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Determining appropriate instream flows for anadromous fish passage on an intermittent mainstem river, coastal southern California, USA

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ABSTRACT

Setting instream flows to protect aquatic resources is required by California state law, but this task is not straightforward for an intermittent river that is naturally dry six or more months of every year. The Santa Maria River, 200 km northwest of the Los Angeles metropolitan area, lies within the northern range of the federally endangered southern California steelhead (*Oncorhynchus mykiss*) and is a logical candidate for instream flow protection: the watershed historically supported the anadromous life history of this species, but fish must navigate the lowermost 39 km of the commonly dry mainstem river to move between the ocean and freshwater habitats in the upper watershed. Mainstem flows are partly controlled by Twitchell Dam, constructed across one of the Santa Maria River's two main tributaries in 1962. The dam is operated to maximize groundwater recharge through the bed of the mainstem Santa Maria River, thus minimizing discharge to the Pacific Ocean and so reducing already limited steelhead passage opportunities. Conventional criteria for determining suitable instream flows for steelhead passage are ill-suited to intermittent, Mediterranean-type rivers because they ignore the dynamic channel morphology and critical importance of headwater flows in providing cues that once presaged passage-adequate mainstem discharges but no longer do so. Hydrologic analysis of pre-dam flows, coupled with established criteria for successful *O. mykiss* migration, provides an objective basis for evaluating alternative dam-management scenarios for enhancing steelhead passage, although their implementation would redirect some water that for the past half-century has exclusively supported irrigated agriculture and municipal water supplies.

KEY WORDS fish passage; instream flows; regulated river; intermittent river; southern California steelhead; ecohydrology

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INTRODUCTION

Throughout southern California, a wide range of impacts to river flow has resulted from expansion of agriculture and human populations over the past century. Rivers within this Mediterranean climate are naturally intermittent, with long periods of low or no flow to which native species have adapted (Gasith and Resh, 1999; Grantham *et al.*, 2012). Even within this context of high natural flow variability, however, the abstraction of water for human use can be significant (Grantham *et al.*, 2010; Kondolf *et al.*, 2012) and has severely impacted instream biota. In particular, populations of federally endangered *Oncorhynchus mykiss* (steelhead trout) in the northern portion of the Southern California Steelhead Distinct Population Segment (DPS; formerly referred to as Evolutionarily Significant Unit) (62 FR 43937) have experienced historical declines in run sizes of 90% or more (NOAA National Marine Fisheries Service, 2012). Re-establishing access to upper watersheds by restoring natural hydrologic patterns to facilitate fish migration has been identified by NOAA National Marine Fisheries Service (2012) as one of the highest priorities for the recovery of the Southern California Steelhead DPS.

Despite the urgency of these recommendations and the rich scientific literature that has been developed around the magnitude, frequency, and timing of natural flows in rivers in support of ecological conditions (e.g., Poff and Zimmerman, 2010; Poff *et al.*, 2010), methods for identifying and quantifying impaired hydrologic patterns in intermittent, Mediterranean-type rivers are sparse. Existing methods, commonly implemented in the execution of such 'instream flow studies', have been developed

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primarily on perennial single-thread channels (e.g., Hatfield and Bruce, 2000) where the greatest limitations to fish passage are primarily hydraulic – in other words, locations where water depth and/or width is insufficient at a given discharge to allow upstream or downstream fish movement during critical life stages. In intermittent rivers, however, the problem is typically much more fundamental – is there any water at all? Although having a 'sufficient' quantity of water is still as necessary in intermittent systems as in perennial ones, this is a secondary consideration. As a further complication, the commonly applied analytical methods of many instream flow studies presume a static channel geometry in which water levels rise and fall predictably with changing discharge (e.g., physical habitat simulation models; Stalnaker *et al.*, 1995; Annear *et al.*, 2004). Most intermittent rivers of the semi-arid southwestern USA, however, have highly mobile sand beds in their alluvial reaches that violate this fundamental assumption, with substantial channel modifications occurring with almost every fish-passable and sediment-transporting flow.

The goal of this study is therefore to develop an approach to evaluating human-induced changes in the frequency, duration, and timing of fish passage in an intermittent mainstem river. This requires determining (1) the magnitude of fish-passable flows through an easily erodible channel, (2) the pattern of pre-regulated flows as a baseline target for evaluating subsequent flow modifications, and (3) a set of dam operation 'rules' that could contribute to the recovery of historical migration opportunities in a river of regional importance to both species conservation and human occupation of the landscape.

STUDY AREA

The Santa Maria River is one of the largest coastal southern California rivers within the Southern California Steelhead DPS (Figure 1). Its 4820 km^2 watershed supports a self-sustaining population of rainbow trout (the resident life history form of *O. mykiss*) in the upper part of one of its two major tributaries, the Sisquoc River watershed (Shapovalov, 1944; Cardenas, 1996; Boughton and Fish, 2003; Stoecker, 2005). It has also supported spawning of anadromous steelhead (the ocean-going life history form of *O. mykiss*) during some wet years (Shapovalov, 1944, 1945; Stoecker, 2005; Titus *et al.*, 2010) in historical time. The California Department of Fish and Wildlife (CDFW, previously the California Department of Fish and Game) is obligated to identify and list 'those streams and watercourses throughout the state for which minimum flow levels need to be established in order to assure the continued viability of stream-related fish and wildlife resources' (California Public Resources Code §10001). In 2008, the CDFW identified the Santa Maria River on a list of 22 priority streams that require instream flow analysis in order to provide the scientific basis for flow recommendations to support anadromous fish passage.

The Santa Maria River watershed lies in a Mediterranean climatic zone, with a long dry season and episodic wet-season storms. Most precipitation occurs between November and March, with precipitation varying significantly throughout the watershed and most strongly influenced by elevation and distance from the Pacific Ocean. Year-to-year rainfall is also strongly influenced by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation (NWS CPC, 2010). In southern California, El Niño years are generally accompanied by relatively high rainfall intensities, with rivers and streams (such as those in the Santa Maria River watershed) exhibiting higher annual peak flow magnitudes than they do in non-El Niño (i.e., 'La Niña') years.

The mainstem Santa Maria River is approximately 39 km long and is formed by the joining of its two major tributaries, the Cuyama and Sisquoc Rivers. Surface flows

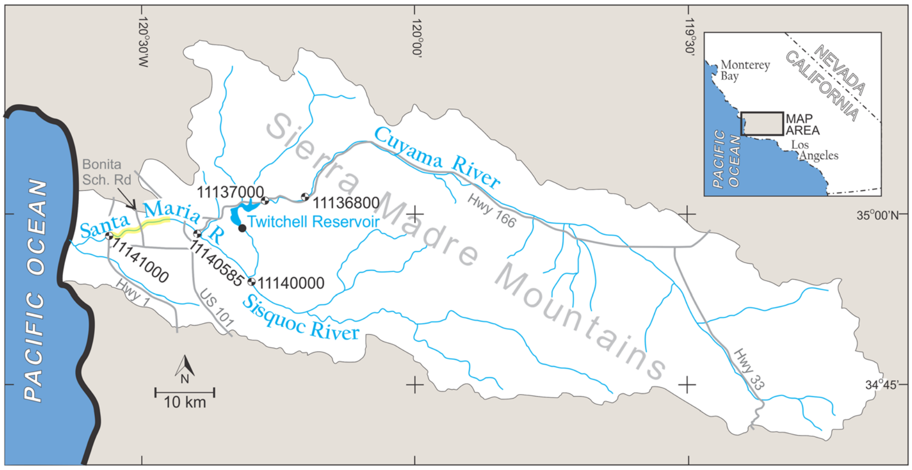


Figure 1. Santa Maria River watershed and location (inset map). Eight-digit numbers reference USGS gaging stations (Table I); yellow-shaded reach of the Santa Maria River upstream of gage 11141000 is the 'critical passage reach' referenced in the text.

throughout the Santa Maria River watershed have been characterized by numerous U.S. Geological Survey (USGS) gages, some of which have been maintained for more than 80 years (Table I). All records are expressed as mean daily discharge; as with most such gaging, finer temporal resolution is simply unavailable. The 93-km-long Sisquoc River drains the marine face of the Sierra Madre Mountains and receives an annual average of 50–80 cm of precipitation (almost all as rainfall). It has no major dams or water diversions; the upper reaches of this tributary have always been the dominant source and/or destination of anadromous *O. mykiss*, owing to its greater persistence of flows and the high quality of its instream habitat (Boughton and Fish, 2003). Its primary gage, Sisquoc River at Garey (USGS 11140000), is located 1·3 km upstream of the confluence with the Cuyama River and reflects the hydrologic condition of the Sisquoc River as it enters the mainstem. At this location from 1941 to the present, the channel has been dry [i.e., $<0{\cdot}03\ \mathrm{m^3\,s^{-1}}$ (1 cfs) average daily flow] on average more than 9 months of the year.

In contrast, the 170-km-long Cuyama River drains the ‘back’ side of the Sierra Madre Mountains and the lower, drier hills and mountains farther inland, with an average annual precipitation about half that of the Sisquoc River watershed (and thus about one-third of the total precipitation over the entire Santa Maria River watershed). It is fully impounded near its confluence with the Sisquoc River by Twitchell Dam, which was first put into operation in 1962 (TMA and MNS, 2010). Stream gages have operated along its lower reaches continuously since 1929, both immediately upstream and immediately downstream of Twitchell Reservoir. The reservoir has a nominal capacity of $277 \times 10^6\ \mathrm{m^3}$ (224 300 ac-ft), most of which is used to store water during winter storms and then released at a rate to maximize percolation into the downstream bed of the mainstem Santa Maria River, thus recharging the underlying groundwater basin (Worts, 1951). During the first 49 years of its operation, from 1962 to 2011, about $2{\cdot}5 \times 10^9\ \mathrm{m^3}$ (2×10^6 ac-ft) of water from the Cuyama River has been held behind the dam for periods ranging from a few weeks to more than a year (i.e., over $5 \times 10^7\ \mathrm{m^3}$ of average annual storage). This record also includes several multi-year periods of low rainfall, however, when no water was stored at all. Limited historical records of *O. mykiss* presence and reports of arid conditions suggest insignificant anadromous fish use of the upper Cuyama River watershed, either pre-dam or post-dam.

The mainstem Santa Maria River below the confluence of the Cuyama and Sisquoc Rivers is a braided, sand-bedded channel that is dry, on average, more than 90% of the time; the Guadalupe gage (USGS 11141000) record from 1941 to 1987 reported periods every year of continuous zero discharge, with some lasting up to 3 years in duration. When the river does flow, the transported sediment is highly

Table I. Major flow-gaging sites in the Santa Maria River watershed (see Figure 1 for locations).

USGS Gage No.	Gage location	Period of record					
		1920–30s	1940s	1950s	1960s	1970–80s	1990–present
11141000	Santa Maria River near Guadalupe		Start: 10/1940	▨	▨	End: 9/1987	
11140585	Santa Maria River at Suey						4/1999–present
11136800	Cuyama River below Buckhorn			Start: 10/1959	▨	▨	present
11137000	Cuyama River near Santa Maria	Start: 10/1929	▨	▨	End: 9/1962		
11138100	Cuyama River below Twitchell Dam			Start: 10/1958	▨	End: 9/1983	
11140000	Sisquoc River near Garey		Start: 2/1941	▨	▨	▨	present
SMVWCD[a]	Twitchell Dam outflow				Start: 2/1962	▨	present

[a] Data recorded by Santa Maria Valley Water Conservation District (www. smvwcd.org/)

mobile, and channels are rapidly eroded into the channel-bed and floodplain surfaces. Human disturbance is also common, which includes both authorized activities to improve flood conveyance (e.g., levees and the excavation of low-flow channels) and unauthorized off-road vehicle access. All of these conditions combine to render the topography of the channel a transient and rapidly changeable attribute of the river.

For the first 25 km of the mainstem Santa Maria River below the Sisquoc–Cuyama confluence, groundwater lies well below the channel bed (CDWR, 2004), and so any surface water consistently infiltrates downward through the unsaturated zone to the groundwater table (i.e., a losing reach). Within this zone of the mainstem river, the downstream-most 8 km has been long-recognized by direct observation and multiple anecdotal reports by residents, dam operators, and county staff as the length of river most prone to drying and so most limiting to steelhead passage (hereafter termed the 'critical passage reach'; Figure 1). This reach includes all locations during the winter of 2010/2011 where receding surface flows were observed to first disappear completely into the subsurface (although the specific location varies within the critical passage reach by flow event).

In the 14 km downstream of the critical passage reach to the Pacific Ocean, confining clay lenses just beneath the river bed raise groundwater levels in the upper (and perched) aquifer system, and surface flows generally increase. However, the river is intermittently isolated from the Pacific Ocean by a sandbar at the mouth of its estuary, although this potential obstruction to *O. mykiss* migration breaches rapidly under even minimal fish-passable mainstem flows because of the limited volume of the impounded estuary (Elwany, 2011; Jacobs *et al.*, 2011; Stillwater Sciences, 2012).

METHODS

Determining the magnitude of steelhead-passable flows

Thresholds of flow depth, width, and velocity judged adequate for steelhead passage (herein termed 'hydraulic passage criteria'), both for adult upstream migration and juvenile downstream migration, were identified for this study on the basis of literature values and local practice (e.g., SYTRAC, 1999). A minimum depth of 0·21 m (0·7 ft) for upstream adult steelhead migration was selected to account for the body size of the largest adult steelhead expected to pass, with additional buffer to avoid abrasion (Thompson, 1972; Webb, 1975; Dryden and Stein, 1975, both as cited in Powers and Orsborn, 1985; Bell, 1986). For downstream juvenile migration, the depth criterion was reduced to 0·15 m (0·5 ft) to match existing California Department of Fish and Wildlife criteria. A minimum contiguous width [3 m (10 ft)] was selected over which the depth criterion must be met, for both adult and juveniles, based on the same literature and with the added recommendation from resource agencies to include a minimum buffering width to reduce potential for predation from terrestrial predators. A maximum velocity of 2 m s^{-1} was identified from literature values (e.g., Bjornn and Reiser, 1991; Spence *et al.*, 1996) but was found to be an irrelevant constraint throughout the range of low to moderate discharges affected by operation of Twitchell Dam.

Translating these hydraulic passage criteria into minimum river discharges was approached in two ways. First, a topographic survey of the entire river channel and surrounding floodplain, conducted via airborne Light Detection and Ranging (LiDAR) in September 2010, provided a snapshot view of the river topography. It was conducted 5 months after the last prior flows (in April 2010), a period in which indeterminate human and natural alterations to the channel occurred. Twenty-six evenly spaced cross sections were evaluated from the LiDAR data through the critical passage reach. Functional relationships between discharge, flow depth, and flow width were determined for each of the 26 LiDAR cross sections.

Water discharge was calculated at each cross section with the one-dimensional Manning's equation to obtain predicted relationships between the width criteria and discharge:

$$Q_{\mathrm{w}} = \frac{1}{n} A_{\mathrm{w}} R_{\mathrm{h}}{}^{2/3} S^{1/2} \tag{1}$$

where Q_{w} denotes water discharge (m^3 s^{-1}), n denotes Manning's n, A_{w} is wetted cross-sectional area (m^2), R_{h} is hydraulic radius (m), and S is channel gradient (m m^{-1}). This simplistic approach is imprecise for complex flow paths and shallow depths (Brown and Pasternack, 2009; Grantham, 2013), but an even greater limitation of this method results from the channel-bed erosion induced by most discharges in this primarily sand-bedded channel. This erosion creates a deeper section in the river, concentrating water and producing a deeper flow than calculated on the basis of a presumed static channel cross section (Kondolf *et al.*, 2000). Because these deepened channels are not fully preserved as the flood recedes and so are not necessarily captured in the subsequent LiDAR survey, the results of this analysis likely overestimate the minimum flow needed to meet hydraulic passage criteria.

Our second approach for identifying the minimum discharge needed to meet the hydraulic passage criteria was based on field-collected cross sections, measured in the critical passage reach during a range of low to moderate flow events on seven separate dates between January and April 2011. At each time and location, four to five transects were executed using a rod, transit, and flow meter to measure water depth and velocity at 25–30 stations along each transect according to general guidelines for measuring discharge (e.g., Harrelson *et al.*, 1994). Transects were selected either to provide the most accurate measurement of discharge (e.g., relatively narrow channel without mid-channel bars or debris) or to represent conditions and locations under which fish passage was most likely to be limited first during the receding hydrograph (e.g., a wide, braided channel). Under conditions of rapidly changing flow or where very high discharge precluded safe surveying, more qualitative estimates (+/−20%) of discharge and maximum flow depth were made without a full cross-sectional survey at multiple times and locations within relatively limited time windows.

Hydrologic analysis of pre-dam and post-dam periods

Meeting a minimum discharge is necessary, but not sufficient, to assure fish passage. The magnitude, duration, and sequence of daily flows must provide the hydrologic attraction cues to initiate both the upstream migration of adult steelhead and the downstream movement of smolts into and out of the Santa Maria River, but we found no definitive guidelines for these key parameters in either the published literature or local practice. For purposes of this study, hydrologic metrics derived from the 'natural' (i.e., pre-dam) gage record of the mainstem Santa Maria River were assumed to be the most reliable indicator of the hydrologic conditions suitable for migration (herein termed 'hydrologic passage criteria'). Given the long history of diversions, levees, bridges, and groundwater extraction in the region, the pre-dam hydrograph cannot be considered fully natural, but the multiple reports of anadromous steelhead migration during the pre-dam period suggest that this historical record provides an adequate, if not optimal, flow regime for migration.

The minimum duration of flows required for upstream and downstream migration was based on review of the available literature for swimming speeds of steelhead and other anadromous salmonids. A 3-day period was determined from literature values to be a reasonable minimum time needed for adult steelhead to migrate the 39 km from the Pacific Ocean to the confluence of the Sisquoc and Cuyama Rivers. Adult steelhead have been reported to migrate upstream over 50 km day^{-1}, although they tend to average less than 35 km day^{-1} in streams with perennial passage (Greene, 1911; Lough, 1981; Bjornn *et al.*, 2003). Bell (1986) reports cruising speeds (typically used for steelhead upstream migration) up to 1·4 m s^{-1}, nearly three times the average speed needed to traverse this reach. Although possibly conservative, the temporal criteria for upstream migration also allow time for the estuary to fill and its confining sandbar to breach, and for steelhead in the ocean to detect the migration opportunity and begin active migration.

Only 1 day was assumed to be needed for juvenile steelhead to migrate from the Sisquoc–Cuyama confluence downstream to the Pacific Ocean. This is equivalent to an average outmigration rate of approximately 0·5 m s^{-1}. Presuming smolt outmigration rates in the Santa Maria River are largely passive and approach stream velocities during migration periods, travel rates would generally be double this rate or more.

The raw gage data (Table I) available for the hydrologic analysis are abundant but of relatively low quality. On the basis of the annual station notes, USGS personnel typically visited these sites between 8 and 16 times each year. They repositioned gages and/or dug channels to provide flow–gage communication, they measured the flow and adjusted the rating curve as needed, and they adjusted the final record of flow since the previous measurement as deemed appropriate by referring to other flow and rainfall gages in the watershed. The quality of the flow records were generally characterized as poor (i.e., measured values differ >15% from 'true' values) to fair (10–15% error), owing to the ever-shifting channel geomorphology and extreme variability of discharge. In total, the gaged flow record is likely least accurate during the largest annual or multi-year discharges (by virtue of rapidly changing channel conditions during high flow events) and below about 0·1 m^3 s^{-1} (for lack of flow–gage communication). Neither condition, however, is judged critical to the present study, because inaccuracies in gaging at either extreme of the range of discharges do not alter the reconstruction of the frequency or duration of the range of marginally fish-passable flows.

The gage of greatest relevance to the present study, that at Guadalupe (USGS 11141000) near the lower end of the critical passage reach at the Highway 1 road crossing, was maintained for 46 years (1941–1987) and so provides more than two decades of mainstem flow data in both the pre-dam and post-dam periods. The lower Sisquoc River has been gaged (USGS 11140000) from 1941 to the present. On the lower Cuyama River, two sources of flow data are available: the Cuyama below Twitchell gage (USGS 11138100) was operational during the period 1962–1983, whereas just upstream the daily operation of Twitchell Dam was recorded on handwritten sheets from 1964 to 2003 and on electronic forms thereafter to the present day. Thus, these two records were measured independently within just a few kilometres of each other for 21 years, permitting multiple opportunities to evaluate the quality of the data from dam operations.

Using these records, we applied a variety of methods to reconstruct a picture of daily discharges in the Santa Maria, Cuyama, and Sisquoc Rivers, beginning in water year 1941 with the installation of the one mainstem gage and continuing through August 2011. These gage records, in turn, were divided into three periods (by water year from October 1 of the preceding calendar year to September 30 of the named year) corresponding to the pre-dam (1941–1962), post-dam (1962–1987), and post-dam ungaged (i.e., post-USGS 11141000; 1987–2011) conditions. A variety of hydrologic metrics characterizing the frequency, timing, and duration of fish-passable flows through the critical passage reach of the mainstem Santa Maria River were compared for each period, under the guiding assumption that the pre-dam period reflected a time when the flow regime of the Santa Maria River, although likely impaired by several prior decades of groundwater pumping to support nearby agriculture, was nonetheless sufficient to maintain an apparently self-sustaining population of anadromous steelhead.

We relied solely on measured flow data (uniformly recorded and expressed as average daily values) to assess discharges across the channel network. We applied simple assumptions for typical infiltration losses along the mainstem river based on the 46 years of gaged flows above and below the critical passage reach. All discharges were expressed in cubic foot per second for consistency with the raw USGS and Twitchell Dam records (these were later converted to $m^3 s^{-1}$) and organized and analysed in Excel spreadsheets across the 25 766 days of the study period (1 February 1941, the first day of operation of the Sisquoc River at Garey gage, through 18 August 2011, the last day of this study record). Although hydrologic modelling would have permitted the exploration of a broader range of management scenarios (such as the representation of spatially complex surface water–groundwater interactions, or past and future climate-change scenarios), the timely development and calibration of a hydrologic model was infeasible (as is the case with many such applications). Our approach is therefore likely to be more broadly applicable to management applications than more time-intensive and computationally intensive efforts heretofore published (e.g., Fleckenstein *et al.*, 2010; Grantham *et al.*, 2013).

Alternative flow-release scenarios from Twitchell Dam

The historical flow record, both pre-dam and post-dam, provides an unusual opportunity to explore alternative rules for dam operation with the joint objectives of reproducing the pre-dam frequency, timing, and duration of fish-passable flows, while minimizing the reduction in groundwater recharge utilizing the water stored in (and subsequently released from) Twitchell Reservoir. This analysis focused on the 1962–1987 period, when operation of the mainstem Guadalupe gage (USGS 11141000) was directly measuring flow data through the critical passage reach. For all alternative scenarios, the rate of infiltration below the Sisquoc–Cuyama confluence was assumed uniform and equal to the actual median value determined throughout the period when gages on both tributaries and the mainstem were operational (1941–1987). The average annual reduction in groundwater recharge, which represents the primary ‘cost’ of alternative flow-release scenarios, was calculated as the product of the minimum passage flow and the increased number of days for which it would have been achieved at the Guadalupe gage (i.e., the volume of water discharged to the estuary as surface flow instead of recharged to groundwater). A variety of alternative rules, triggered by a specified minimum daily flow in the gage record of the Sisquoc River, were applied to simulate presumptive releases from Twitchell Reservoir in support of mainstem fish passage. For each set of rules, daily flows in the mainstem Santa Maria River through the critical passage reach were calculated as the simulated reservoir release plus the actual (unregulated) discharge of the Sisquoc River at Garey gage (USGS 11140000), minus the median infiltration loss between the Garey and Guadalupe gages.

RESULTS

Hydraulic passage criteria

The critical discharge (Q_{crit}) necessary to meet the hydraulic criteria of minimum flow depth and width varies by location along the critical passage reach. It was first determined at each of the 26 cross sections derived from the LiDAR survey using Equation (1). The calculation returns a critical discharge at each cross section, for which the largest ($9{\cdot}9\ m^3 s^{-1}$ for upstream adult migration and $4{\cdot}2\ m^3 s^{-1}$ for downstream juvenile migration) was assumed to be the limiting value for the reach as a whole, because passage would be achieved at every other cross section once this discharge had been achieved. These results, however, are dependent on the assumption of a stable cross section that corresponds to the (dry) channel topography of September 2010, an assumption that is demonstrably not met (Figure 2).

Q_{crit} was also determined by direct observation of actual flow events on the river (Table II). On the basis of the presumed greater reliability of these results, given their direct measurement and self-consistency, a discharge of $7{\cdot}1\ m^3 s^{-1}$ (250 cfs) was used as the minimum threshold value for successful upstream adult steelhead passage through the critical passage reach in all subsequent hydrologic analyses. In contrast, the number of observations was so limited in the range of presumptive juvenile passage (i.e., ~$4{\cdot}2\ m^3 s^{-1}$ from Equation (1) and the LiDAR cross sections) that we continued to use this value without modification. Interestingly, these results are remarkably similar to those predicted and observed by Mosley (1982, his Figure 5) on braided New Zealand rivers of similar dimensions using equivalent minimum depths.

Evaluating the quality of the gage data

Given the concerns raised in USGS station notes of gage data quality, we sought multiple avenues to evaluate the consequences of potential inaccuracies in the hydrologic data. Simultaneously recorded daily average flows throughout

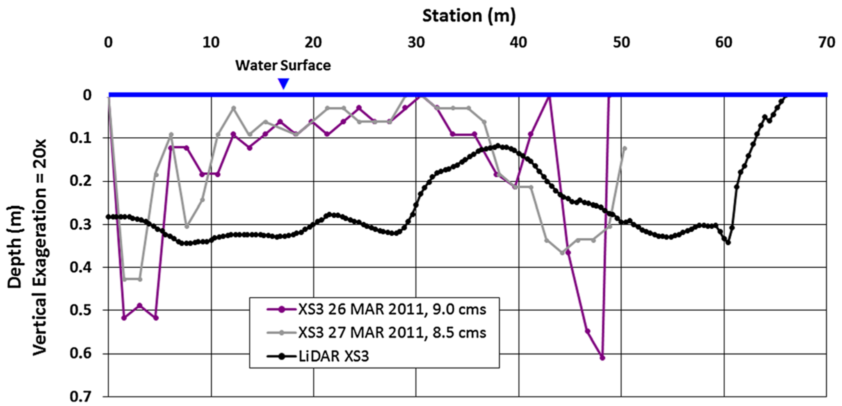


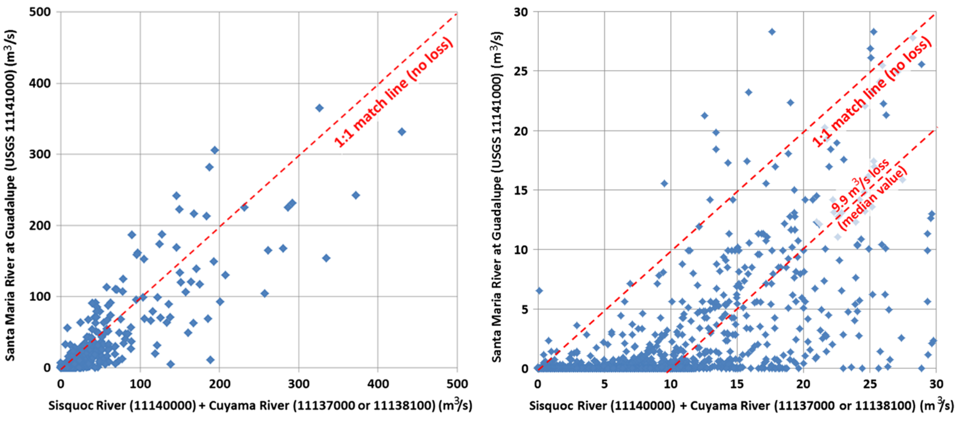
Figure 2. Comparison of field-surveyed cross sections during a moderate flow event (26–28 March 2011) with the broader and more subdued LiDAR-derived cross sections surveyed under dry conditions at the same location.

Table II. All field-measured discharges and evaluation of fish passage (red, none; green, yes) made in the winter and spring of 2011, sorted by discharge at the time of measurement.

Location within critical passage reach	Date	Flow m^3 s^{-1}	Width at minimum passable depth (m)
Highway 1 vicinity	5/4/2011	0·03	none
Highway 1 vicinity	5/4/2011	0·06	none
Suey vicinity (above critical passage reach)	12/1/2011	0·14	<3
Bonita School Rd to Highway 101	5/4/2011	0·20	none
Highway 1 to Bonita School Rd	5/4/2011	0·20	<3
Bonita School Rd to Highway 101	5/4/2011	0·28	none
Highway 1 vicinity	4/1/2011	0·28	<3
Bonita School Rd vicinity	4/1/2011	0·31	none
Bonita School Rd vicinity	27/2/2011	0·71	none
Suey vicinity (above critical passage reach)	4/1/2011	4·30	>10
Bonita School Rd to Highway 101	28/3/2011	5·47	>6
Bonita School Rd to Highway 101	28/3/2011	7·11	>6
Highway 1 to Bonita School Rd	28/3/2011	7·11	3
Highway 1 to Bonita School Rd	28/3/2011	7·70	>13
Highway 1 vicinity	27/3/2011	8·52	>10
Highway 1 to Bonita School Rd	27/3/2011	8·86	>20
Highway 1 vicinity	26/3/2011	9·03	>13
Bonita School Rd to Highway 101	27/3/2011	9·54	>10
Highway 1 vicinity	27/3/2011	10·56	>13
Highway 1 vicinity	26/3/2011	10·79	>15
Highway 1 vicinity	26/3/2011	10·90	>15
Highway 1 vicinity	26/3/2011	10·99	>13

On the basis of these data, a discharge of 7·1 m^3 s^{-1} in the critical passage reach of the Santa Maria River (gray shaded) appears to provide adult passage under essentially all observed combinations of channel geometry and flow.

the lower watershed provide several such opportunities. For the mainstem river, comparing same-day flows at the Guadalupe gage with the sum of the two major tributaries (Sisquoc and Cuyama) displays the challenges of accurately measuring very high discharges, but it also suggests that the record of flows in the range of potential fish passage (i.e., ~3–30 m^3 s^{-1}) is relatively robust (Figure 3), with a wide scatter to the data but one that follows the expected



a b

Figure 3. Comparison of same-day flows for 1941–1987 (i.e., the period of record of the Guadalupe gage). Flows above the red-dotted 1:1 line imply accretion of water downstream of the confluence of the Cuyama and Sisquoc Rivers; those below the line imply loss (the geologically more likely condition). At discharges above a few hundred $m^3 s^{-1}$ (emphasized in the left panel), the scatter is nearly symmetrical about the 1:1 line and likely results from measurement errors of as much as ~30%. For flows less than $30 m^3 s^{-1}$ (right panel, note change of scale), the historic data show a median infiltration loss from surface flow between the confluence and the Guadalupe gage of $9{\cdot}9 m^3 s^{-1}$.

pattern of downstream infiltration. These data also allow us to determine the magnitude of surface-water loss to groundwater through the bed of the mainstem Santa Maria River upstream of the Guadalupe gage (and near the bottom of the critical passage reach), with a median value of $9{\cdot}9 m^3 s^{-1}$.

The quality of the reconstructed Twitchell release data was independently assessed for the period 1962–1983 when both the Santa Maria Valley Water Conservation District's records and those of the Cuyama below Twitchell gage (USGS 11138100) coincide. The same-day data show very good correspondence with a few dominant patterns:

1. Overall, the two records align with no systematic underprediction or overprediction. A 1:1 line lies within 2% of the best-fit linear trend, and it expresses strong correlation ($r^2 = 0{\cdot}97, p < 0{\cdot}001$) between the two data sets.
2. The very largest recorded flows from Twitchell (>60 $m^3 s^{-1}$) tend to systematically exceed the corresponding USGS gage data, suggesting that the former were either estimated or not full-day releases at that level. Every such flow occurred between February 25 and 10 March 1969, a period of particularly challenging flow-gaging conditions throughout southern California.
3. The zero-recorded Twitchell discharges corresponding to non-zero USGS flows likely reflect a combination of downstream accretion and blank entries on the Twitchell Dam data form being (mis)construed as zero discharges, particularly for those with USGS flows above about $1{\cdot}4 m^3 s^{-1}$ (50 cfs). These comprise only 24 of the 5386 (0·4%) of the dual records, however, and so are not judged consequential for subsequent analyses.

General attributes of the flow regime of the Santa Maria River

The general patterns of flow in the Santa Maria River over a multi-decadal period are best described by the Guadalupe gage (USGS 11141000). This gage was operated by the USGS from 1 February 1941 to 30 September 1987. It therefore includes 20 years of record prior to the closure of Twitchell Dam and more than 26 years after closure. The first two decades of gaging show a highly episodic river (Figure 4) that was dry over 93% of the time (an average of 341 days $year^{-1}$). The longest dry period was nearly 3.5 years long, ending on 9 February 1962.

Twitchell Dam began holding back flows on 16 February 1962, one week after the 1959–1962 drought

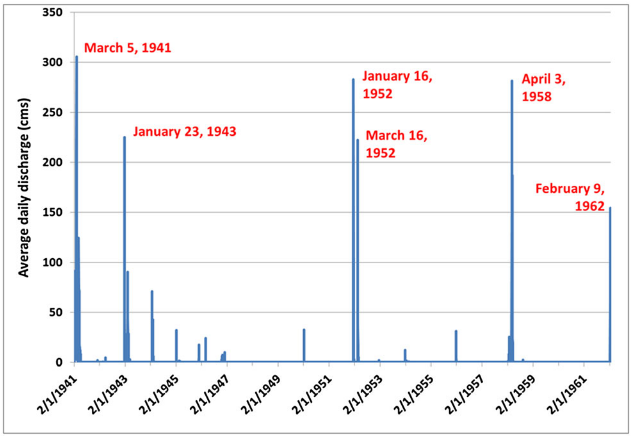


Figure 4. Discharge of the Santa Maria River at the Guadalupe gage (USGS 11141000) for the full period of the pre-Twitchell Dam record. Dates of the largest daily discharges labelled.

ended. Post-dam, the overall hydrograph suggests little overall change, at least to the moderate and high flows that are readily visible in such a flow record. True zero discharges (i.e., excluding non-zero values below 0·03 m^3 s^{-1}) occurred almost precisely as frequently during this period as pre-dam (average of 340 days year^{-1}, compared with a pre-dam average of 341 days year^{-1}). Multi-year periods of no flow also occurred during this period, particularly 1962–1965 and throughout the 1970s.

Given the infrequency of flow in the Santa Maria River, conditions suitable for fish passage are uncommon, episodic, and confined to a well-defined period of the year. Indeed, the Santa Maria River is virtually always dry for more than 7 months of the year, a condition that has not materially changed with operation of Twitchell Dam (Figure 5).

Post-dam changes to the flow regime

Fish passage during extreme events (both low and high) has been little affected by the post-dam flow regime: very low flows do not provide passage regardless of their frequency, and large floods are beyond the capacity of the dam to influence under normal operations. In contrast, the intermediate flows that meet minimum criteria for fish passage (i.e., in the range of about 3–30 m^3 s^{-1}) have been reduced in frequency by about 2 days year^{-1} (Figure 6), a result that is independent of the precise value identified for the 'critical passage flow'. This range of discharges also corresponds to conditions when gaging quality is likely highest, overcoming the recognized problems of 'no communication' common to very low flows and a rapidly shifting rating curve at very high flows.

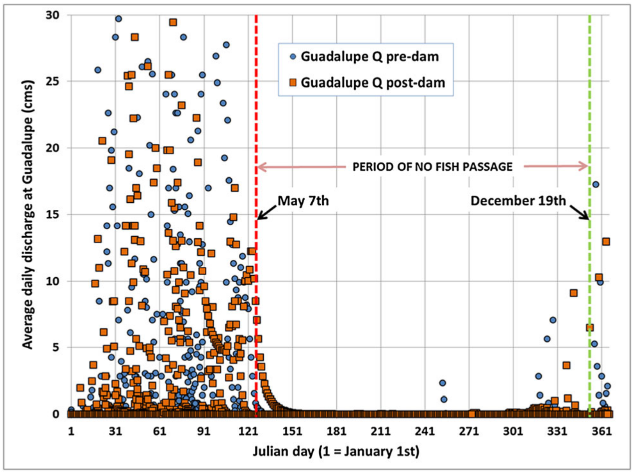


Figure 5. All recorded flows at the Guadalupe gage (USGS 11141000), plotted by Julian day and discriminated by pre-dam and post-dam periods (round and square markers, respectively). Only flows <30 m^3 s^{-1} are shown, to emphasize the range of discharges over which the conditions of fish passage are most critical. Passable conditions ended in nearly every year by early May; they restart no sooner than mid-December.

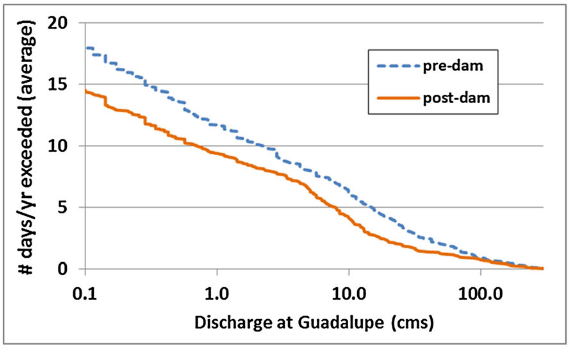


Figure 6. Flow–duration curve for daily discharges of the Santa Maria River at the Guadalupe gage (USGS 11141000), with the fraction of daily discharges above the specified discharge expressed as the average number of days year^{-1} (e.g., 4 days ≈ 11% of the time). The curves for the pre-dam (blue dashed line; 1 February 1941 to 15 February 1962) and post-dam (orange solid line; 16 February 1962 to September 1987) converge above about 100 m^3 s^{-1}; at all flows below about 30 m^3 s^{-1}, which include the range of effective steelhead-passable flows, durations are reduced on average by 1·5 to 2·5 days year^{-1}. Note that the precise choice of a 'critical passage discharge' does not materially affect these results.

Although the sheer aggregate number of passable days is one plausible metric of hydrologic alteration, the *sequence* and the *duration* of such flows is also important, both to evaluate whether a given year will present at least one passage event (Figure 4 – many years do not, even pre-dam) and whether adult steelhead will be provided with the multi-day flows needed to traverse the lower river (Table III). For downstream juvenile passage post-dam, the number of years with at least one passage opportunity has decreased slightly, with the reduction in passage most prominent for the longest multi-day events (by more than one-third, from 19% to 12% of years). For upstream adult passage post-dam, the number of years with at least one passage event has actually increased, but entirely as a result of the shortest-duration events; as with downstream passage, the frequency of long-duration events has substantially decreased (again, by more than one-third).

Although the aggregate behaviour of flows in the Santa Maria River suggests only modest alteration to the flow regime imposed by Twitchell Dam operations, substantial changes are apparent when considering the interaction of daily flows on the two major tributaries. Pre-dam, the relationship between simultaneous daily discharges from the Sisquoc and Cuyama Rivers is quite regular (Figure 7, left panel), and the correlation between discharge at the lowermost gage on the Sisquoc River (USGS 1114000) and the same-day discharge at the lowermost Cuyama River gage (USGS 11137000) is high ($r^2 = 0·81$). Post-dam, however, tributary flows are no longer correlated between the two tributaries (Figure 7, right panel); indeed, their lack of correlation, particularly during high-flow events on the Sisquoc River while Twitchell Reservoir is presumably capturing all flow from the Cuyama River, is the explicit intention of dam operations. These flows are

Table III. Tally of the percent of years in the gage record (total of 20 years, pre-dam; 26 years, post-dam) with at least one event that meets the discharge criteria for steelhead passage ($\geq 4{\cdot}2\ \mathrm{m^3\,s^{-1}}$ for juveniles, $\geq 7{\cdot}1\ \mathrm{m^3\,s^{-1}}$ for adults).

	Downstream juvenile passage				Upstream adult passage			
	No. passage	1–3 days	4–12 days	>12 days	No. passage (includes 1-day and 2-day events)	3 days	4–12 days	>12 days
Pre-dam	48%	19%	14%	19%	81%	0%	5%	14%
Post-dam	50%	15%	23%	12%	69%	15%	8%	8%

Passable flows (i.e., above the appropriate discharge threshold) are stratified into categories of duration; note that for adult passage, 3 days is the minimum passable condition.

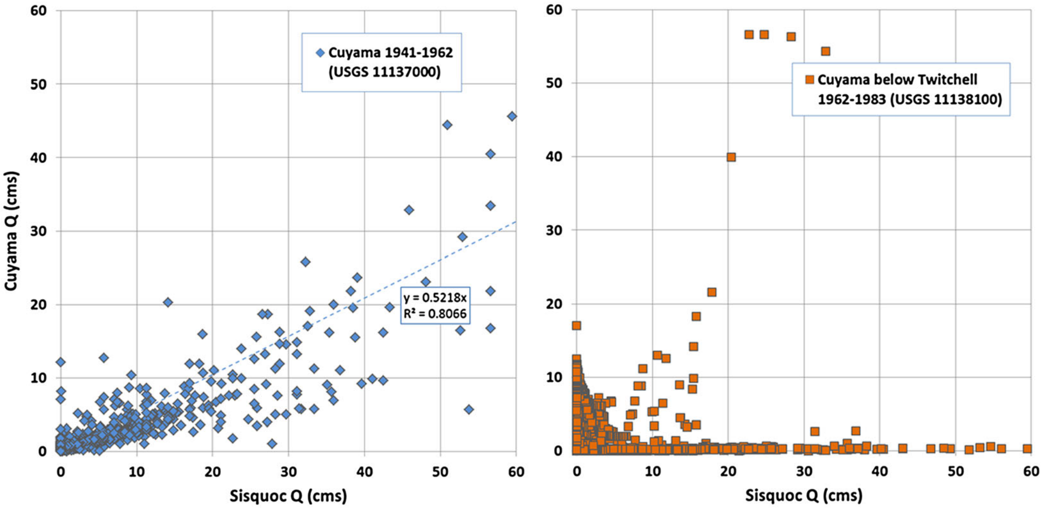


Figure 7. Correlation of pre-dam (left) and post-dam (right) daily average flows for the Sisquoc River at Garey gage (USGS 11140000) and the Cuyama River near Santa Maria gage (USGS 11137000) for the same date. Trend line for the pre-dam period is calculated on the full range of data (maximum Sisquoc value is $165\ \mathrm{m^3\,s^{-1}}$; maximum Cuyama value is $85\ \mathrm{m^3\,s^{-1}}$), but only those below $60\ \mathrm{m^3\,s^{-1}}$ are displayed here. The post-dam period shows essentially no correlation between flows from the two tributaries.

subsequently released during periods of low or no flow in the Sisquoc River (i.e., the mass of points when the Sisquoc River is $<7{\cdot}1\ \mathrm{m^3\,s^{-1}}$ and the Cuyama River discharges are up to twice as great) to achieve a more uniform discharge down the mainstem Santa Maria River, promoting infiltration in the Santa Maria River valley but with little or no surface flow released to the estuary.

Thus, dam operation has had the following consequences for the flow regime in the Santa Maria River:

1. By aggregate metrics (e.g., average number of days of passage), reduction in the availability of steelhead-passable conditions are on the order of $2\ \mathrm{days\ year^{-1}}$.
2. The frequency of steelhead-passable events has changed little, but for both adult and juvenile passage these events are now of generally shorter duration.
3. Sisquoc River and Cuyama River flows are no longer correlated, because dam operations tends to ‘smooth’ out the resulting discharge in the Santa Maria River with an intentional bias towards achieving flows that are insufficient to maintain a surface-water connection to the estuary.

Flow cues for migration through the Santa Maria River system

For adult steelhead, upstream migration from the ocean is presumably triggered by flows emerging from the estuary. Comparison of the pre-dam and post-dam record shows not only the previously calculated reduction in total passable days (about $2\ \mathrm{year^{-1}}$; see also Figure 6) but also the increase likelihood of an adult steelhead beginning its passage under favourable flow conditions at the estuary but encountering the receding limb of a hydrograph that blocks further upstream passage prior to reaching the confluence of the Sisquoc and Cuyama Rivers (Table IV; ‘failed passage’).

Another potential impediment to achieving successful adult passage, namely the attainment of steelhead-passable conditions in the mainstem Santa Maria River (i.e., 3 days of flow $\geq 7{\cdot}1\ \mathrm{m^3\,s^{-1}}$) but insufficient discharge for continued upstream passage through the (unregulated)

Table IV. Comparison of pre-dam and post-dam flow regimes relative to upstream adult passage.

	Pre-dam (1941–1961)	Post-dam (1962–1987)
No. days per year $\geq 7{\cdot}1\,\mathrm{m^3\,s^{-1}}$	7·4	5·2
No. days per year $\geq 7{\cdot}1\,\mathrm{m^3\,s^{-1}}$ with two more following (successful passage)	5·2	3·2
No. days per year $\geq 7{\cdot}1\,\mathrm{m^3\,s^{-1}}$ without 2 days following (failed passage)	2·2	2·0

Once a fish-passable flow has been achieved at the mouth of the river in the post-dam state, the opportunities for a successful conclusion to upstream migration (i.e., 2 more days of flow $\geq 7{\cdot}1\,\mathrm{m^3\,s^{-1}}$) have been reduced by almost 40% relative to the pre-dam state. ‘Failed’ passage attempts now represent almost 40% of all triggered passage events.

lower Sisquoc River, is a rare occurrence in either the pre-dam or post-dam periods. For the period 1941–1961, this occurred in 6 of 110 (mainstem) passage days (5·4%); for 1962–1987, 3 of 83 such days (3·6%). We therefore did not further consider this factor in characterizing the alteration in fish-passage opportunities.

For downstream juvenile passage, the criteria for mainstem passage are less complex (1 day of mainstem flow $\geq 4{\cdot}2\,\mathrm{m^3\,s^{-1}}$), but the only cue for downstream migration available for juvenile steelhead is the flow in the Sisquoc River. Pre-dam, this flow was strongly correlated with the contribution from the Cuyama River (Figure 7, left panel) and thus in the mainstem Santa Maria River as well; but post-dam, this correlation has been nearly obliterated (Figure 7, right panel). In other words, juvenile steelhead in the upper Sisquoc River experience flows that once signalled free-flowing conditions all the way to the open ocean, but operation of Twitchell Dam now results more frequently in an impassable mainstem for their final day of presumptive downstream passage through the mainstem.

In the pre-dam period, flows in the Sisquoc River (as measured, for example, at the Garey gage) are a relatively good predictor of downstream-passable flows in the mainstem Santa Maria River (as measured at the Guadalupe gage) (Figure 8(a)). With Sisquoc River flows in the range of $10\text{–}12\,\mathrm{m^3\,s^{-1}}$, downstream passage through mainstem Santa Maria River has about a 50/50 chance of success. Once the daily average flow exceeds $12\,\mathrm{m^3\,s^{-1}}$ in the Sisquoc River, full downstream passage occurred 80% of the time; and above $14\,\mathrm{m^3\,s^{-1}}$, both upstream and downstream passage was all but assured. This occurs despite the median $9{\cdot}9\,\mathrm{m^3\,s^{-1}}$ loss of surface water to groundwater in the mainstem downstream of the confluence, because a reliable flow contribution of this approximate magnitude from the Cuyama River provided sufficient total flow to maintain flows $>4{\cdot}2\,\mathrm{m^3\,s^{-1}}$ throughout the critical passage reach.

In the post-dam period, however, the flow cues in the Sisquoc River that promised near-certain passage downstream in the mainstem Santa Maria River no longer provide the same guidance (Figure 8(b)). During the 1962–1987 period, Sisquoc River flows of $10\text{–}12\,\mathrm{m^3\,s^{-1}}$ provided virtually no opportunity for successful passage in either direction (because most or all of this water is subsequently infiltrated to groundwater while contributions from the Cuyama River are being intercepted by Twitchell Reservoir); and those of $>14\,\mathrm{m^3\,s^{-1}}$ will still fail to support passage almost one-half of the time. There are no records of smolt outmigration to guide our expectation of the specific discharge that provides the cue for downstream migration, but over a relatively wide range of such flows, the potential for downstream stranding is now quite high.

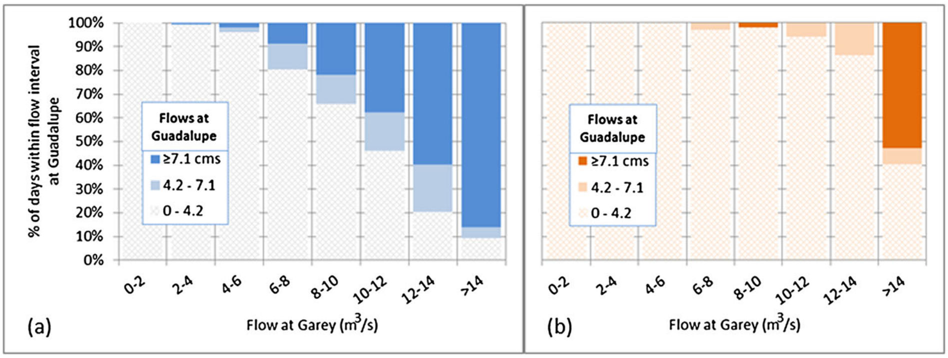


Figure 8. Predicting steelhead passage through the mainstem Santa Maria River (coloured bars) based on same-day flows in the Sisquoc River at the Garey gage (USGS 11140000; *x*-axis). Each graph ‘bins’ the flows at Garey, displaying the relative fraction of mainstem flows for the same day (at the Guadalupe gage; USGS 11141000) in each of the three flow categories. The dark bars indicate successful adult passage conditions in the mainstem Santa Maria River, with the lighter bars including successful juvenile passage. (a) Pre-dam conditions; (b) post-dam conditions 1962–1987.

Results of alternative flow-release scenarios

The fundamental change to the post-dam flow regime of the Santa Maria River, namely the asynchroneity of peak flows from the Sisquoc and Cuyama Rivers (Figure 7, right panel), also points to the strategy with the greatest likelihood of enhancing steelhead migration opportunities: changing the operational rules for Twitchell Dam to augment flow in the Cuyama River when the Sisquoc River is flowing at a rate that, historically, would have resulted in potentially suitable steelhead-passage conditions in the mainstem Santa Maria River.

A first, 'naïve' set of flow-augmentation rules were thus applied as follows:

1. Flow augmentation from releases at Twitchell Dam should be made whenever discharge in the lower Sisquoc River (at the Garey gage) falls between 9·9 and 15·6 $\mathrm{m^3\,s^{-1}}$ (350–550 cfs), reflecting the range of flows when steelhead passage in the mainstem would have likely been possible at least half of the time, pre-dam. For purposes of testing the efficacy of this rule, a combined tributary flow of 17 $\mathrm{m^3\,s^{-1}}$ is presumed to assure upstream adult passage throughout the critical passage reach (to retain 7·1 $\mathrm{m^3\,s^{-1}}$ in through the critical passage reach after subtracting transmission losses of 9·9 $\mathrm{m^3\,s^{-1}}$). Of course, this presumptive augmentation could only occur if water was present behind the dam.
2. Flow augmentation should only occur during the period of historical steelhead passage (December to April).
3. When an average daily discharge of 7·1 $\mathrm{m^3\,s^{-1}}$ (250 cfs) in the critical passage reach has been achieved, sufficient flows should be released if/as needed to ensure that this condition is maintained for at least two additional days, but only if and for as long as passage is feasible through the lower Sisquoc River (as indicated by the recorded discharge at USGS 1114000).

Initial testing of these three rules against the 1962–1987 flow did not yield unequivocally positive results for predicted fish passage. This is primarily because a single day of Sisquoc River flow in the triggering range of 9·9 and 15·6 $\mathrm{m^3\,s^{-1}}$ is not always followed by more such days. When it is not, the effect of these naïve augmentation rules is to increase the number of single-day upstream passable flows but not the number of true (i.e., continuous 3-day) passage events. These rules also fail to take advantage of 1-day lulls in flow between two large storms that could be linked by a single day's supplemental release to create a single period of passage that lasts for many days or a week or more. This second opportunity for improved operations arose on 5 days in the 1962–1987 period (once each in 1967, 1969, 1978, 1983, and 1986); the availability of multi-day weather forecasting tools (e.g., http://www.cnrfc.noaa.gov/) suggests that such conditions could be recognized under a modified set of operational rules.

The naïve rules were also reconsidered on the assumption that extending the duration of fish passage can reach a point of diminishing returns during wet hydrologic years when passage opportunities are so plentiful that flow augmentation using stored water may be unnecessary. This occurred four times in the 1962–1987 period (and in particular during water years 1969 and 1983). For purposes of the simulation, the rule modification was to terminate all artificial releases from Twitchell Reservoir for a given water year once a continuous 12-day passage window had been achieved in that water year. Other maximum-duration periods as short as 6 days were tested against the flow record with virtually no change to the magnitude of released water, because these long-duration flow events generally continued for much more than a week.

When these modifications to the original flow-augmentation rules are applied and evaluated against the criteria for passage established by the pre-dam flow record, they compare very well (Figure 9). Opportunities for fish passage exceed actual post-dam events by nearly 3 days $\mathrm{year^{-1}}$, a somewhat more successful outcome than the 2-day reduction seen in actual pre-dam versus post-dam passage conditions (Figure 6). Both upstream and downstream migration opportunities occur slightly more frequently than in the pre-dam record. They also show other improvements, particularly for reducing the frequency of false positives (i.e., discharges in the Sisquoc River that historically correlated with downstream-passable or upstream-passable conditions to or from the estuary, but which no longer do) for juveniles in Sisquoc River tributaries who must anticipate the likelihood of passable conditions all

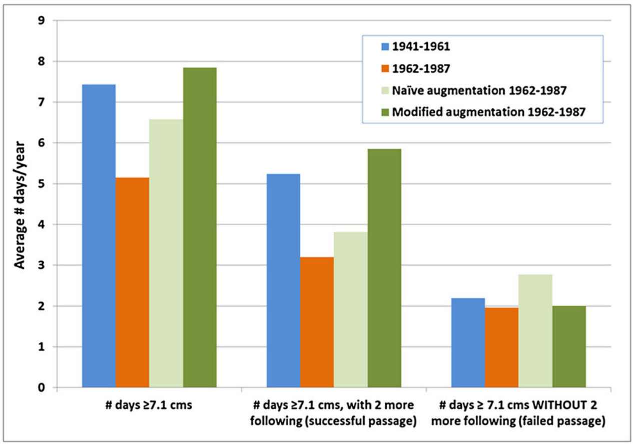


Figure 9. Opportunities for successful passage are returned to slightly better than pre-dam levels through operational modifications at Twitchell Dam (dark green bars) through the modified rule combination. Note that flow augmentation designed to meet only a single-day discharge target (gray bars; naïve) without consideration of multi-day patterns increases both successful and failed passage conditions almost equally.

the way to the estuary only on the basis of local flows in the Sisquoc River.

Although the flow regime based on the modified flow-augmentation rules exceeds the overarching goal of returning the post-dam flow regime to pre-dam levels with respect to fish passage, alternative operational rules using less water from Twitchell Reservoir were explored but were ineffective at meeting this fundamental goal. Thus, we determined that recovering the frequency of pre-dam passage opportunities requires the average annual release of about $1{\cdot}9 \times 10^6\,\mathrm{m}^3$ (1500 ac-ft) of water from Twitchell Reservoir over the 26-year period 1962–1987, about 3% of the average annual volume of water stored behind the dam.

DISCUSSION

Dryland rivers are fundamentally different from their perennial counterparts (Bull and Kirby, 2002), and their successful management requires analytical approaches and evaluation criteria that are tailored to their intermittent nature (Kennard *et al*., 2009). Successful fish passage in such systems is not simply a matter of meeting a threshold discharge, because (much) more often than not, such a discharge was never achieved in the watershed's natural state, and its attainment would be neither feasible nor desirable.

Passage is also not achieved just by ensuring that such discharges persist at a critical point for a minimum number of days in sequence or at the right time of year, criteria that are often applied as part of a seemingly comprehensive analysis of flow alteration and mitigation perennial and intermittent rivers alike (for examples of the latter, see Principato and Viggiani, 2009; Bond *et al*., 2010; Belmar *et al*., 2013). In a channel network, however, anadromous fish can only evaluate the prospects for successful passage, from both marine to freshwater and freshwater to marine, on the basis of the flow occurring at a single point in time and space (i.e., where the fish is located). Thus, any changes in the *correlation* between that local flow and conditions elsewhere along the migratory path can have potentially significant consequences for the success of the migration and ultimately for successful reproduction. Determination of true fish-passable events thus requires evaluation of the combined flow record along the entire channel network, recognizing that adequate flow at one point in the network does not guarantee continuous passage between the ocean and the headwaters in a highly regulated system. Such changes are not captured by generalized or typically evaluated hydrologic flow metrics (e.g., Richter and Thomas, 2007; Vogel *et al*., 2007; Gao *et al*., 2009; Poff *et al*., 2010), despite their likely critical importance for fish passage in an intermittent Mediterranean-type river.

Even the spatial distribution of passable flows, however, cannot fully identify the key hydrologic parameter(s) of greatest importance to the migration of steelhead. During a wet hydrologic year, for example, do these fish benefit from fewer but longer passage windows, or more frequent but shorter ones? Or, is the population as a whole best supported by maximizing the number of separate years in which such an event happens at least once? The existing literature on *O. mykiss* does not answer these questions (NOAA, 2012), which has therefore required a more inferential approach to their resolution in this study by appeal to the historical pre-dam record. We used various metrics to evaluate post-dam impairment and hypothetical flow-augmentation benefits – aggregate number of passage days, number of successful passage events, and number of false positives – but we acknowledge the present inability to identify the critical parameter(s) of greatest importance to steelhead migratory success with any certainty.

Despite this ambiguity in the choice of parameters, operation of Twitchell Dam has almost certainly reduced the number of successful opportunities for both upstream and downstream steelhead migration along the Santa Maria River. On the basis of the magnitude of documented changes and the migration behavior of steelhead, the following alterations to the flow regime as a result of historic dam operation have likely imposed the greatest impacts to successful upstream and downstream migration, alterations that are likely common to all partially regulated river systems designed to minimize flow variability or to maximize downstream groundwater recharge:

1. increased frequency of false positives in the flow of the Sisquoc River, cuing downstream smolt migration without sufficient discharge in the mainstem river downstream to support successful passage to the ocean (compare Figure 8(a) and (b));
2. reduced overall frequency of downstream steelhead-passable conditions (Table III); and
3. increased number of days with upstream steelhead-passable flows that are *not* followed by at least two additional steelhead-passable flow days (Table IV), creating impassable conditions for migrating adults.

Any operational changes to an impoundment that materially affects the spatial and temporal pattern of discharge and infiltration in a dryland river should emphasize the avoidance of such conditions. We therefore suggest a more generalized set of operational goals to support anadromous fish populations in such systems:

G1. Avoid the spatial de-correlation of tributary flows in the range of discharges most likely to trigger migration.
G2. Increase the overall frequency of passable conditions, commensurate with the changes imposed by prior flow regulation; for large systems, ensure adequate multi-day passage windows.

G3. Manage flow releases to support a minimum continuing duration of fish-passable flows once a threshold discharge likely to trigger passage has been achieved.

CONCLUSIONS

Conventional approaches to setting instream flows are ill-suited to characterizing or mitigating the impairment from certain types of flow regulation on dryland rivers, because these approaches do not address whether the identified instream flow is reasonable or appropriate given the naturally intermittent flow regime, they are based on channel geometry assumptions that are typically not met in sand-bedded alluvial channels, and they do not evaluate passage throughout the critical extent of the river network. On the Santa Maria River, fortuitous operation of a mainstem gage for two decades both before and after closure of a tributary dam has permitted the characterization of pre-dam flows with respect to both upstream and downstream migration of anadromous southern California steelhead and the identification of likely attributes of the post-dam flow regime that most critically impede successful passage relative to pre-dam levels. Dam operations that maximize groundwater recharge and minimize through-going flows to the Pacific Ocean have modestly reduced the average number of days of potential upstream fish passage per year, and they have greatly altered the degree to which upstream tributary flows provide a reliable indicator of successful downstream migration. Metrics of flow magnitude alone do not reveal these changes; even ecologically based indicators of flow frequency and duration previously applied to evaluation of intermittent rivers have limited utility in such a setting and do not reveal the likely magnitude of impacts. With adequate assessment tools and a sufficiently complete record, however, a credible strategy based on changes to dam operations can be identified to largely recover historical passage opportunities without severely compromising other management objectives in this managed river.

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