot) and velocity (0.6 versus 1.0 ft/s). Given that these preference ranges are neither well known nor hard-and-fast, fish might be willing to spawn in less-than-optimal conditions given the lack of anything better. Thus, the average percentage of suitable width in Table 4 might underestimate the true spawning habitat resource.

Table 4 might also underestimate spawning habitat availability because water depth was measured in summer, when flows are smaller than during the winter/spring spawning season. Natural runoff in winter and spring -- plus spills from Lake Berryessa in some years -- elevates flow for periods of time. Unfortunately, runoff events elevate flow only briefly, and median monthly flows in winter have historically been only 10-25 cfs greater than the required release from Putah Diversion Dam (Jones & Stokes Associates 1992). Hydraulics calculations were not completed for each cross section, but Equation 1 represents the typical relationship between flow and water depth at locations similar to the potential spawning sites. Equation 1 indicates that an increase in flow from 25 to 50 cfs would typically increase water depth by 0.3 feet. This might increase the average percentage of channel width suitable for spawning by 10 or 20 percent of total width. If fish chose to spawn during periods of active runoff or spills from Lake Berryessa, depth would cease to be limiting at most of the cross sections, and high velocity would become the dominant problem. For example, flows greater than 100 cfs occurred an average of 29 days per year prior to the instream flow settlement agreement of 2000. Note that the agreement is not expected to substantially change the occurrence of spills and runoff. Pre-agreement data are used mainly because the agreement is too new to statistically evaluate post-agreement flow regimes. At 100 cfs, average flow depth in a typical run is 1.5 feet (suitable), but average velocity is 3.5 ft/s (too high for salmon, lamprey and resident natives). In view of these tradeoffs, it would be reasonable to assume that the average percentage of channel width suitable for spawning in winter and spring is less than 50 percent.

The total surface area of creekbed suitable for spawning can be estimated by multiplying the number of river miles deemed suitable based on the survey of centerline hydraulic and substrate conditions (see Table 2) by the width likely to meet the criteria for the species of interest (see Tables 4 and A-1). The resulting estimates of total available spawning area are 1.2, 4.4, 1.1, and 1.0 acres for salmon, trout/steelhead, lamprey, and resident natives, respectively. Although highly approximate, these estimates indicate the order of magnitude of available spawning habitat area for each species group.

Gravel Texture

A sample grain-size distribution plot for site 146 is shown in Figure 10, with the curves for both samples collected at that site shown on the same plot. Grain-size distribution curves for all of the samples are shown in Appendix B, with one plot per site arranged in downstream order. All of the samples are well-graded (poorly-sorted) mixtures of a range of grain sizes. At most sites, the curves for the two samples were fairly similar (within 15% of the same percentage finer than any given grain size), but at a few sites the curves were separated by up to 35% for certain sizes. Because of their complex shapes, the curves are difficult to compare visually among the plots. Figure 11 shows boxplots that summarize the grain size distributions plotted side-by-side for all of the samples, arranged in downstream order. The black diamond in the center of each box represents the median grain size. The top and bottom of the box represent the 75th and 25th percentiles of grain size, respectively. The whiskers at each end of the box extend to the 90th and 10th percentiles. The grain sizes corresponding to these percentiles are customarily denoted d_{90}, d_{75}, d_{50}, d_{25} and d_{10}. At the right side of the graph are boxplots representing the typical textures favored by salmon, trout and steelhead based on the spawning site criteria listed in Table 1.

Two conclusions can immediately be drawn from the boxplots. First, the gravel texture is consistently finer than the size range preferred by salmon, trout and steelhead. None of the samples had a 75th percentile size as large as the upper quartile size preferred by salmonids, and the discrepancy was particularly large for salmon. All but three samples had a d_{75} smaller than 70 mm, as compared with the d_{75} of 250 mm preferred by chinook salmon. Similarly, all but three samples had a d_{25} smaller than the d_{25} preferred by salmon (22 mm). Second, there is no apparent trend in grain size in the downstream direction. Two samples were noticeably coarser than the rest, and these were collected from site 144 located 0.8 mile downstream of Stevenson Bridge Road. There

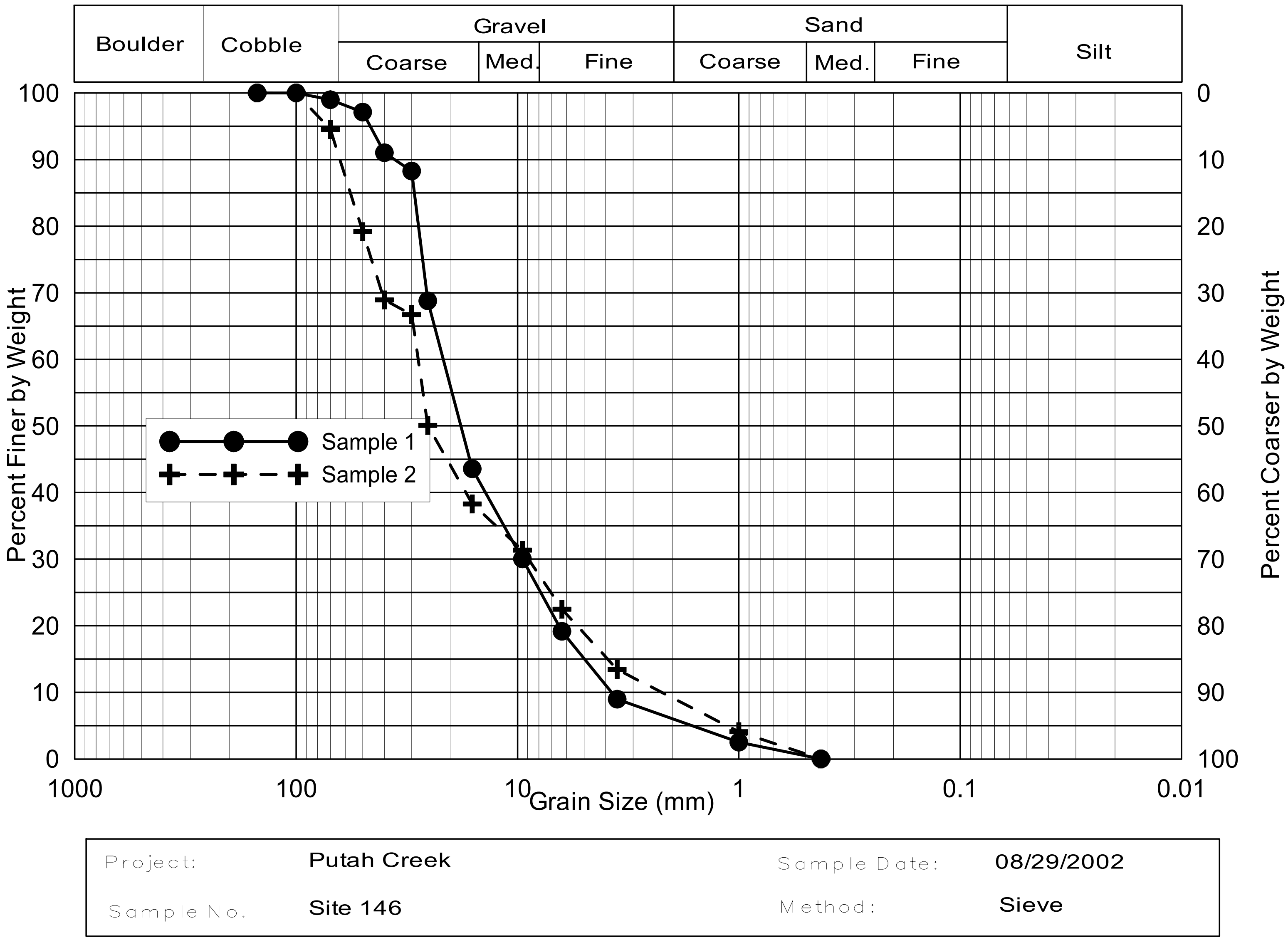


Figure 10. Grain Size Distribution of Noncohesive Sediments at Gravel Sample Site 146

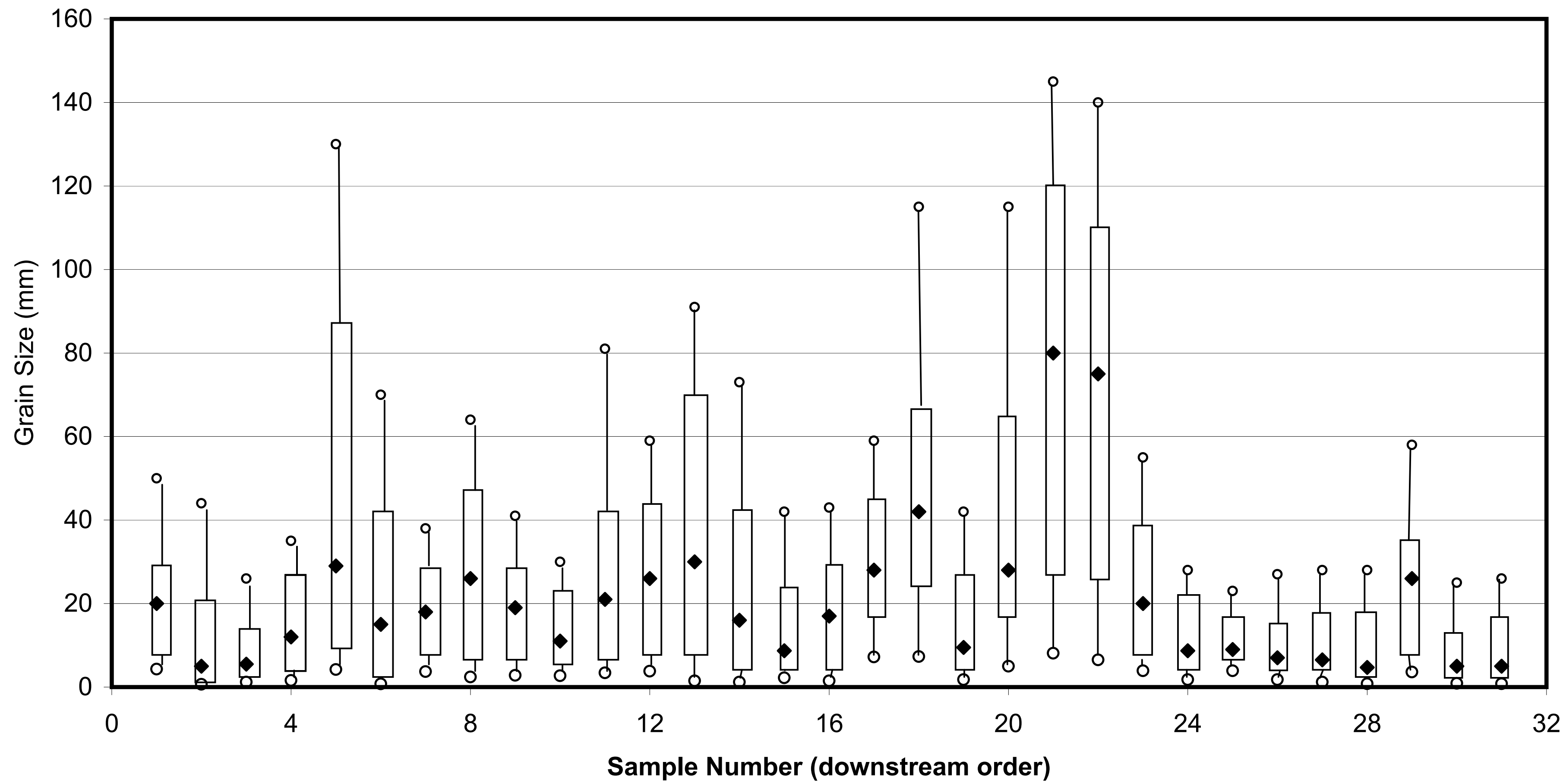


Figure 11. Boxplots Summarizing the Grain-Size Distribution of Noncohesive Sediments along Lower Putah Creek

is no external source of coarse sediment such as a tributary anywhere near that location. The relatively coarse texture of both samples collected at that site could possibly derive from a local deposit of ancient channel gravels traversed by the creek, although no such deposit has been reported in that area. It could also simply reflect the normal range of sediment sorting related to local hydraulic conditions along the creek.

The percentage of moderately fine material (<10 mm) is high in many samples, but the percentage of fine material (<1 mm) is generally acceptable. This is demonstrated in Figure 12, which shows the percentage of total sample weight finer than 10 mm and 1 mm. Material smaller than 10 mm can obstruct fry emergence from the gravels, and material smaller than 1 mm is thought to restrict water circulation and oxygen delivery to eggs in the interstices of the gravel. The recommended percentage ranges for each size are shaded. The percentage of material less than 10 mm is often quite variable in the field (Kondolf 2000) and the suitable range is consequently poorly defined. Even assuming a fairly large range (12-40%), half of the samples exceeded the maximum acceptable percentage, consistent with the above finding that the gravels are generally too fine-grained to be optimal or even acceptable for salmonids. In contrast, the percentage of material smaller than 1 mm is below the upper limit of acceptability (12%). These results indicate that the excess fine material in the creek is not silt and fine sand, but coarse sand to medium gravel (1-20 mm).

Asian clams (*Corbicula*) are extremely abundant in Putah Creek and comprised 10-20 percent of the gravel sample volume at some sites. The clam shells are typically 3-15 mm wide and long. The effect of the clam shells on spawning success is unknown. It would appear, however, that a bed of clam shells would be capable of providing the same basic functions of spawning gravels: providing physical protection for fish eggs and allowing ample flow of oxygenated water past the eggs.

Algae

The types and distribution of algae present in the creek were noted during the gravel surveys at locations where algae was abundant, and samples of some of the common types were collected for identification by a botanist. Beginning about 2 miles below Putah Diversion Dam, attached (benthic) algae becomes abundant and forms a forest of stalks. In some places, the algae covers most of the creekbed, and the stalks extend up to the water surface. This type of dense growth is more common in pools than in riffles or runs, however. Common types of algae found in the creek are Siberian water milfoil (*Myriophyllum sibiricum*), crispate-leaved pondweed (*Potamogeton crispus*), and elodea (*Elodea canadensis, Egera densa*) or hydrilla (*Hydrilla verticillata*), which are similar in appearance (Preston pers. comm.). The impact of algae on spawning is unclear. The algae reportedly dies back considerably in winter, when water temperatures are colder (Moyle pers. comm.)

Embeddedness

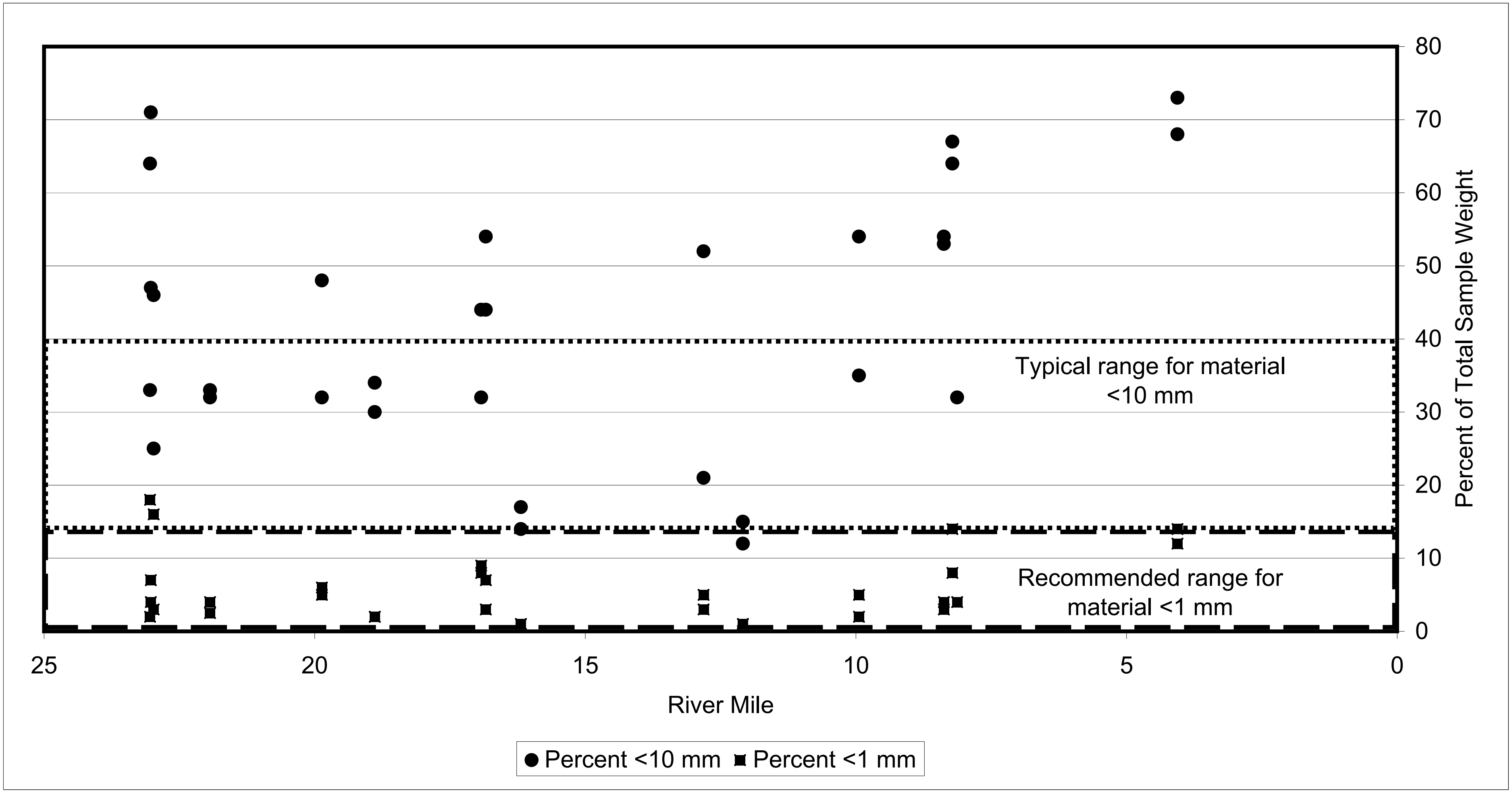


Figure 12. Percentage of material less than 10 mm and less than 1 mm in Substrate Samples from Lower Putah Creek

At many locations, creekbed gravels were densely packed and filled in with finer material to at least 50% of the diameter of the surface gravel grains. In addition to sand and silt, the gravel surface in some areas had a thin coating of a dark slimy algae. No systematic or quantitative measurements of embeddedness were made during the surveys. However, the feasibility of loosening the gravels was tested at a number of locations. The tests consisted of a hydrographer firmly swishing his hand (fingers pointed down) back and forth close to the gravel surface, mimicking the hydraulic effect of a fish tail. It was generally found that 5-10 seconds of this procedure would clear off the surficial fines and begin to loosen the gravels and that further loosening and cleaning became increasingly easy. This test obviously does not prove that a fish would choose such a site for spawning, but it does suggest that at least the larger fish (salmon and steelhead) would probably be physically capable of constructing a redd in the material.

SEDIMENT SOURCE

The long-term availability of spawning gravels along lower Putah Creek depends partly on the source of the gravels. If gravels that are presently found along the channel originated from areas upstream of Putah Diversion Dam prior to construction of the Solano Project, the amount of gravel can be expected to decline in the future as gravel is moved down the channel during high-flow events and not replaced by influx from upstream reaches. On the other hand, if gravels along lower Putah Creek derive from sources downstream of Putah Diversion Dam, the future outlook for replenishment is brighter. The potential sources of spawning gravels along lower Putah Creek are:

- Putah Creek watershed above Monticello Dam
- Putah Creek tributaries along the interdam reach
- Alluvial deposits traversed by the creek downstream of Putah Diversion Dam
- Dry Creek
- High terraces and subaerial gravel bars along the low-flow channel

Methods

The relative amount of gravel supplied by each source could potentially be estimated on the basis of sediment lithology, provided that each of the source areas exhibits unique lithologic characteristics. This approach was tested by comparing the lithology of gravels in Dry Creek and Putah Creek above and below their confluence. Because the creeks drain different watersheds, they are the two sources most likely to have distinct lithologies. Samples containing approximately 200 stones each in the 0.5-15 cm size range were collected from Dry Creek approimately 300 feet upstream of Putah Creek and from Putah Creek approximately 300 ft upstream and 1,000 ft downstream of Dry Creek. The sample from Putah Creek downstream of the confluence presumably consisted of a mixture of sediment from Dry Creek and Putah Creek.

The stones in each sample were separated into groups based on color, shape, texture, mineralogy, and weathering. These characteristics were evaluated by eye and with a 10x hand lens.

Emphasis was placed on identifying distinctive lithologies that could potentially be used for quantitative mixing calculations. Some groups had as few as one stone representing a particular category. A simple mixing-model calculation was planned to determine the percentage of downstream material derived from each of the upstream sources, but the lithology proved to be too diverse and variable to justify a quantitative analysis.

Results

A total of 20 distinct lithologies were identified by their visual characteristics. The lithologic descriptions are listed in Table 5, along with their tentative petrographic classifications and relative abundance at each of the three sample sites. In general, the Dry Creek sample was lighter in hue and more colorful than either of the Putah Creek samples, with more abundant orange, blueish and greenish lithologies amidst the common drab colors. However, this pattern was not sufficiently clear at the level of individual lithologies to complete a mixing analysis.

The overriding conclusions that can be drawn from the analysis are that the lithology of geologic formations in the Coast Ranges is extremely diverse and that none of the observed lithologies appears suitable for quantitative mixing analysis. For example, several of the lithologic types in Table 5 do not conform to a pattern that would result from mixing of two sources. The light gray pegmatite (lithology type 2 in the table) is moderately abundant in the upstream Putah Creek and Dry Creek samples but entirely absent from the downstream Putah Creek sample. Similarly, the white vein quartz (type 7) was much more abundant in the upstream samples than in the downstream sample. The orange argillite (type 10) was also present in the upstream samples and absent in the downstream sample, but this could be the result of rapid decomposition of this relatively soft rock type during transport.

Also contrary to a simple mixing pattern was the presence of three lithologies (types 13, 16 and 18) in the downstream sample that were not found in either of the upstream samples. A larger sample size might overcome some of the limitations of the initial analysis. This is because many of the most distintive lithologies were also relatively rare, so that large sample sizes would be needed to quantify their relative abundances reliably enough for quantitative mixing analysis. For example, lithology types 6, 7 and 10 are fairly distinctive and appear to have different relative abundances in the Dry Creek and upper Putah Creek samples. Nevertheless, the preliminary analysis reported here suggests that the high degree of lithologic diversity in all of the samples and the lack of clear distinctions between the Dry Creek and upper Putah Creek samples is likely to defeat a mixing analysis even with larger sample sizes.

CHANNEL GEOMORPHOLOGY

Historical changes in the alignment, profile and geometry of lower Putah Creek were used to investigate geomorphic channel dynamics and the associated implications for sediment supply and transport. Lateral movements in channel alignment indicate ample sediment transport capacity

Table 5. Lithology of Creekbed Gravels Above and Below the Confluence of Dry Creek and Putah Creek

	Lithology	Approximate Fraction of Sample (based on number of stones)		
		Putah Cr. above Dry Creek	Dry Creek	Putah Cr. below Dry Cr.
1	Sandstone or wacke: uniform dull tan to light gray exterior; dark brown (occasionally dark gray) interior; very rounded.	10%	10%	10%
2	Pegmatite: light gray; rounded; weathered; feldspar phenocrysts to 1 cm (10-40%), (usually <3% but up to 10%); interior feldspars and biotite commonly weathered to orange; rounded shape and lack of visible free quartz suggests a low-silica intrusive; weathers to smooth conglomerate appearance.	15%	15%	
3	Red chert: brick red with slightly to moderately vitreous lustre; some stones with white quartz veins to 2 mm thick	6%	10%	10% (low lustre)
4	Black chert (argillite?): rounded; hard; shiny.	15%	2 stones	10%
5	Blue chert (argillite?): dark shiny blue-black; hard; rounded		5%	
6	Green chert: gradational color white to pale green; vitreous lustre; dense and hard.	1 stone	1%	1 stone
7	Quartz: vein quartz; all-white to 30% coarsely marbled with blue to orange minerals; vitreous lustre	4% (veined only)	5%	0.5%
8	White welded tuff: (?): uniform white to light gray color with occasional orange staining; aphanitic texture; weathers to buff color and sandy texture.	2%		
9	Meta-gabbro(?): hard; white sparkly angular feldspar phenocrysts in a slightly translucent green-gray intrusive-looking matrix.	2%		
10	Orange argillite: very rounded, bright orange siltstone or mudstone; smooth matte exterior; small stones (< 2 cm) only.	0.5%	2%	
11	Yellow siltstone: friable, bright orange-yellow		1 stone	
12	Andesite(?): light gray; matte lustre; very rounded; orange-weathered biotite phenocrysts plus very small sparkly sanidine(?) phenocrysts.		2 stones	
13	Conglomerate #1: rounded pebbles of gray siltstone 2-60 mm in uniformly light blue-gray matrix that weathers to pure white			1 large stone
14	Conglomerate #2: rounded orange-gray-black pebbles 2-15 mm in white sand matrix. (The single stone is small and could be a completely-weathered piece of conglomerate #1 with no large pebbles)		1 stone	
15	Feldspar porphyry: bright white plagioclase phenocrysts in dark gray aphanitic groundmass	2 stones		
16	Quartzite: very hard; rounded; uniform matte tan-gray interior with tiny recrystallization sparkles; weathers to dark tan exterior.	1 stone		1 stone
17	Fine-textured granite (?): 60% mafic minerals 1-2 mm in white quartz-feldspar (?) matrix; weathers to pronounced salt-and-pepper appearance.		1 stone	
18	Coarse-textured granite (?): 50% mafic minerals, including brown-weathered olivine or pyroxene (0.5-1.0 mm) and dark blue-green hornblende and biotite (0.5-3.0 mm); 50% white quartz-feldspar matrix; weathers to dull dark-and-light gray appearance.			1 stone
19	Argillite: dark gray; matte lustre; common white quartz veins to 3 mm thick in random orientation			10%
20	Miscellaneous metamorphic rocks: dark gray; moderately rounded; fine-textured; mostly clastic origin (chert, argillite, wacke?).	47%	48%	67%

and enable the creek to recruit gravels from old channel deposits located nearby in the floodplain. Aggradation of the longitudinal profile would indicate a large sediment supply and depositional environment, whereas degradation would indicate the opposite. Changes in channel width and depth over time or along the length of the creek shed further light on depositional processes and whether those are changing.

Methods

The alignments of lower Putah Creek, Dry Creek and several nearby drainage channels were plotted from historical topographic maps and recent aerial photographs. The first topographic maps of the area were published by the U. S. Geological Survey (USGS) in 1911 based on surveys completed in 1905. These maps were at a scale of 1:31,680, which is slightly smaller-scale than the current 7.5-minute topographic maps (1:24,000). Paper copies of the Mt. Vaca, Wolfskill, Winters, Merritt, Swingle and Lovdal quadrangles were obtained from the California State Archives, scanned, and registered to geographic coordinates. The channel alignments were digitized in ArcView at a screen scale of approximately 1:12,000 and saved as shapefiles. The next series of USGS topographic maps was published in the early 1950s based on aerial photographs taken during 1947-1949. These maps were 7.5-minute series maps with the current quadrangle names (Mt. Vaca, Allendale, Winters, Merritt, Davis, and West Sacramento). Copies of these were obtained from the Shields Library map collection at U. C. Davis and similarly scanned, registered and digitized. The recent channel alignments were digitized from digital orthophotoquads published by the USGS. These are aerial photographs that are rectified to eliminate distortion and are geographically referenced. All of the channel shapefiles were converted to the projection of the orthophotoquads (UTM zone 10, NAD83, meters).

Historical channel profiles were obtained from several sets of data. Detailed channel surveys between the North Fork split and the Yolo Bypass were completed in 1947 by USACE as the basis for designing the flood control levees. The as-built engineering drawings for the levees include cross sections approximately every 400 feet along the 9-mile leveed reach, from which a channel profile was constructed. The survey was based on the U. S Engineer's Datum, and all elevations were converted to the NGVD 1929 datum (by subtracting 3.0 feet) for comparison among data sets. A water resources investigation by the U. S. Geological Survey at about the same time included wellhead elevations for 12 shallow monitoring wells installed in the creek channel between Winters and Mace Boulevard (Thomasson and others 1960). At the three well locations within the leveed reach, the elevations agree with profile developed from the USACE surveys. An aerial topographic survey of the entire length of lower Putah Creek was completed by the Yolo County Flood Control and Water Conservation District in 1994 using 2-foot contours, and the data were subsequently used by USACE to prepare a HEC-2 flood hydraulics model (Yarwood pers. comm., USACE 1995). The model files were obtained from USACE, imported to HEC-RAS, and a longitudinal profile was developed from the channel invert elevation at the 166 cross section locations in the model. The UNET model, developed by USACE for its comprehensive study of flood control in the Central Valley, included 21 cross sections along lower Putah Creek between about I-80 and Mace Boulevard. These were based on aerial photographs taken in 1997, and the low point in each cross section was the low-flow water surface, not the channel invert. Finally, DWR completed ground-based topographic surveys along lower Putah Creek between County Road 106A (river mile 1.16) and the Los Rios Farms/CDFG check dam (river mile -1.98) in spring 2002. All of these data sets were superimposed on a single profile plot to reveal whether there were any trends toward incision or aggradation between 1947 and 2002.

Channel width and depth were also extracted from the 1947 and 1995 survey data. Longitudinal profiles of top width and approximate area (width x depth) were tabulated to investigate spatial and temporal trends in channel geometry.

Results

Figure 13 shows the alignments of Putah Creek in 1905, 1947-1949, and 1993. Also shown are the alignments of Dry Creek, North Fork Putah Creek and several other minor drainage channels. Differences between the alignments can result from several possible causes:

- Errors in mapping, particularly for the 1905 data
- Artificial realignment of the channel
- Natural channel meander or avulsion processes

The channel alignment of Putah Creek has been remarkably stable for the past century, but there are several locations where shifts have occurred. In most cases, the shifts can be confidently attributed to one of the three possible causes. Fortuitously, the three dates bracket two periods of about 40 years each that nearly coincide with the periods before and after construction of Monticello Dam. The dam greatly decreased the sediment supply and sediment transport capacity, which would be expected to decrease the rate of geomorphic change. Thus, the data can also be used to draw tentative conclusions regarding the effects of the Solano Project on geomorphic dynamics.

The most consistent pattern for all of the channels is that the 1993 alignment is much more similar to the 1947-1949 alignment than to the 1905 alignment. This pattern could plausibly be the result of the decrease in energy and sediment supply associated with the Solano Project. However, a similar pattern evident in the alignments of other nearby stable channels indicates that errors in the 1905 surveys are the more likely cause of most of the the differences in channel alignment. In the case of Dry Creek, the creek retained its natural flow regime throughout the two time intervals. Its sinuous alignment indicates the presence of active meander processes. The fact that almost all of the changes in channel alignment appear to have occurred during the first four-decade period suggests that mapping errors in the 1905 data are a likely cause of the apparent shifts. This logic applies even more strongly to North Fork Putah Creek and the drainage channel that parallels Russell Boulevard, neither of which convey significant flows. With negligible amounts of flow, no change in channel alignment would be expected. But like the Putah Creek and Dry Creek channels, there are noticeable differences between the 1905 and 1947-1949 alignments and almost no difference between the 1947-1949 and 1993 alignments.

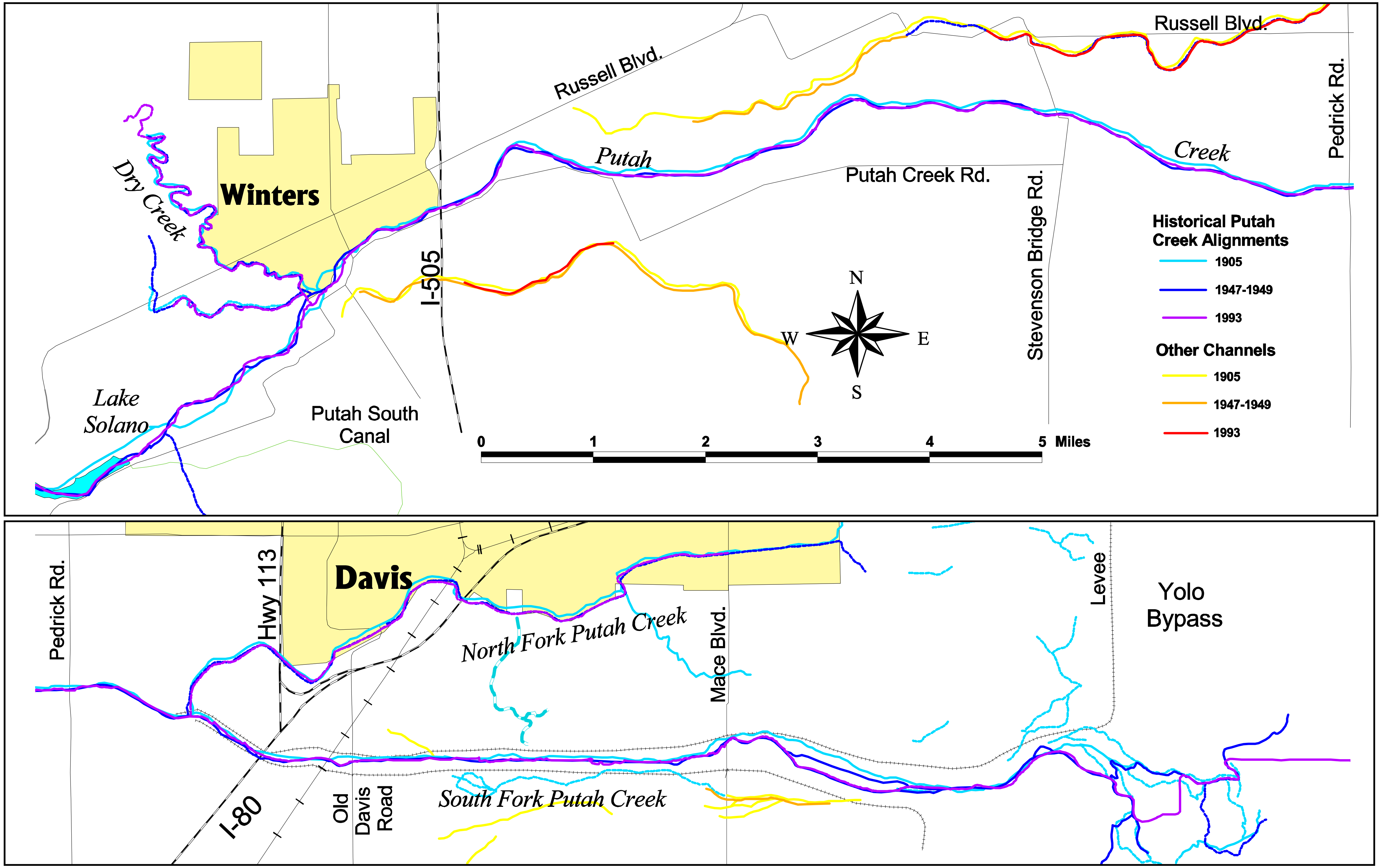


Figure 13. Historical Alignments of Lower Putah Creek and Nearby Channels

There are a few locations where the channel has clearly been artificially realigned, because the new channel is straight. The best examples are the final mile of channel where it crosses the Yolo Bypass between the check dam and the Toe Drain, and the straight north-south segment about 0.5 mile upstream of the check dam. The reach between Old Davis Road and Mace Boulevard also appears to have been slightly straightened.

In the small number of locations where natural processes appear to have shifted the channel alignment, most of the change occurred prior to construction of the Solano Project. One location is near river mile 0 (the west levee of the Yolo Bypass). In 1905, the channel followed a broad bend to the north before entering a reach with several distinct kinks. By 1947-1949, the channel had avulsed from midway through the bend along a southeasterly route that picked up two small subsidiary channels that had been evident on the 1905 maps. Landowners had reconnected the channel to its former alignment via the aforementioned north-south segment. The original channel was still present and apparently functional as an overflow channel. Another location is the change in alignment about 1 mile downstream of Mace Boulevard. A slightly sinous broad bend to the north in 1905 had changed to a more sinous alignment a few hundred feet to the south. A split channel also developed, but the straight, parallel alignments of the two halves of the split suggest that it might have been artificially constructed. At both of these locations, all of the change occurred prior to construction of the Solano Project.

The only location where significant channel realignment due to natural processes appears to have occurred since construction of the Solano Project is near the confluence with Dry Creek. This is the logical result of sediment influx from Dry Creek. During the first four-decade period, a pronounced S-curve near the confluence had inverted itself to a Z-curve. There were additional alignment changes of up to hundreds of feet along the reach between Lake Solano and Dry Creek. During the four decades following construction of the Solano Project, the channel near the Dry Creek confluence has shifted to the south. Putah Creek was less able to transport the influx of Dry Creek sediment during that period, and Dry Creek consequently "pushed" the Putah Creek channel to the south. Additional southward shifting has occurred since 1993. Minor changes in channel alignment upstream of Dry Creek during the second four-decade period could have resulted from gravel mining, which was widespread along that reach during the 1960s.

Historical profiles of channel thalweg (invert) elevation are shown in Figure 14. Unfortunately, no data are available from the 1905 survey. The earliest data are from the USACE and USGS surveys in 1947 and 1951. By that time, the creek had incised greatly as an apparent result of construction of the South Fork channel. The USACE data included one cross section across the old North Fork channel a few hundred feet from the main channel, where the South Fork departs from the original alignment. By 1947, the main channel had incised 22 feet below the elevation of the North Fork channel. This is not surprising, given that the channel of Putah Creek was perched on a ridge built of its own natural levee deposits. The alluvial fan surface near Putah Creek actually slopes away from the creek, not toward it. Thus, once the creek was directed into a new alignment across lower ground, the entire profile readjusted accordingly. This shift mimicked the normal mode of channel migration on channel-ridge alluvial fans, which is by channel avulsion. Avulsion is an

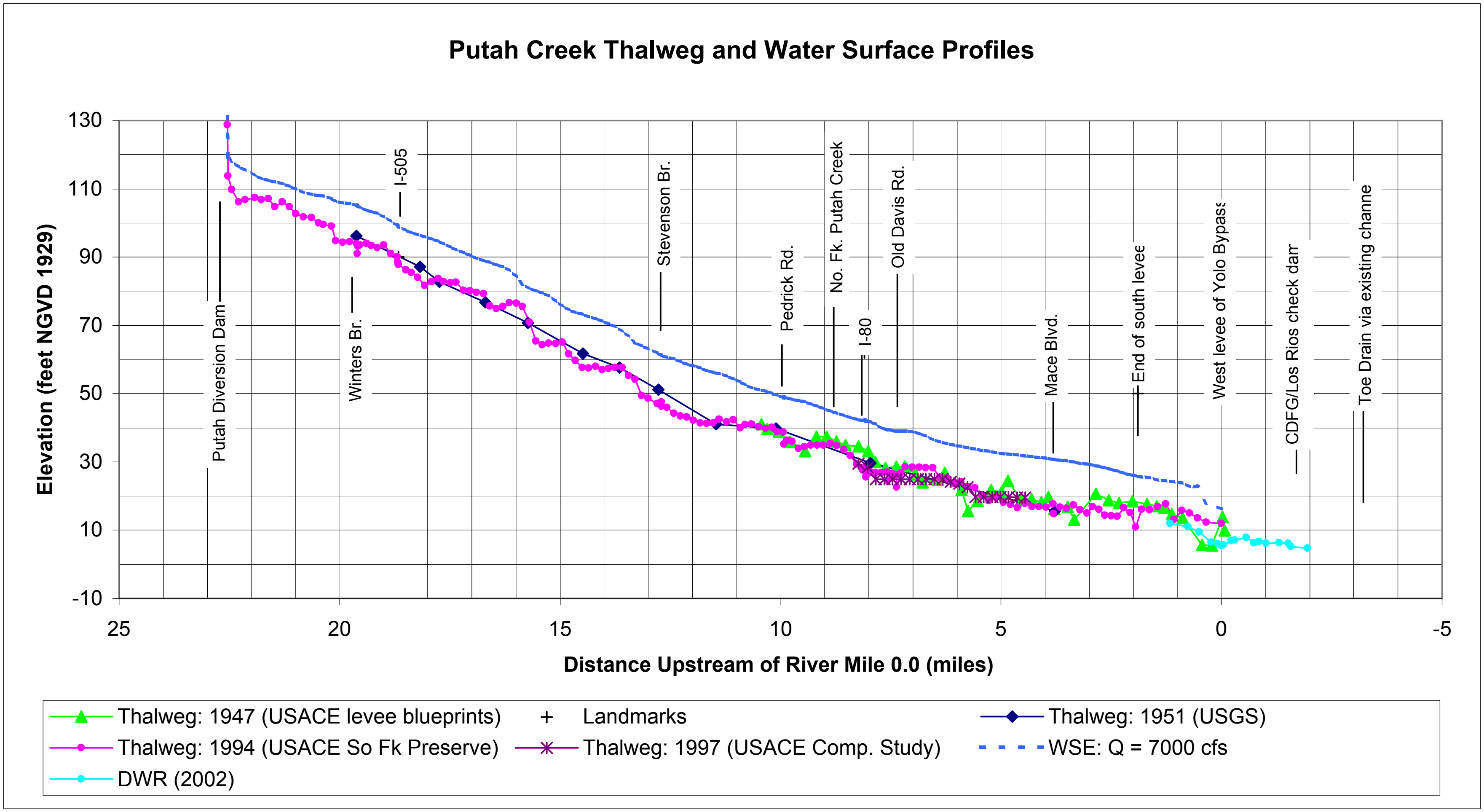


Figure 14. Historical Profiles of Thalweg Elevation along Lower Putah Creek

abrupt switch to an entirely new alignment during a flood event. For example, the channel that originates close to the south bank of Putah Creek near Winters and flows to the east and south (see Figure 13) is a geologically recent former channel of Putah Creek.

The most remarkable aspect of the historical thalweg profiles is their similarity. In spite of the large time span encompassed (55 years) and the different survey methods and purposes, the profiles all fall nearly on top of one another. The incision that occurred priod to 1947 does not appear to have continued, in spite of the decrease in sediment input following construction of the Solano Project. Possibly, the decrease in stream energy and the low erodibility of the dense clay-silt creekbed have jointly slowed the rate at which incision can occur.

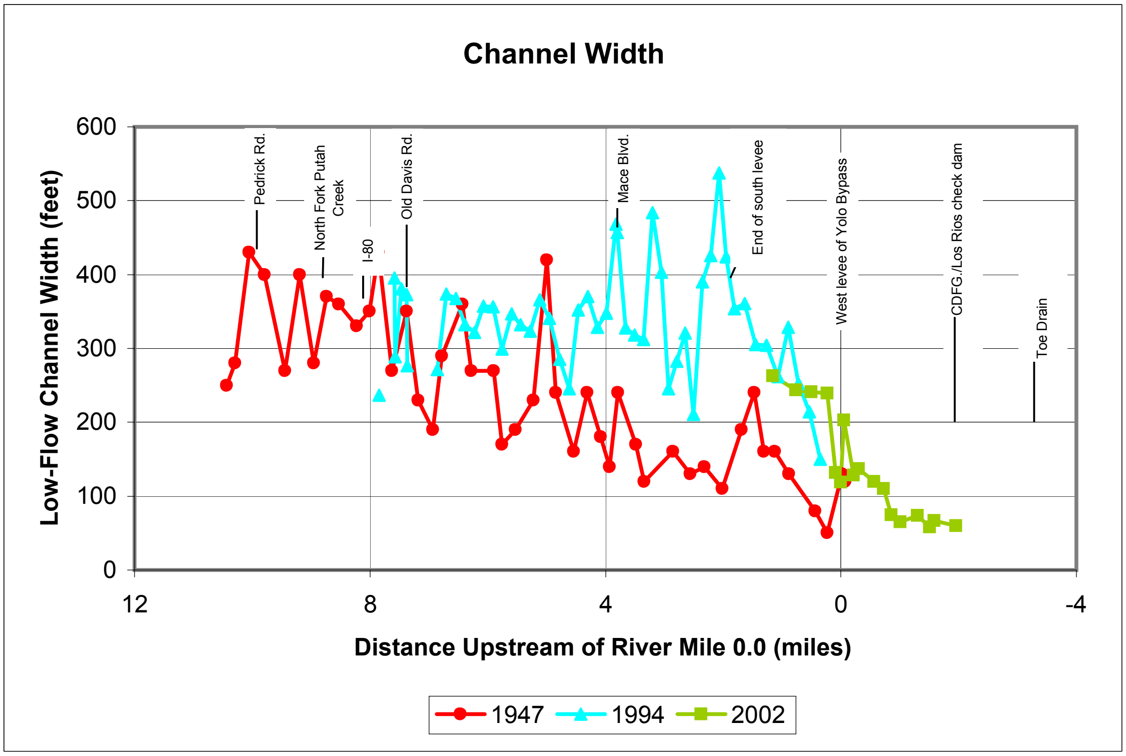
A slight bulge is visible in the 1947 and 1994 thalweg profiles near the east end of the south Putah Creek levee. It would seem plausible that a zone of high deposition would occur where flood flows leave the confinement of the levees and enter the Yolo Bypass, with an attendant decrease in velocity. However, the channel substrate surveys revealed that the bulge consists of clay-silt with only a patchy veneer of sand and gravel. Thus, the bulge more likely represents an outcropping of relatively consolidated clay-silt material within the valley alluvium.

Profiles of channel top width and approximate cross-sectional area (width x depth) are shown in Figure 15. The width and cross-sectional area of the low-flow channel both clearly become smaller along the final 10-12 miles of the creek. This pattern is not surprising for the distal end of an alluvial fan, where flood events would naturally spill over into a distributary network of channels as it merges with the backwater effects of the Yolo Basin wetlands. Perhaps more remarkable is that this pattern has not changed substantially following the construction of the Yolo Bypass Toe Drain, which drained the wetlands. There appears to have been a slight widening between river miles 0 and 6, but no clear change upstream or downstream of that reach.

In summary, the alignment and profiles of lower Putah Creek have been quite stable over the past century. Almost all of the change that occurred was prior to 1947. The only noteworthy exception is channel meandering near the confluence with Dry Creek during the past 50 years. The general lack of adjustment may be the result of insufficient stream energy to effect geomorphic change following the construction of Monticello Dam.

SEDIMENT MOBILITY

A quantitatve analysis of sediment mobility was beyond the scope of the present project. However, clues regarding the mobility of unconsolidated material on the creekbed can be gleaned from the distribution of sediment texture along the channel, historical changes in channel alignment, sedimentation rates at Lake Solano, and miscellaneous observations of scour and deposition. Application of theoretical sediment transport equations to simulated bed shear stress also indicate the range of flows under which material is expected to be mobile.



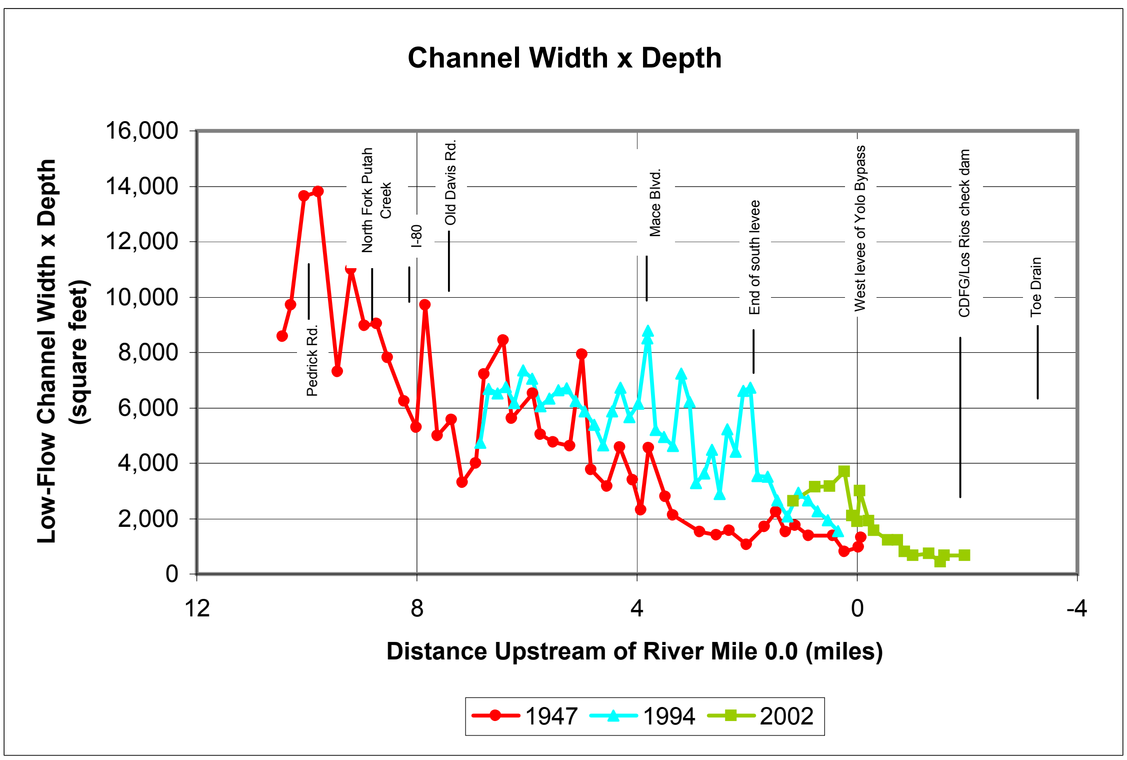


Figure 15. Historical Profiles of Channel Width and Cross-Sectional Area

Methods

Most of the inferences about sediment transport in this section are qualitative in nature. However, quantitative estimates of theoretical sediment mobility were developed using the HEC-RAS model and the Shields criterion for incipient motion of individual sediment grains. The HEC-RAS model automatically calculates bed shear stress at each cross section. The Du Boys equation relates shear stress to water depth and channel slope:

$$\tau_0 = \gamma_f R S \qquad \text{(Eq. 3)}$$

in which

τ_0 = shear stress at the creekbed surface (pounds per square foot)
γ_f = specific weight of water (pounds per cubic foot)
R = hydraulic radius, which approximately equals water depth (feet)
S = channel slope (dimensionless)

The Shields criterion relates bed shear stress to the maximum particle size that will be moved by the current:

$$\tau^* = \frac{\tau_0}{(\gamma_s - \gamma_f)\, d} \qquad \text{(Eq. 4)}$$

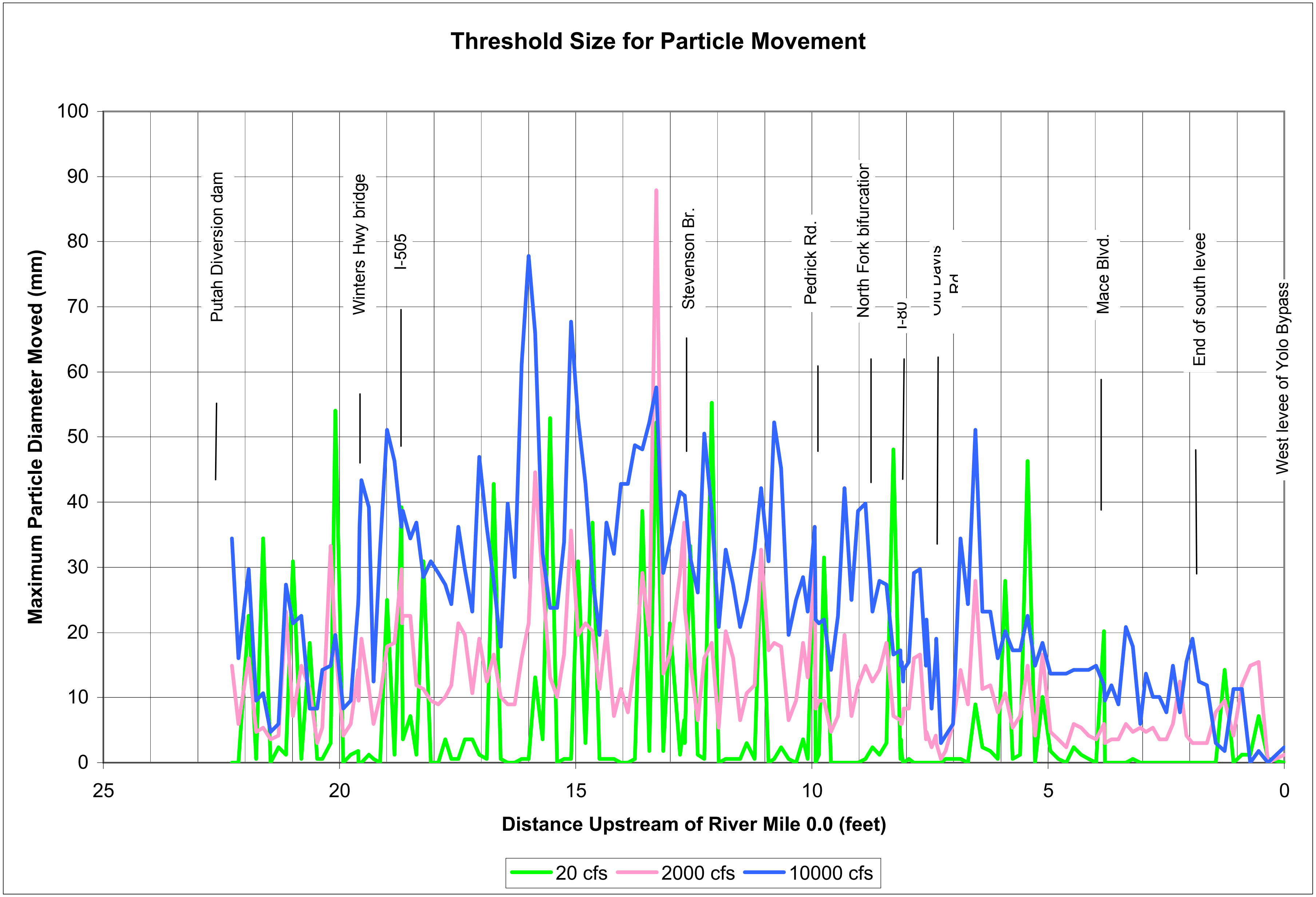
in which

τ^* = empirical dimensionless ratio
γ_s = specific weight of the sediment particle (pounds per cubic foot)
d = diameter of the sediment particle (foot)

In a series of experiments with uniform-sized cohesionless sediment particles, Shields found that τ^* is typically around 0.04-0.05 (Shen and Julien 1993). For a rough estimate of mobile particle sizes, a value of $\tau^* = 0.04$ was assumed, and equation 4 was solved for d at each cross-section in the model.

Results

The local variability of shear stress is quite large, as revealed by the longitudinal profiles of simulated bed shear stress along the length of the creek shown in the upper graph in Figure 16. Shear stress varies tremendously from one cross section to the next, by factors of up to 50 for small flows and up to 10 for larger flows. Shear stress also varies substantially with flow. On average, higher flows are associated with higher bed shear stress, but locally the pattern is reversed. Consequently, flow fluctuations expose sediments along the creek to a spatially and temporally


Threshold Size for Particle Movement
Maximum Particle Diameter Moved (mm)
Distance Upstream of River Mile 0.0 (feet)
100
90
80
70
60
50
40
30
20
10
0
25
20
15
10
5
0
Putah Diversion dam
Winters Hwy bridge
I-505
Stevenson Br.
Pedrick Rd.
North Fork bifurcation
I-80
Old Davis Rd
Mace Blvd.
End of south levee
West levee of Yolo Bypass
20 cfs
2000 cfs
10000 cfs

complex pattern of shear stress that presumably contributes to the uneven distribution of sediment observed during the gravel surveys.

The variability in bed shear stress translates directly to variability in the size of sediment the creek is capable of transporting, as shown in the lower graph in Figure 16. The graph indicates the largest diameter of sediment particle likely to move at the indicated flow and location. Even at flows as low as 20 cfs, there appear to be locations where pebbles up to 50 mm in diameter would begin to move. Along about half the length of the creek, however, that flow would be capable of transporting only material smaller than 5 mm. At the other extreme, a flow of 10,000 cfs could mobilize particles up to 20 mm in diameter continuously along most of the length of the creek and locally move particles up to 80 mm.

The Shields criterion relating shear stress to particle size assumes loose grains of relatively uniform size. Sediments along lower Putah Creek are a mixture of sizes and in many places are slightly compacted, with finer material filling the interstices between larger. Under such circumstances, there typically is little or no sediment movement until a threshold shear stress is reached, at which point all sizes (up to some upper limit) move simultaneously. This is known as the "equal mobility" hypothesis, which is commonly reflected in an assumption that the threshold size indicated by the Shields criterion corresponds to the median grain size of the sediment mixture. All but three of the 31 gravel samples analyzed for this study had median grain sizes between 4 and 30 mm. The finer samples would be theoretically mobile along about half the length of the creek at flows of 20 cfs. A flow of 2,000 cfs would theoretically mobilize material with a median grain size up to 8 mm (about one-third of the samples) along most of the length of the creek. A flow of 10,000 cfs would mobilize almost all of the sampled textures throughout the reach between Winters and Old Davis Road, and most of the sampled textures along the remaining reaches.

Informal observations by this author before and after high flow events confirm that sediment is at least locally mobile at fairly low flows and that vegetation and bed form also affect sediment mobility. When the creek was largely dry for several months in 1990, a small delta of gravel was formed at the inlet to a pool near Stevenson Bridge as a result of several one-day releases of 100 cfs from Putah Diversion Dam. Vegetated gravel bars above the low-flow water level often emerge from flood events either relatively undisturbed or completely denuded -- as illustrated in Figure 17 -- suggesting that plant roots stabilize the unconsolidated sediment and intensify the threshold effect for initiating transport. On sparsely vegetated bars, however, small scour depressions between shrubs are sometimes present, indicating that the plants stabilized sediment in their immediate vicinity while the intervening material remained mobile. An accidental breach along the bank of Willow Canal during the summer of 2001 deposited a mass of sand up to 4 feet deep and 100 feet long in the channel of Putah Creek approzimately 0.8 mile below Stevenson Bridge. Runoff was light the following winter, with a maximum daily flow of 428 cfs on December 2 and six days of flow between 172 and 329 cfs during December 28-January 2. Although theoretically capable of mobilizing all of the sand, the flows simply planed off the top of the deposit and scoured a path along one edge of it down to the original creekbed elevation. The width of the scoured area was about one-third the width of the creek The mobilized material was distributed along several hundred feet of the creek channel downstream of the site.

Putah Diversion Dam blocks the transport of coarse sediment and some fine sediment from upstream reaches. Sediment accumulated in Lake Solano at an average rate of 5,600 cubic yards per year during 1958-1997 (Northwest Hydraulic Consultants, Inc. 1998). Except at the upstream end of the lake and in the deltas at the mouths of Pleasants Creek and Proctors Draw, sediments deposited in the lake consist only of sand and finer material. Some of the finer material passes Putah Diversion Dam and enters lower Putah Creek when the sluice gate is opened at the dam and lake level is lowered for maintenance activities. Based on the distribution of sediments in the lake, it does not appear that gravel passes the dam during these sluicing events.

During the 45 years since the completion of the Solano Project, sediment discharge from Dry Creek has exceeded the diminished ability of Putah Creek to transport the sediment. Gravel bars have developed at the confluence that have pushed the alignment of Putah Creek southward (see "Channel Geomorphology" above). This phenomenon does not mean that Putah Creek is unable to move the sediment, but only that the long-term average transport capacity is smaller than it was prior to construction of the Solano Project.

LONGITUDINAL WATER TEMPERATURE PROFILES

Water temperature is an important physical habitat characteristic for fish in Putah Creek and limits the distribution of native species in summer. Although temperature is not directly related to the distribution of gravels, the canoe-based gravel surveys offered a convenient opportunity to measure water temperature along the creek and test a hypothesis regarding the influence of beaver dams on stream temperature. Beaver dams create pools that increase the surface area of the creek (and hence the rate of solar warming) and also increase the residence time of water flowing down the creek. These two effects are expected to shorten the distance that cold water released from Putah Diversion Dam travels down the creek before equilibrating with ambient air temperature. Toward the end of the 1987-1992 drought, approximately 25 beaver dams were present along the creek from midway between Putah Diversion Dam and Winters to around Davis (others were probably present farther downstream but were not surveyed). Most of the dams were washed out by high-flow events in the mid-1990s. The average low-flow water surface of the creek fell by 2-3 feet along much of the length of the creek, which presumably decreased the average residence time of water in the channel and allowed cold water to travel farther downtstream. The semi-permanent decline in low-flow water surface elevation was recorded by the position of pedestal grass clumps along the bank. Pedestal grass forms a tall cylindrical root mass topped with foot-long grass blades. The dividing line between roots and leaves becomes established at the average low-flow water surface elevation. After the semi-permanent drop in water surface elevation, many pedestal grass clumps were left entirely out of the water, as illustrated in Figure 17. By comparing longitudinal temperature profiles before and after the beaver dams were removed, the effect of the dams can be evaluated. Summertime longitudinal temperature profiles prior to the high-flow events were measured in 1993 and 1994 (Jones & Stokes Associates, Inc. 1994). Temperature profiles were measured by Solano County Water Agency in 1998 and 1999, after the high-flow events, and longitudinal temperature profiles were surveyed for this study on August 20 and 27, 2002.

Methods

Water temperature was measured at eight locations along lower Putah Creek on 11 occasions during the summers of 1993 and 1994. Temperatures were measured approximately 0.2 foot below the water surface using a bulb thermometer with 0.5 EC graduations. The same locations were sampled on each date and were at riffles or runs where thermal stratification would not occur. Several profiles representing two flow levels and two ranges of air temperature (hot day and warm day) were selected for comparison with more recent data.

The data from 1998-1999 are midday water temperatures obtained from submerged data loggers (site details not available). Water temperatures in 2002 were measured at runs or riffles approximately 1 foot below the water surface with a YSI 30 digital temperature/conductivity probe. Locations were recorded by GPS and converted to river miles.

Water temperatures along lower Putah Creek are influenced by several factors in addition to beaver dams. To the extent possible, sampling dates from the 1998-1999 and 2002 surveys were selected to replicate conditions during the 1993-1994 surveys to minimize the extraneous effects of these factors. The factors include:

- Diurnal temperature fluctuations. Creek temperature fluctuates over a range of 2-5 EC on a typical hot summer day. Neither of the manual surveys recorded temperatures at all locations simultaneously. Temperatures for those surveys were measured in the downstream direction over the space of several hours between late morning and late afternoon. However, differences in time of day and the hydrographer's rate of travel down the creek could potentially shift the temperature at any point along the warming profile by several degrees.

- Season. Solar angle and day length both significantly affect creek temperatures. Because the creek banks are lined with tall trees in most locations, a small change in sun angle can significantly alter the number of hours each day that the creek surface is in the shade.

- Air temperature. Air temperature affects the "equilibration" temperature that the warming profile reaches in the downstream direction. The profile reaches a higher temperature on a hot day than a cool or warm day.

- Flow. All other factors being equal, a larger release from Putah Diversion Dam will increase mean flow velocity and push cold water farther down the creek, flattening the warming profile.

It was not possible to systematically control for all of the above variables during the sampling effort in 2002. The number of profiles available for comparison before and after the removal of the beaver dams is too small to statistically extract the effects of individual factors. However, the data are sufficient to qualitatively assess the relative importance of some of the factors.

Results

The longitudinal temperature profiles selected for analysis from the 1993-1994, 1998-1999 and 2002 data sets are plotted together on the graphs in Figure 18. The upper graph shows profiles on hot days (maximum air temperature 38 EC), and the lower temperature shows profiles on warm days (maximum air temperature 29-30 EC). Most of the warming occurred along the first 4 miles below Putah Diversion Dam and is represented by only three points on the profiles. Although the details of the warming curve are poorly defined along this reach, any large differences in the warming rate might still be detectable. Points farther downstream reveal differences in the equlibrium temperature of the creek. The "plateau" in the temperature profiles upstream of Stevenson Bridge is the result of groundwater seepage into the creek. Groundwater in this area has a relatively constant year-round temperature of about 17 EC (Thomasson and others 1960).

Time of year appears to have the strongest influence on water temperature because of differences in solar angle and shading of the creek surface. The creek is oriented almost exactly east-west, and the south bank is lined with mature trees along most of its length. These trees project shadows onto the creek surface when the sun is low in the sky, especially in fall, winter and spring when the sun rises and sets somewhat south of due east and west. The projected shadows amplify the seasonal variations in solar angle and azimuth, creating large variations in the amount of solar radiation striking the creek surface. The lowest warming rates in both graphs were on dates near the beginning or end of summer. The rates of warming were much smaller in spite of relatively low flows that provide additional residence time.

Surprisingly, maximum daily air temperature does not appear to have a strong effect on the temperature profiles. The range of temperatures for the mid-summer profiles at Winters, Stevenson Bridge and Mace Boulevard are approximately the same for hot days and warm days in spite of an 8-9 degree difference in maximum air temperature.

Flow also appears to have a relatively minor effect. In both graphs, there is as much difference between the two profiles for releases of 33-34 cfs (at Putah Diversion Dam) as there is between those profiles and the 39-43 cfs profiles.

Allowing for the effects of time of year, air temperature and flow, it appears that removal of the beaver dams did result in a slight lowering of the temperature profile. In the upper graph, for example, the profile measured on August 27, 2002 was 2-3 EC lower than the profile measured on the same day in 1993 with identical flow and air temperature conditions. Similarly, the August 20, 2002 profile in the lower graph is at least 2 EC cooler than the three profiles from 1993-1994 at most locations. The effect of beaver dam removal appears to accumulate along the reach from Putah Diversion Dam to Winters, at which point it remains constant along much of the rest of the creek.

An additional detailed temperature survey between Putah Diversion Dam and Winters was completed on September 5, 2002, to determine whether the warming rate along that reach was gradual or stepwise. Although warming occurs along the entire reach, one location was discovered with a particulary large temperature increase. This was a pool 100-200 feet wide with very low water velocities near river mile 20.4 (2.1 miles below Putah Diversion Dam). The pool is probably an artifact of gravel mining activities in the 1960s. A temperature increase of 2 EC was measured across this pool. This was also the location where algae became abundant; temperatures farther upstream were apparently too cold to support much algae. The temperature jump at this location confirms that low velocities and lack of shading contribute to rapid warming and limit the number of miles of cold-water habitat below Putah Diversion Dam.

CONCLUSIONS

- In terms of its distribution along the length of the creek, gravel substrate is neither abundant nor scarce. It is the substrate along a cumulative total of about 8 river miles, or one-third of the length of lower Putah Creek.

- Gravel substrate is distributed along the entire length of lower Putah Creek, although its abundance decreases somewhat with distance downstream of Putah Diversion Dam.

- Gravel substrate in combination with suitable flow hydraulic conditions for spawning is much scarcer, amounting to only 6-16 percent of the length of the creek, depending on fish species.

- In terms of quality, gravel deposits are commonly too thin and too fine-grained to be optimal for spawning for most species. However, fish may be able to successfully spawn under sub-optimal conditions if no better alternative is available.

- In stream segments with generally suitable spawning conditions along the creek centerline, only about one-fifth to one-third of the creek width typically meets the preferred spawning site criteria, although the fraction would be higher during the spawning season when flows are often higher.

- Gravel in Putah and Dry Creeks is composed of an exceedingly diverse range of rock types, which precluded the use of a lithologic mixing model to estimate the percentage of Putah Creek gravel derived from Dry Creek.

- The alignment of the creek channel has been very stable over the past century. The few apparently natural changes in alignment all occurred prior to construction of Monticello Dam except at the confluence with Dry Creek. Sediment discharge from Dry Creek has accumulated in the Putah Creek channel, pushing the low-flow alignment slightly to the south.

- Profiles of channel invert elevation and cross-sectional area have also remained quite stable since prior to construction of Monticello Dam. Eliminating the sediment supply from upstream sources does not appear to have resulted in significant incision or widening.

- Simulated bed shear stress is extremely variable in space and time, which probably contributes to the uneven distribution of coarse sediment along the length of the creek.

- Applying grain-size mobility criteria to bed shear stress indicates that perhaps one-third of the relatively coarse sediment found along the creek would be mobilized by a flow of 2,000 cfs.

- A few casual observations of sediment redistribution over short periods of time confirm that even low-to-moderate flows can transport sediment, at least in some locations.

- Removal of numerous beaver dams by floods during the mid-1990s appears to have lowered midday summer creek temperatures by approximately 2 EC. This effect is thought to be the result of decreased flow width and volume, which in turn decrease the area of creek surface exposed to the sun and the hydraulic residence time. The warming rate is consequently slower.

RECOMMENDATIONS

The foremost recommendation of the present investigators is that this report be circulated among fish biologists, other hydrologists and fluvial geomorphologists to broaden the interpretation of the data, particularly with respect to the adequacy of the existing gravels for fish spawning.

The present study documented the distribution and texture of noncohesive substrate along the channel of lower Putah Creek, and it presented a long-term view of geomorphological channel dynamics. However, it did not answer three important questions related to those sediments:

- Is the amount of gravel a limitation for native fish populations?

- What are the sources of the gravels presently found in the channel?

- Is the amount of gravel decreasing over time?

Addtional field studies and modeling analysis may be able to answer these questions. Appropriate tasks include the following:

1. Characterize Pre-Project Sediment Texture

The gravel surveys completed for the present study did not evaluate whether the quantity and texture of sediment has changed significantly since construction of Monticello Dam. Grain-size analysis of a small number of samples from the following locations would provide a rough indication of pre-project sediment texture: 1) old gravel bar deposits along lower Putah Creek, 2) Dry Creek, 3) the interdam reach, and 4) Putah Creek upstream of Lake Berryessa. Historical mineral resource surveys of sand and gravel deposits might also contain older sediment texture data for Putah Creek. In addition to indicating trends in gravel texture and abundance, this information could serve as a reference point for estimating historical spawning opportunities and for designing gravel augmentation efforts.

2. Survey the Volume of Gravel in Subaerial Bars and Terraces

The present survey focused on sediment within the low-flow channel. The approximate locations of prominent subaerial gravel bars and terraces adjacent to the low-flow channel were recorded during the longitudinal surveys, but no measurements were made of those deposits. The volume of gravel stored in the bars and terraces could be large relative to the average annual rate of sediment transport. This stored material is probably scoured during flood events, replenishing material in the low-flow channel. To the extent that this stored material is accessible for transport, it retards the long-term depletion of sediment that presumably began with the construction of Monticello Dam and Putah Diversion Dam. Dense vegetation and the need to auger through the deposits to estimate their thickness would make a detailed survey challenging. Preliminary tests of various surveying methods – including detailed air photo analysis – are recommended as a first step toward devising a practical scope of work.

3. Estimate Present Sediment Transport Rates along Lower Putah Creek

Long-term loss of gravel substrate along the channel of Lower Putah Creek would gradually diminish spawning opportunities for resident and anadromous native fish. Sediment transport rates can be estimated by measuring sediment-versus-flow relationships in the field and integrating the resulting sediment rating curves over time using the historical flow record, as follows:

1. Sediment-versus-flow rating curves could be developed by collecting suspended-sediment and bedload samples during moderate and high-flow events. These would be collected from bridges using Helley-Smith bedload samplers and depth-integrating bottle samplers. Movement of painted stones during high-flow events could also be measured after flows recede to calibrate bedload transport simulations.

2. Long-term average sediment transport rates could be estimated by integrating the sediment rating curves with a 30-year record of daily and peak flows.

3. Sediment flux rates could be converted to an average annual channel erosion (incision) rate at the measurement locations

4. The existing HEC-RAS hydraulics model could be expanded to simulate sediment transport (HEC-6) by incorporating the sediment rating curves. This would reveal variations in long-term erosion/deposition rates along the reaches between the sediment sampling locations.

4. Implement a Gravel Replenishment Pilot Project

The present study revealed that most of the gravel along lower Putah Creek is finer than the texture normally utilized by steelhead, salmon and lamprey for spawning. Anectodal observations of lamprey spawning at vehicle fords constructed of relatively coarse gravels suggests that the lack of coarse gravels may be limiting salmonid reproduction. A gravel-replenishment pilot project would reveal the extent to which fish perceive inadequate gravel resources as a significant constraint based on the strength of their preference for artificially-introduced coarse material. For this pilot project, coarse gravel could be added on top of naturally-occurring fine gravels at one or more hydraulically suitable spawning locations, and subsequent use of the area for spawning could be monitored. Spawning use of nearby control sites could also be monitored to verify fish preference and estimate the benefits of the gravel addition. Movement and/or burial of the added gravels could also be monitored. Long-term retention of the emplaced gravels would be estimated using sediment-transport equations and the recurrence interval of the threshold flow at which the gravel would be mobilized. Some of the monitoring activities could potentially be incorporated into the existing fish monitoring activities of the Lower Putah Creek Coordinating Committee.

REFERENCES CITED

Printed References

Church, M. A., D. G. McLean, and J. F. Wolcott. 1987. River bed gravels: sampling and analysis. *In:* Sediment transport in gravel bed rivers. C. R. Thorne, J. C. Bathurst, and R. D. Hey, editors. John Wiley and Sons, Chichester, United Kingdom, pp. 43-79.

Conwell, J. 1976. Spills at Monticello Dam. Unpublished memorandum to William Larramendy (BLM). February 12. U. S. Bureau of Reclamation, Sacramento, CA.

Jones & Stokes Associates, Inc. 1992. Hydraulic, hydrologic, vegetation, and fisheries analysis for the U. S. Fish and Wildlife Service Putah Creek Resource Management Plan. Final. July. Sacramento, CA. Prepared for U. S. Fish and Wildlife Service, Sacramento, CA.

Keller, E. A. 1969. Form and flucial processes of Dry Creek, near Winters, California. M. S. Thesis. University of California, Davis, CA.

Kondolf, G. M. 1997. Application of the pebble count: notes on purpose, method, and variants. Jounal of the American Water Resources Association 33(1):79-87.

____________. 2002. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society 129:262-281.

Larkey, J. L. 1969. Davisville '68: the history and heritage of the City of Davis. Davis Historical Landmark Commission.

Moyle, P. B. 1992. History and management of fisheries in lower Putah Creek. Department of Wildlife and Fisheries Biology. University of California, Davis, CA.

__________________. 2002. Inland fishes of California, revised and expanded. University of California Press, Berkeley.

Northwest Hydraulic Consultants, Inc.. 1998. Lake Solano sediment removal and management study. Phase I final report. November. West Sacramento, CA. Prepared for Solano County Water Agency, Vacaville, CA.

Shen, H. W. and P. Julien. 1993. Erosion and sediment transport. Chapter 12 *in* D. R. Maidment, ed. Handbook of hydrology. McGraw-Hill, Inc. New York, NY.

Sherwin, E. 1998. Reason to celebrate: salmon in creek! Spring. Putah Creek News 1(2):1-3.

Texas Natural Resource Conservation Commission. 1999. Surface water quality monitoring procedures manual. Austin, TX.

Thomasson, H. G. Jr., F. H. Olmsted, and E. F. LeRoux. 1960. Geology, water resources, and usable ground-water storage capacity of part of Solano County, California. Water-Supply Paper 1464. U. S. Geological Survey, Washington D. C.

Trihey & Associates, Inc. 1996. Native species recovery plan for lower Putah Creek. Concord, CA. Prepared for Law Offices of Martha H. Lennihan, Sacramento, CA.

U. S. Army Corps of Engineers (USACE), Sacramento District. 1995. Winters & vicinity reconnaissance report. Two volumes. April. Sacramento, CA.

Personal Communications

Moyle, Peter. Professor. Department of Wildlife and Fisheries Conservation Biology, University of California, Davis, CA. February 8, 2003 – E-mail to Gus Yates

Preston, Rob. Botanist. Davis, CA. September 22, 2002 -- meeting with Gus Yates

Yarwood, Mel. Hydraulic engineer. U. S. Army Corps of Engineers, Sacramento, CA. May 20, 2002 – telephone conversation with Gus Yates