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USE OF HYDRAULIC MODELLING TO ASSESS PASSAGE FLOW CONNECTIVITY FOR SALMON IN STREAMS

T. E. GRANTHAM*

Department of Environmental Science, Policy and Management, University of California, Berkeley, Berkeley, California, USA

ABSTRACT

The maintenance of hydrologic connectivity in river networks has become an important principle for guiding management and conservation planning for threatened salmon populations, yet our understanding of how fish movement is impaired by spatial and temporal variation in connectivity remains limited. In this study, a two-dimensional hydraulic modelling approach is presented to evaluate flow connectivity in relation to passage requirements of adult steelhead trout (*Oncorhynchus mykiss*) in coastal California streams. High-resolution topographic data of stream reaches with distinct channel morphology were collected using terrestrial light detection and ranging surveys and linked with water surface measurements to calibrate hydraulic model simulations. Quantitative metrics of longitudinal flow connectivity were developed to assess fish passage suitability in relation to stream discharge. Measured flow data from the 2008–2009 winter season and simulated long-term records indicated that suitable passage flows occur with relatively low frequency and duration at all sites, suggesting that instream flow protections for fish passage are warranted. Results from the hydraulic modelling simulations were then compared with two alternative methods for assessing passage flows. A regional formula used by the State of California to identify minimum instream flow needs provided conservative estimates of passage flow requirements, whereas an approach based on riffle crest water depths underestimated flow needs. The hydraulic modelling approach appears well suited for simulating flows for fish passage studies and may be particularly useful for testing alternative environmental flow assessment methods and evaluating habitat–flow relationships in stream reaches of importance, such as critical habitat for threatened fish species. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: steelhead trout; *Oncorhynchus mykiss*; environmental flows; hydrologic connectivity; two-dimensional hydrodynamic modelling; terrestrial LiDAR; fish passage assessment

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INTRODUCTION

Human water management practices have extensively fragmented river networks and contributed to the degradation of freshwater ecosystems at a global scale (Nilsson *et al*., 2005; Dudgeon *et al*., 2006). The construction and operation of dams, weirs and water diversions disrupt natural patterns of physical and biotic connectivity and have been shown to affect sediment transport (Kondolf, 1997; Vörösmorty *et al*., 2003), impede the movement of organisms (Merritt and Wohl, 2006; Sheer and Steel, 2006) and alter a wide range of ecological processes (Ward and Stanford, 1995; Pringle, 2003; Fukushima *et al*., 2007). The fragmentation of river ecosystems also is implicated in population declines of migratory fish, such as salmon, sturgeon and other species of significant economic and cultural value (Nehlsen *et al*., 1991; Kareiva *et al*., 2000; Mora *et al*., 2009). Therefore, the restoration and maintenance of connectivity in river networks has become an important principle for guiding freshwater ecosystem management and conservation (Bunn and Arthington, 2002; Kondolf *et al*., 2006; Pringle, 2006).

The maintenance of natural hydrologic connectivity is particularly important for anadromous salmonids that must migrate through river networks to complete their life cycle (Bisson *et al*., 2009). Water projects, such as dams and weirs, present direct physical obstacles to migration, whereas diversions and flow regulation can prevent fish passage by creating downstream shallow-water or high-velocity flow barriers. Furthermore, the freshwater life stages of salmon have distinct habitat requirements that are highly sensitive to temporal and spatial variability in hydrologic connectivity (ISP, 2002; Fullerton *et al*., 2010). For example, temporal or spatial shifts in the degree of flow-mediated connectivity can influence the permeability of migration barriers (Puth and Wilson, 2001), the suitability of breeding habitats (Beechie *et al*., 2008) and the ability of juveniles to move between main channel and tributary-stream habitats (Ebersole *et al*., 2006).

Given the critical importance of hydrologic connectivity to salmonids, much attention has been given to identifying barriers to fish movement and re-engineering dams and other instream structures to allow for the upstream passage

*Correspondence to: T. E. Grantham, Department d'Ecologia, Universidad de Barcelona, Ave. Diagonal 645, Barcelona 08028, Spain.
E-mail: ted.grantham@gmail.com

of adults and out-migration of juveniles (Thompson, 1970; Winter and van Densen, 2001; Clarkin *et al*., 2005; de Leaniz, 2008). Minimum flow releases for salmon also have been incorporated into dam operations for many large regulated rivers to maintain adequate connectivity and suitable habitat conditions in downstream reaches (Decker *et al*., 2008; Beechie *et al*., 2010). Despite these improvements, protection of hydrologic connectivity for salmon passage and habitat maintenance remains inadequate, particularly in small streams (CDFG-NMFS, 2002; ISP, 2002). In coastal California, for example, the upstream movement of salmon generally occurs after storms (Hunstman, 1948), when elevated streamflows facilitate fish passage through riffles and other low-flow barriers (Vadas, 2000). As a consequence, the ability of salmon to successfully reach upstream spawning sites is highly dependent on the occurrence of flows that exceed minimum passage depth thresholds. Winter flow dynamics are primarily driven by regional precipitation patterns. However, streams in coastal California are increasingly subject to diversions to meet agricultural and domestic water demands (Deitch *et al*., 2009a). Such small-scale water diversions are individually not capable of altering flow regimes to the same extent as large dams, but multiple diversions within a common stream network have the potential to cumulatively impair ecologically relevant flow characteristics (Merenlender *et al*., 2008; Deitch *et al*., 2009b), including the frequency and duration of hydrological connectivity required for salmon passage.

In response to concerns over the potential impacts of small-scale water diversions on salmon populations in northern California, the State Water Resources Control Board (SWRCB) adopted the North Coast Instream Flows Policy, which prescribes protective measures for streamflows by restricting the periods in which water users can divert and store water (SWRCB, 2010). The policy establishes regional criteria for minimum instream flows and guidelines for evaluating the potential individual and cumulative effects of new diversions on adult salmon passage. The regional criteria are intended to provide conservative estimates of instream flow requirements for all streams in the region and are based on an empirically derived regression formula that describes how local minimum passage flow requirements vary in relation to drainage area and mean annual precipitation. The policy also allows for site-specific studies to determine instream flow needs at a particular location. The recommended approach for assessing site-specific salmon passage flows needs involves monitoring water depths at stream channel transects across a range of discharge. Monitoring transects are typically placed at riffle crests or cascades, which often are the shallowest sections of flowing water within a channel reach and therefore represent the critical constraint to fish passage (Mosley, 1982; Reiser *et al*., 2006). Although the conditions for successful passage vary by species and size of individual fish, there is general agreement that upstream movement of adult salmonids may be impaired when water depths fall below 0.2–0.3 m (Evans and Johnston, 1980; Powers and Orsborn, 1985; Bjornn and Reiser, 1991). Therefore, the objective of site-specific fish passage studies is to identify the discharge needed to maintain longitudinal connectivity of adequate water depths in all monitoring transects along the stream channel.

Two-dimensional (2D) numerical hydraulic modelling also has been employed to investigate how fish passage conditions vary with flow (Reinfelds *et al*., 2010). Numerical hydraulic models compute water depths and velocities based on conservation of fluid mass and momentum, the channel form, and measured or calculated values of discharge and stage at downstream cross sections. 2D models are capable of simulating the fine-scale spatial distribution of depths and velocity of streamflow and are increasingly used to assess relationships between discharge and parameters of ecological relevance (e.g. Leclerc *et al*., 1995; Lacey and Millar, 2004; Stewart *et al*., 2005; Elkins *et al*., 2007; Clark *et al*., 2008; Harrison *et al*., 2011). For ecological applications, 2D models are typically used to predict flow conditions at 0.1- to 1-m resolution to represent the scales at which relevant biological (e.g. microhabitat utilization) and physical processes (e.g. sediment entrainment) occur. The accuracy of 2D model results is strongly dependent on the resolution and accuracy of the underlying topographic measurements and corresponding digital elevation model (Ghanem *et al*., 1996; Pasternack *et al*., 2004; Legleiter *et al*., 2011). Thus, mapping the stream channel at sufficient spatial resolution is a critical component for optimizing model performance. The representation of micro-scale topographic features, such as boulders and root wads, is particularly important because these types of instream obstructions can have a strong influence on velocity gradients and water depths (Crowder and Diplas, 2000; Waddle, 2010). However, measuring high-resolution (< 1 m) channel features is time intensive using traditional survey methods (e.g. total station), so there is a trade-off between fine-scale field mapping and the quality of model results (Pasternack *et al*., 2004), which may explain why many studies that have focused on small-scale hydraulics in relation to ecological parameters have been restricted to relatively short (~100 m) river reaches (e.g. Clark *et al*., 2008; Reinfelds *et al*., 2010).

In this study, a 2D hydraulic modelling approach is used to evaluate the passage flow requirements of steelhead trout (*Oncorhynchus mykiss*) in coastal California streams. The approach relies on terrestrial light detection and ranging (LiDAR) surveys to generate high-resolution topographic measurements in three intermittent stream sites with distinct channel morphology. The detailed topographic data, combined with empirical field measurements of discharge-stage relations, are used to calibrate 2D hydraulic model

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simulations. Model predictions of the spatial distribution of water depths are then used to develop quantitative metrics of passage flow connectivity in relation to discharge. Passage flow connectivity requirements indicated by the model results are compared with alternative assessment methods: first, by calculating the recommended site-specific passage flow criteria under the State's regional-formula approach and then identifying the minimum flow required to exceed passage depths at riffle-crest transects within the study reaches. In summary, the specific objectives of the study are the following: (i) to test the applicability of a 2D hydrodynamic model for predicting water depths in small, salmon-bearing streams, (ii) to demonstrate the use of model simulation results to quantify passage flow connectivity, considering both spatial and temporal variation in hydraulic conditions, and (iii) to compare the outcomes and assumptions of alternative methods commonly employed in salmon passage flow assessments.

STUDY AREA

Gill and Sausal Creek reaches

To evaluate the applicability of 2D hydrodynamic models for supporting fish passage flow assessments in small, salmon-bearing streams, we focused on two tributary streams to the Russian River in eastern Sonoma County, California (Figure 1). Gill Creek and Saual Creek are located on the southwest-facing slope of the Mayacamas Mountains and descend from approximately 875 to 50 m above sea level at the confluence with the Russian River. The upper catchments are characterized by moderately sloped hills covered by oak woodland vegetation, vineyards and low-density residential development. Stream channels in the upper catchment are generally steep and confined to narrow canyons. The streams descend to the alluvial plan of Alexander Valley, where the streambed slope decreases and channel widths increase. Nearly all of Alexander Valley is planted in vineyards for wine-grape production. In total, vineyards represent 7% and 15% of the total catchment areas of Gill and Sausal Creek, respectively. The region is characterized by a Mediterranean climate, with mean annual rainfall of approximately 800 mm. Nearly all annual rainfall occurs between November and May and is typically delivered in brief, intense storms. Winter streamflow tracks rainfall patterns, yielding a flashy hydrograph with peak flows that often are orders of magnitude greater than baseflows. During the dry season (June to October), flows in these streams gradually recede to intermittent conditions. In the confined, upper reaches, streams contract to a series of disconnected pools by the late summer, whereas in the lower, alluvial reaches, the stream channel completely dries.

Three study reaches were identified on Gill and Sausal Creek to examine the relationships between winter stream discharge and fish passage suitability. A confined, canyon reach and an unconfined, alluvial channel reach were selected on Sausal Creek, and a single confined channel reach was identified on Gill Creek (Figures 1 and 2). Site selection was focused on reaches characterized by riffle-pool channel morphology and the absence of natural or artificial barriers (e.g. cascades, waterfalls and dams) but also was determined by accessibility and proximity to stream gauging stations. In addition, the paired-study sites on Sausal Creek

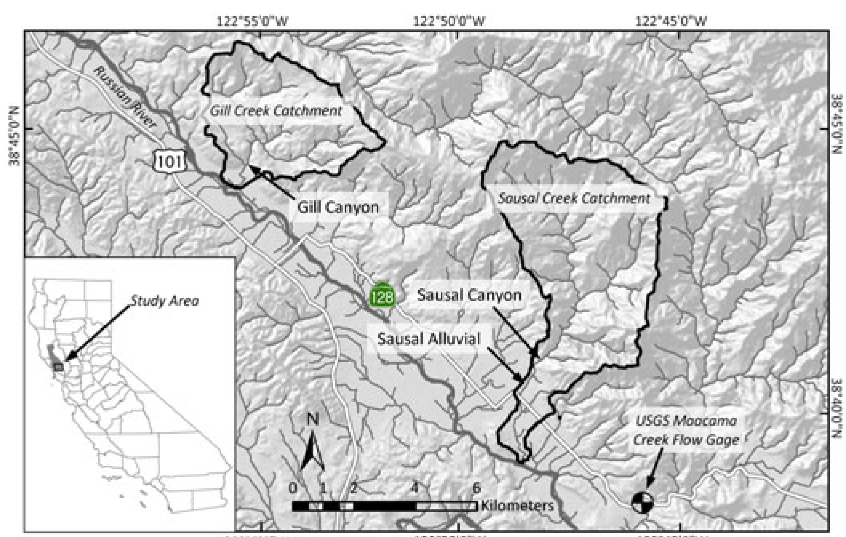

Figure 1. Study locations on Gill Creek and Sausal Creek in the Russian River basin, eastern Sonoma County, California, USA

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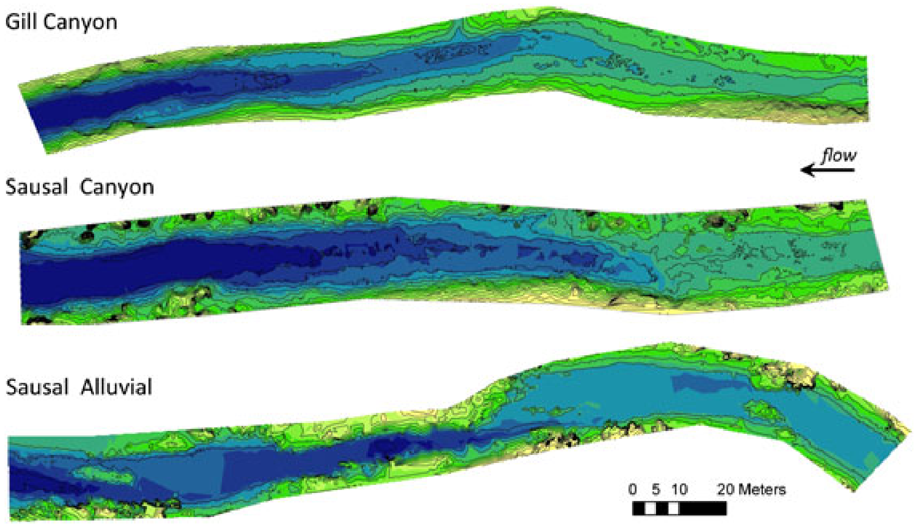

Figure 2. Gill Canyon, Sausal Canyon and Sausal Alluvial site topography, collected by terrestrial light detection and ranging surveys. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

were selected to evaluate how the transition in channel morphology from confined, channel reaches to unconfined, alluvial reaches potentially affects fish passage flow requirements. All study reaches were approximately 200 m long, which represents more than 20 channel widths in length and is considered an appropriate scale to characterize local stream channel processes (Montgomery and Buffington, 1997). The Gill Canyon reach is relatively straight with a well-defined low-flow channel that has a mean width of 4.3 m and slope of 0.021 (Table 1). Bed substrate is characterized by heterogeneous patches of gravel and cobbles and scattered boulders. The Sausal Canyon reach has an average low-flow channel width of 7.1 m and a bed slope of 0.013. Channel substrates in riffles are dominated by large cobbles, whereas pools are characterized by small cobble and gravel bar deposits. The Sausal Alluvial reach has a mean channel width of 7.4 m but more variation in channel form than the other sites (Figure 2). There is a meander bend in the upper section of the reach and a constriction in the channel near the middle of the reach. Mean bed slope is 0.008. Pools and areas of slow-moving water have deposits of gravel, sand and fine sediments, whereas riffles are characterized by small and large cobble substrate.

Management context

The Russian River supports three species of salmonids: coho salmon, Chinook salmon and steelhead trout. Gill and Sausal Creek, and other tributary streams to the Russian River, are primarily utilized by steelhead trout. Returning adult steelhead enter the Russian River watershed in the winter between November and April (Fry, 1973) and migrate through the mainstem river to upland tributary streams. Spawning typically occurs in late spring to avoid the potentially damaging effects of winter floods (Moyle, 2002). The Russian River basin historically supported the largest population of Central California Coast (CCC) steelhead trout but is thought to have lost approximately 90% of its natural breeding population over the past 60 years (Busby *et al*., 1996). The CCC steelhead was listed as threated under the federal Endangered Species Act in 1997. Principal factors contributing to population declines in the Russian River include dams and other migration barriers, water diversions and the degradation of stream habitat (Busby *et al*., 1996; Good *et al*., 2005).

Table I. Description of study reaches

Site	Catchment area (km^2)	Reach length (m)	Mean slope ($m \cdot m^{-1}$)	Mean channel width (m)[a]	Median winter discharge ($m^3 \cdot s^{-1}$)[b]	Channel morphology
Gill Canyon	14.6	200	0.012	4.3	0.20	Confined
Sausal Canyon	27.4	210	0.013	7.1	0.37	Confined
Sausal Alluvial	28.6	195	0.008	7.4	0.38	Alluvial fan

[a]Mean width of low-flow channel based on measured bed-and-bank topography at multiple cross sections extracted from the digital elevation model.
[b]Mean daily winter (November 1 to March 31) discharge estimated from 20 years of modelled data from US Geological Survey gauge station records.

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There are two large dams in the Russian River watershed that are managed for flood protection and to supply water to urban centers in the region. However, most agricultural and rural water users rely on private, small-scale infrastructure to pump groundwater or divert surface water from the Russian River and its tributary streams (Deitch *et al*., 2009a). The expansion vineyards and exurban development in small, upland catchments in the region (Merenlender, 2000; Newburn and Berck, 2006) have been accompanied by an increase in the number of water diversions in tributary streams (Merenlender *et al*., 2008). Decentralized networks of water diversions have been shown to reduce stream discharge during baseflow periods (Deitch *et al*., 2009b) and have the potential to impair flows needed for salmon passage and spawning. Thus, small water diversions are recognized as an important and growing threat to the persistence of threatened salmon populations in north coast California streams (Busby *et al*., 1996; Moyle, 2002). In response to pressure from environmental groups and government agencies, in 2010, the State Water Board adopted the North Coast Instream Flows Policy (SWCRB, 2010). The policy restricts all new proposed water diversions to the winter, rainy season (November 1 to March 31) and establishes minimum flow requirements to protect passage and spawning flows for salmon and steelhead trout. The policy is focused on management of flows in small salmon-bearing streams, such as Gill and Sausal Creek, which are affected by the expansion of residential development and vineyard agriculture.

METHODS

Terrestrial LiDAR topographic surveys and data processing

Detailed topographic data of the study reaches were collected with a terrestrial LiDAR unit (I-SITE 4400 IR). The technique is well suited for surveying the three-dimensional topography of fluvial geomorphic features with high resolution and accuracy (Collins and Kayen, 2006; Heritage and Hetherington, 2007; Heritage and Milan, 2009). The method was used to survey the full lengths of the study reaches, with an emphasis on mapping fine-scale channel features that were likely to influence flow fields. The tripod-mounted laser scanner was used in medium-resolution mode, which collects targeted points with a separation of 4 cm at 5-m distance and a point separation of approximately 150 cm at 200 m. Each 4-min scan collects approximately 800 000 data points as the LiDAR unit rotates 360 degrees around its vertical axis. During the site surveys, the laser scanner was positioned within the stream channel in 7 to 10 locations. Neighbouring scan positions were separated by less than 40 m to minimize data gaps from shadow effects and ensure a fairly continuous, high-resolution (<0.25 m) coverage of data points in the stream channel. Vegetation within the stream channels at the study sites was minimal but, where present, was either removed or manipulated by hand to maintain an unobstructed line of sight between the stream channel surface and the laser scanner. Each scanner location was mapped with a total station (Nikon DTM-352) and georeferenced to established survey control and backsight points for data rectification. At the time of the surveys (October 2008), the streams in the Gill Creek Canyon and Sausal Creek Canyon sites were flowing at a low rate ($< 0.001\ m^3 \cdot s^{-1}$) and occupied less than 10% of the low-flow channel. Because the laser does not penetrate water, the total station was used to survey individual points beneath the water surface. The stream channel was completely dry at the Sausal Creek Alluvial site when the survey was conducted.

Data processing was performed using the I-SITE Studio software program (Maptek, 2010), which is designed to visualize and manipulate large point files of terrestrial laser scanning data. Each scan yields a cloud of points reflected off surfaces surrounding the LiDAR unit. The survey data from each scan were merged based on the geographical coordinate location of each scan and orientation to a survey benchmark. A series of topographic filters were then applied to eliminate survey points outside the study area, to remove points reflected off vegetation above the ground surface and to limit the minimum distance between points to 0.1 m. Finally, the survey points collected beneath the water surface were added to complete the topographic map. The final topographic data set for Gill Canyon included a total of 88 025 points with an average density of 10 points per square metre. There were 149 799 survey data points for Sausal Canyon and 126 028 data points for Sausal Alluvial reaches, corresponding to average densities of 20 and 25 points per square metre, respectively.

Flow and hydraulic habitat measurements

To measure changes in flows within the study reaches, pressure transducer–type water level gauges (InSitu) were installed to record stage at 10-min intervals for the 2009 water year (1 October 2008 to 30 September 2009). Each pressure transducer probe was encased in flexible PVC tubing and attached to solid substrate at the bottom of a pool within the stream channel. Measurements of water surface elevation (WSE) were transmitted to a logger, where the data were retrieved by manually downloading the data to a PC. Discharge measurements were taken at approximately biweekly intervals using Pygmy or AA current meters throughout the water year. Velocities were measured at 10–15 points along a cross section at a location of the stream channel with approximately uniform flow. In water less than 0.8 m deep, measurements were taken at $0.6 \times$ depth (d) to estimate mean column velocity. At greater than 0.8 m depths,

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velocity measurements were taken at 0.8 × d and 0.2 × d, and the recorded values were averaged. The point velocities were multiplied by the estimate area of each vertical column of the cross section and then summed to obtain the discharge. The discharge measurements and stage data were then used to develop rating curves and generate a continuous record of flow conditions at the site, in accordance with standard US Geological Survey methods for stream gauging (Rantz *et al*., 1982).

Water surface elevations were surveyed at three to five discharge levels at each site between November 2008 and May 2009 using a total station (Topcon GTS-213) and prism reflector. Coordinate point locations were recorded at the water's edge on both sides of the stream channel along the full extent of the study reach. Measurements were taken at all habitat transitions (e.g. pool to riffle) along the reach to capture breaks in water surface slope. For model validation, water depth and velocity measurements also were taken at 20–50 randomly selected points within the stream channel at a single discharge event for each site. A current meter was used to measure the average velocity of the vertical water column (at 0.6 × d or 0.2 × d and 0.8 × d), and each measurement location was surveyed with the total station.

The channel substrate in each reach was characterized by mapping regions of distinct sediment sizes (i.e. grain-size facies), based on the length of the intermediate axis of the dominant particle size (Dunne and Leopold, 1978; Buffington and Montgomery, 1999). Patches of similar sediment sizes were visually mapped onto an image of the surface topography generated from the LiDAR surveys. Sediment patches were classified as sand (less than 0.0025 m), gravel (0.05 m), gravel/cobble (0.08 m), large cobble (0.15 m) and boulder (0.2 m). Patches vegetated with willow (*Salix* spp.) within the stream channel also were mapped to account for the influence of vegetation on channel roughness (Wu *et al*., 1999).

Hydraulic modelling

Topography, flow, and WSE data were used as input to the Multi-dimensional Surface Water Modelling System (MD_SWMS), a graphical user interface developed by the US Geological Survey for numerical models of surface-water hydraulics and sediment transport in rivers (McDonald *et al*., 2005). MD_SWMS was used to run a depth-averaged 2D flow model, Flow and Sediment Transport and Morphological Evolution of CHannels (FaSTMECH), to simulate hydraulic conditions at different discharges. FaSTMECH is designed to model flow hydraulics in river and stream channels and calculates both downstream and transverse velocity components and flow depths at each node of a regular grid cast in a channel-centered coordinate system, with one axis along the centerline and the other axis oriented perpendicular to the local centerline (Smith and McLean, 1984). The flow model uses an iterative finite difference numerical scheme to solve the momentum equations and determine WSEs at each node; iteration proceeds until the model converges upon a steady-state solution. The topographic data from the LiDAR surveys were mapped onto the curvilinear orthogonal grid oriented on a digitized channel centerline. The model grid was 16 m wide for Gill Canyon and 20 m wide for Sausal Canyon and Sausal Alluvial, with node spacing of 0.2 m in the streamwise and cross-stream direction for all sites. The average density of the grid nodes was between 12 and 20 points per square metre, which was approximately the same point density as the topographic surveys.

A downstream WSE and discharge measured in the field were specified as boundary conditions to run the model, which was then calibrated by adjusting a uniform drag coefficient parameter until the predicted and measured water-surface elevations were in agreement. Patches of distinct sediment sizes were then specified to produce a revised solution accounting for variable channel roughness. Roughness values were estimated at each node from the mapped dominant grain size and the depth solution from previous simulations based on a constant drag coefficient (McDonald *et al*., 2005). The drag coefficient (C_d) calculation assumes a logarithmic velocity profile described by the equation:

$$C_d = \left[\frac{1}{k}\left(\ln\left(\frac{h}{z_0}\right) - 1\right)\right]^{-2} \quad (1)$$

where is h is the depth of flow, k is Von Kármán's constant equal to 0.403 and z_0 is the roughness length parameter, which was set at 0.1 times the grain size (derived from the facies field maps). The model also includes a lateral eddy viscosity term that accounts for lateral momentum exchange because of turbulence or other variability not generated at the bed (Nelson *et al*. 2003). Lateral eddy viscosity is approximately equal to the product of mean depth and mean velocity of the simulated flow field and is computed iteratively during model calibration.

The 2D hydraulic model was first used to run and calibrate steady-state flow simulations at three to four observed discharges at each site. Based on the relationship between measured downstream WSE and the recorded stage at the flow gauge, a linear interpolation was used to predict the downstream WSE across a range of discharges between 0.1 and 5 $m^3 \cdot s^{-1}$. At each site, a total of 12 flow simulations were performed to generate predictions of depth and velocity for all wetted nodes in the model grid.

Model validation was performed by comparing modelled results to measured values of depth and velocity. For one simulation at each site, modelled depth and average velocity values were recorded at the node closest to each measurement location, and the error between simulated and observed values was evaluated.

Passage flow connectivity assessment

To assess how changes in streamflow affect adult steelhead trout migrating through the study reaches, the extent of hydrologic connectivity of suitable passage depths was calculated over the range of simulated discharges. The minimum passage depth required for adult fish passage was defined as 0.25 m, consistent with current instream flow policy criteria for steelhead trout (SWRCB, 2010). This depth criterion is based on previous studies of fish passage requirements (e.g. Thompson, 1970; Powers and Orsborn, 1985) and is related to the body depth of a typical adult steelhead trout (0.15–0.20 m) swimming 0.05 m above the streambed. An individual fish moving through the channel is assumed to follow a continuous path, from the downstream to upstream end of the reach. Therefore, the most accessible passage route through a small stream would follow a least-cost path, where shallower waters are avoided and deeper waters preferred. To identify the least-cost migration path, the solution grid of simulated depths was imported from MD_SWMS into an ArcGIS (ESRI, 2009) spatial data file. The inverse depth of each node (1/depth) was specified as the cost layer, and the least cost path was computed using the Spatial Analysis Extension (McKoy and Johnston, 2001), which indicated the potential migration route along the deepest, contiguous path of cells, extending from the downstream to the upstream end of the reach. A series of adjacent cells along the route that exceed the minimum depth threshold comprise a "suitable" path segment. The total length and number of suitable path segments that exceed the minimum depth threshold is expected to increase with increasing flow, until complete passage flow connectivity is achieved.

Several metrics were calculated to describe the extent of suitable passage connectivity along the migration path, including the proportion of cells exceeding the minimum depth criterion, the total path length of suitable depths, and the number and length of unsuitable (shallow) path segments. Only path segments of two or more contiguous cells (equal or greater than 0.4 m in length) were considered breaks in passage connectivity for the analysis. To assess the sensitivity of passage flow estimates to model uncertainty, the connectivity analysis was repeated over the range of depth prediction error. The standard error of depth predictions (estimated in the model validation analysis) was added and subtracted from the modelled depths at each node to generate new depth fields for each flow simulation. The least-cost path was then recalculated to assess passage connectivity for the new simulated depth fields. The sensitivity analysis thus yields lower and upper estimates of passage flow connectivity for ± 1 SE of model depth prediction error.

The influence of flow velocity on passage suitability was not considered in this analysis. In general, high water velocities become an effective barrier when the entire flow becomes concentrated in a fast chute, the length and speed of which combine to overcome the fish's swimming ability. These conditions most often are encountered at culverts or natural cascades (Reiser *et al*., 2006) and are not present in the study reaches. Furthermore, previous studies indicate that steelhead trout are capable of sustained swimming against currents of $3\ \mathrm{m{\cdot}s^{-1}}$ and can achieve burst swimming speeds of $4–8\ \mathrm{m{\cdot}s^{-1}}$ to negotiate falls and high-velocity areas (Stringham, 1924; Powers and Orsborn, 1985). Based on the characteristics of the stream channels and the range of flows considered in this analysis, velocity barriers are unlikely to be a constraint to fish passage.

Temporal variability of passage flow connectivity

An assessment of passage flow connectivity requires consideration of not only the spatial hydraulic patterns (e.g. distribution of depths as a function of discharge) but also the temporal dynamics of streamflow. The study reaches are characterized by a highly variable seasonal and interannual hydrograph that influences the periods of potential fish passage. To evaluate the temporal variability in minimum passage flows at the study sites, the frequency and duration of minimum passage flows was calculated using site-specific discharge data, collected at 10-min intervals for the 2008–2009 steelhead migration period (November 1 to March 31). Interannual variation in passage flows also was evaluated by simulating 20 years of daily flow records at the study sites, based on gauging records from Maacama Creek (USGS Station no. 11463900; 1961–1980) located about 5 km south of Sausal Creek (Figure 1), using daily flow values scaled by drainage area and mean annual precipitation. Passage flow duration and frequency statistics were then calculated for each year of the simulated record.

Comparison to alternative passage flow assessment methods

Results of the 2D modelling analysis were compared with regional minimum passage flow requirements, defined by the California State Water Board Instream Flow Policy (SWRCB, 2010). The policy establishes instream flow standards for salmon-bearing streams and defines minimum passage flows (Q_{mpf}) as the 'minimum instantaneous flow rate of water that is adequate for fish breeding, rearing and passage as measured at a particular point in the stream'.

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The flow threshold at a particular site is determined by a regionally derived formula:

$$Q_{mpf} = 8.8 \ Q_m (DA)^{-0.47} \quad (2)$$

where Q_m is the mean annual unimpaired flow in cubic feet per second, and DA is the catchment drainage area in square miles at the point of interest. The mean annual unimpaired flow (Q_m) is estimated at the point of interest from long-term flow records at the closest gauge station, adjusted by drainage area and mean annual precipitation.

The policy also stipulates that as an alternative to the regional formula approach (hereafter, 'regional approach'), field studies can be performed to assess minimum passage flows at points of interest. The recommended approach for fish passage assessments involves quantifying depth-discharge relationships at riffle crests (hereafter, 'riffle-crest approach') and identifying the minimum flow required to achieve passage depths. The riffle crest is an area of accelerating flow associated with a distinct increase in water surface slope, where the stream channel transitions from a deeper area of slow-moving water (e.g. pool) to a shallower area of rapidly flowing water (e.g. riffle). The riffle crest is commonly used as a reference to identify minimum flow requirements for fish passage because it often is where the shallowest flows within a stream channel occurs. The riffle-crest approach involves monitoring water depths at several riffle-crests transects in a channel reach across the range of characteristic discharges and identifying the flow needed to maintain depths sufficient to allow fish passage at all transects. To compare this approach with the 2D hydraulic modelling method employed in this study, all riffle crests within the modelled study reaches were mapped in the field with cross-section endpoints. The cross-section topography and water depth values were then extracted from the model results for each simulated discharge. Depths at the riffle crest thalweg were plotted against discharge for each cross section, and the minimum flow necessary to maintain 0.25-m water depths was estimated from the empirical discharge-depth relationship.

RESULTS

Hydraulic model simulations

Model calibration was performed by minimizing the difference between modelled and measured values of WSE. Flow simulations were calibrated at three to four discharges between 0.02 and 1 $m^3 \cdot s^{-1}$ at each site (Table 2). A peak flood event of 14 $m^3 \cdot s^{-1}$ also was modelled at Gill Canyon using high water marks as a proxy for measured WSE. Overall, predictions for the calibrated simulations accurately reproduced patterns in the observed data. When observed WSEs were plotted against predicted values, the least squares linear regression yielded r^2 values greater than 0.95 and regression slopes of 1.000 ± 0.03 for all simulations. The mean absolute difference between predicted and observed WSE values was 0.041–0.061 m for Sausal Canyon simulations and 0.056–0.096 m for Sausal Alluvial simulations (Table 2). Mean absolute error was 0.035–0.053 m for simulated flows at Gill Canyon between 0.06 and 0.62 $m^3 \cdot s^{-1}$ and was 0.101 m for the 14 $m^3 \cdot s^{-1}$ peak flow event. The model tended to overestimate the WSE at Sausal Alluvial, but the error distributions for all sites suggest that there is no systematic bias in the results (Figure 3).

Model validation was then performed by evaluating simulated values against an independent data set of point measurements for depth and depth-averaged velocity. At Gill Canyon, there was strong agreement between observed and predicted values of water depths (Figure 4A; Table 3). The strength of the relationship between predicted and observed depths was similar for Sausal Alluvial and weaker for Sausal Canyon. At depth measurement locations in Gill Canyon, model predictions deviated from observed depths

Table II. Comparison of predicted and measured values of water surface elevations for model calibration

	Gill Canyon				Sausal Canyon			Sausal Alluvial		
Discharge ($m^3 \cdot s^{-1}$)	0.06	0.44	0.62	14[a]	0.09	0.61	0.67	0.02	0.65	1
Number of points (n)	60	33	17	7	29	27	23	31	29	13
Root mean square error	0.063	0.045	0.054	0.122	0.085	0.049	0.061	0.070	0.080	0.102
Mean difference	0.026	0.001	−0.023	0.056	0.048	0.006	0.039	0.048	0.039	0.024
Mean absolute difference	0.053	0.035	0.038	0.101	0.061	0.041	0.042	0.056	0.096	0.095
Minimum	−0.111	−0.101	−0.142	−0.158	−0.150	−0.089	−0.017	−0.047	−0.099	−0.183
Maximum	0.151	0.073	0.048	0.209	0.196	0.104	0.133	0.178	0.184	0.151
Standard error	0.058	0.046	0.050	0.117	0.071	0.050	0.049	0.051	0.071	0.104
Number outside ±1 SE	19	11	1	2	2	5	7	9	2	4
Number within ±1 SE	41	22	16	5	27	19	16	22	27	9
Per cent within ±1 SE	68.3%	66.7%	94.1%	71.4%	93.1%	70.4%	69.6%	71.0%	93.1%	29.0%

[a]Simulation calibrated with measured high water mark elevations and discharge estimate from flow gauging station.

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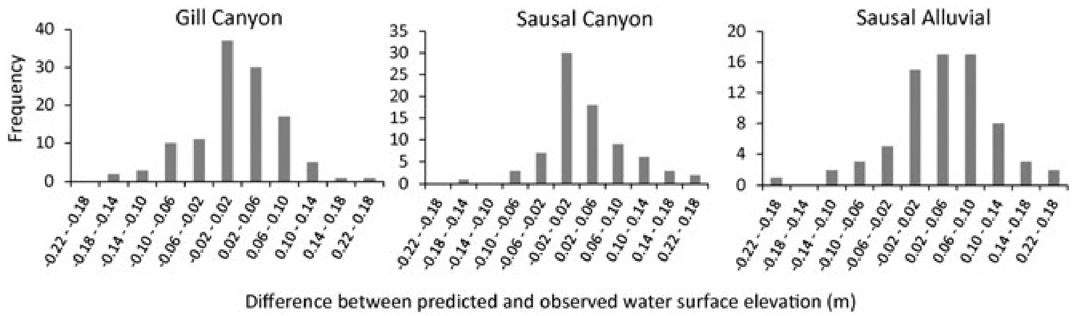

Figure 3. Frequency histogram of measured minus predicted water surface elevation values for calibrated model simulations at Gill Canyon, Sausal Canyon and Sausal Alluvial

by 0.036 ± 0.052 m (mean of absolute differences $\pm$ SE). Depth prediction error was slightly higher for Sausal Canyon (0.058 ± 0.072 m) and Sausal Alluvial (0.072 ± 0.082 m). The observed deviations in measured versus predicted depth values correspond to mean per cent errors of 11.4% at Gill Canyon, 23.3% at Sausal Canyon and 19.0% at Sausal Alluvial. Error in velocity predictions was greater than depth prediction error at all sites. For Gill Canyon and Sausal Alluvial, modelled and measured depth-averaged velocity values were weakly correlated ($r^2 > 0.4$) (Figure 4B). Correlation between measured and prediction velocity values for Sausal Canyon was considerably lower. Flow simulations tended to overpredict average downstream velocity at low measured values ($< 0.5\,\mathrm{m \cdot s^{-1}}$) and underpredict higher velocities ($> 0.5\,\mathrm{m \cdot s^{-1}}$), yielding a more homogeneous flow field relative to observed conditions.

The hydraulic model simulation results describe how changes in flow interact with local channel morphology to produce variable patterns in velocity and depth distributions. Increasing discharge was associated with a shift in depth and velocity distributions to higher values for all sites (Figure 5). However, there were reach-specific responses to flow that reflect differences in channel morphology. In the Gill and Sausal Canyon reaches, the confined stream channels

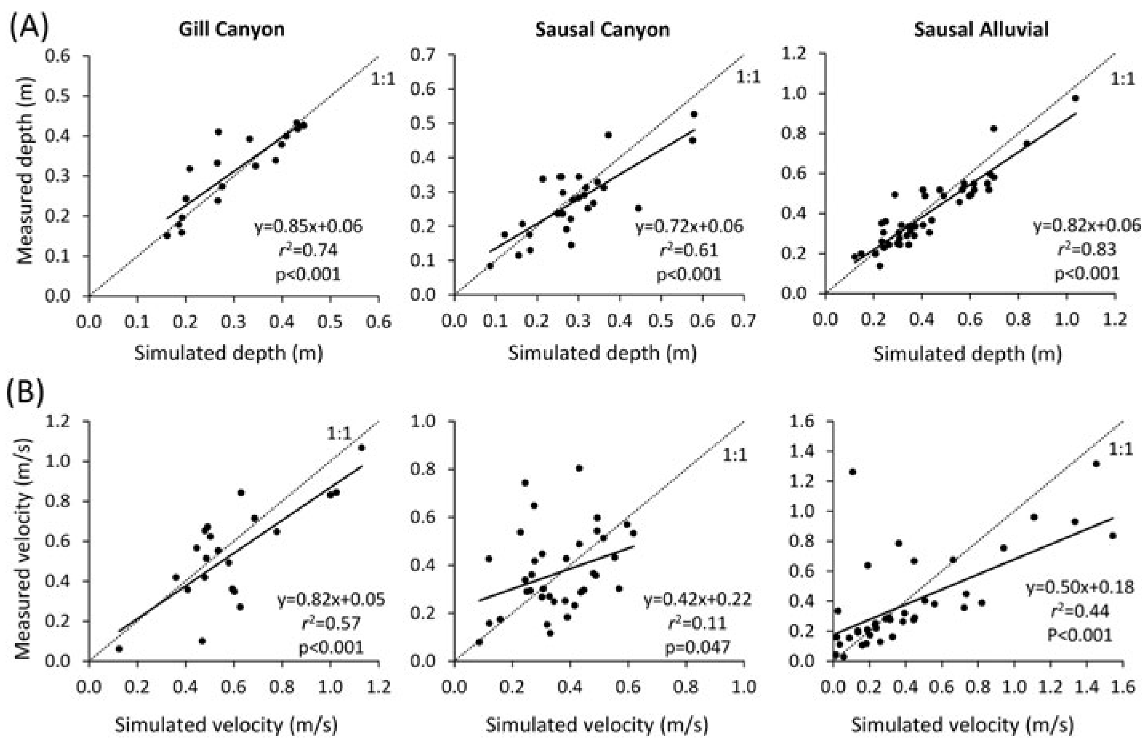

Figure 4. Measured versus simulated depths (A) and depth-averaged velocities (B) for Gill Canyon ($0.62\,\mathrm{m^3 \cdot s^{-1}}$), Sausal Canyon ($0.61\,\mathrm{m^3 \cdot s^{-1}}$) and Sausal Alluvial ($0.65\,\mathrm{m^3 \cdot s^{-1}}$)

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Table III. Comparison of predicted and measured values of depth and velocity

	Gill Canyon (0.62 $m^3 \cdot s^{-1}$)		Sausal Canyon (0.61 $m^3 \cdot s^{-1}$)		Sausal Alluvial (0.65 $m^3 \cdot s^{-1}$)	
	Depth	Velocity	Depth	Velocity	Depth	Velocity
Number of points (n)	18	22	28	37	43	40
Root mean square error	0.051	0.173	0.073	0.179	0.084	0.317
Mean difference	−0.011	0.058	0.018	−0.009	−0.025	−0.047
Mean absolute difference	0.036	0.143	0.058	0.137	0.072	0.200
Minimum difference	−0.141	−0.211	−0.123	−0.498	−0.160	−0.899
Maximum difference	0.048	0.370	0.193	0.267	0.205	1.154
Standard error	0.052	0.178	0.072	0.170	0.082	0.319
Number outside ±1 SE	3	7	7	14	14	9
Number within ±1 SE	15	15	21	23	29	31
Per cent within ±1 SE	83.3%	68.2%	75.0%	62.2%	67.4%	77.5%
Mean per cent error	11.4%	32.6%	23.3%	42.5%	19.0%	51.3%
SD per cent error	10.6%	34.1%	21.4%	39.8%	12.9%	40.0%

resulted in depth distributions that were restricted to a more narrow range of values than the Sausal Alluvial reach, which had a relatively broader channel such that increasing flows tend to extend laterally, maintaining relatively low water depths. The shifts in velocity distributions followed the same general pattern but also revealed unique differences among reaches. The relative increase in velocities with increasing discharge was greater for the confined, canyon reaches in comparison to the alluvial reach, whereas between the canyon reaches, Gill Canyon tended to have higher velocities than the Sausal Canyon reach across the range of simulated discharges.

Passage flow connectivity

The predicted migration route, as defined by the deepest path of contiguous cells from the bottom to the top of each study reach, was used to assess passage connectivity across the range of simulated flows. With increasing discharge, the model solutions indicated an increase in the proportion of path segments at or above the 0.25-m depth threshold (Figure 6A) and a reduction in the minimum length of gaps along the migration path that were less than the required passage depth (Figure 6B). Increasing flows also were associated by an expansion of the wetted channel area

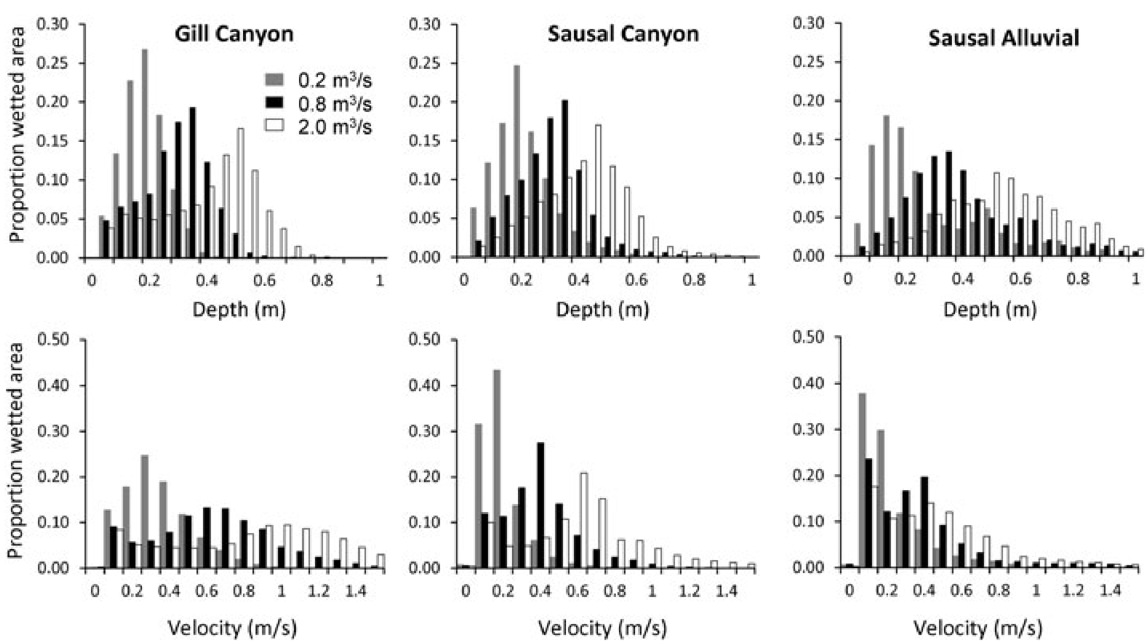

Figure 5. Distributions of depths and velocities over a range of simulated discharges

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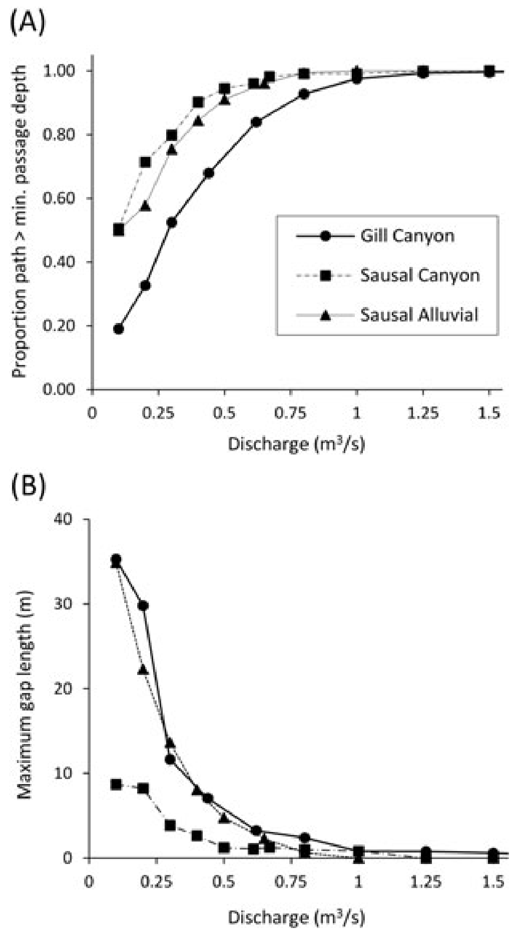

Figure 6. Passage flow connectivity along migration path in relation to discharge. (A) The proportion of cells equal or greater than the minimum depth criteria (0.25 m) along the migration path increases with discharge, and (B) the maximum length of path segments below the minimum depth criteria decreases with discharge

(Figures 7–9). At low flows (e.g. Figure 7A), segments of the channel that fell below the minimum depth threshold predominately occurred in riffles. The water depths in the riffles increased with flow, expanding the areas of suitable passage depths and increasing connectivity along the stream channel. The hydraulic model simulations for Gill Canyon indicated that a discharge of approximately 1.30 $m^3 \cdot s^{-1}$ is required to provide complete connectivity of suitable passage depths along the entire migration path. The discharge required to provide full passage connectivity is approximately 1.10 $m^3 \cdot s^{-1}$ at Sausal Canyon and 0.90 $m^3 \cdot s^{-1}$ at Sausal Alluvial.

To evaluate how the assessment of passage flows is affected by potential model uncertainty, flow connectivity along the migration path was estimated in the simulated depths fields adjusted by $\pm$ 1 SE of depth predictions at all nodes (Table 3). For Gill Canyon, shifts in predicted depths resulted in passage flow estimates of 1.0–1.8 $m^3 \cdot s^{-1}$, representing a −30% to +38% change relative to the original results for minimum passage flow connectivity (1.30 $m^3 \cdot s^{-1}$). Although the model validation analysis indicated greater uncertainty in depth predictions for Sausal Canyon and Sausal Alluvial, the range of passage flow estimates were similar to Gill Canyon when evaluated at depths within 1 SE of predicted values. For Sausal Canyon, minimum passage flows ranged from 0.6 to 1.3 $m^3 \cdot s^{-1}$ (−45% to +18% change). At Sausal Alluvial, the sensitivity analysis indicated that passage flows of 0.5–1.2 $m^3 \cdot s^{-1}$ (−44% to 33% change) over the range of error for depth.

Temporal variability of passage flow connectivity

The 2008–2009 winter had relatively low rainfall and only four major storms (Figure 10). Based on the results derived from the hydraulic modelling analysis, flows at Gill Creek were adequate for fish passage during five events (separated by at least 12 h), each lasting between 40 min to 2.2 days (Table 4). In total, the estimated duration of passage flow connectivity at Gill Canyon was 6.2 days. Estimated passage flow connectivity at Sausal Canyon and Sausal Alluvial occurred on six events (lasting from 3.5 h to 6.1 days) and seven events (lasting from 1.8 h to 13.7 days), respectively. The total estimated duration of suitable passage flow conditions was 18.9 days at Sausal Canyon and 22.5 days at Sausal Alluvial. Based on the 20 years of simulated hydrographs for the study reaches, the duration and frequency of passage flows varied substantially among years (Table 4). On average, there were 5.4 potential passage flow events per year at Gill Canyon and 5.9 passage flow events per year at Sausal Alluvial. The median seasonal duration of passage flow connectivity at Gill Canyon was 18.5 days, but the total duration within each year ranged from 0 to 43 days. At Sausal Canyon, the median duration of passage flow connectivity was 37 days, ranging from 0 to 80 days over the 20-year period of analysis. Seasonal passage flow duration at Sausal Alluvial had a median value of 45 days, ranging from 0 to 101 days.

Alternative passage flow assessment methods

Based on the State's regional approach, minimum flows to protect fish passage at the study reaches would be 1.24 $m^3 \cdot s^{-1}$ at Gill Canyon, 1.77 $m^3 \cdot s^{-1}$ at Sausal Canyon and 1.76 $m^3 \cdot s^{-1}$ at Sausal Alluvial. Therefore, the State's approach yielded results that were comparable to the site-specific hydraulic modelling results for Gill Canyon but were significantly higher than those obtained for Sausal Canyon and Sausal Alluvial (Table 5). Furthermore, the regional approach indicated that passage flows at the Sausal Canyon and Alluvial sites are essentially identical, whereas the hydraulic modelling approach suggested that Sausal Canyon requires approximately 20% more flow than the Alluvial reach to allow fish passage. The riffle-crest

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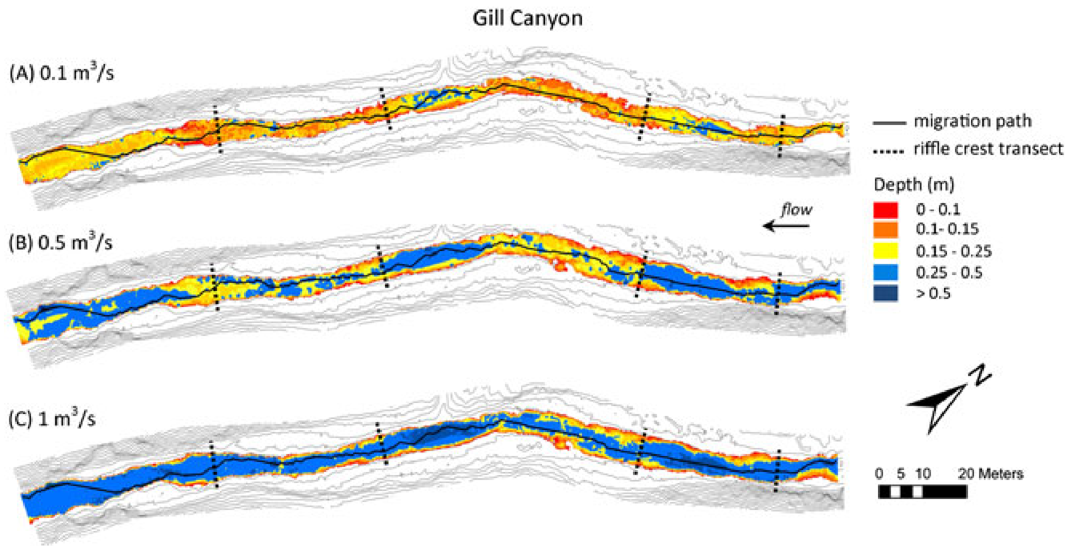

Figure 7. Simulated depths for the Gill Canyon reach at (A) 0.1 $m^3 \cdot s^{-1}$, (B) 0.5 $m^3 \cdot s^{-1}$ and (C) 1 $m^3 \cdot s^{-1}$, indicating deepest potential migration path and riffle-crest transects. Cells in blue are at or above the 0.25-m depth criteria for fish passage. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

approach indicated substantially lower passage requirements than those obtained by both the hydraulic modelling and the regional formula approaches (Table 5). At Gill Canyon, a discharge of 0.75 $m^3 \cdot s^{-1}$ was sufficient to inundate all of the riffle transects to water depths of 0.25 m. Sausal Canyon required only 0.25 $m^3 \cdot s^{-1}$ and Sausal Alluvial 0.5 $m^3 \cdot s^{-1}$ to meet the passage depth criteria. Therefore, the riffle-crest approach indicated that fish passage would be possible at approximately 25–50% of the discharge specified by the hydraulic modelling approach.

DISCUSSION

Hydraulic model performance

The 2D hydraulic model simulations reproduced observed spatial patterns in depth and velocity, and differences between modelled and measured values were within the typical range of error reported for 2D flow models (Pasternack *et al*., 2006; Waddle 2010). Modelling flows in shallow (< 1 m deep), fast-flow streams are particularly prone to error because of the influence of objects and

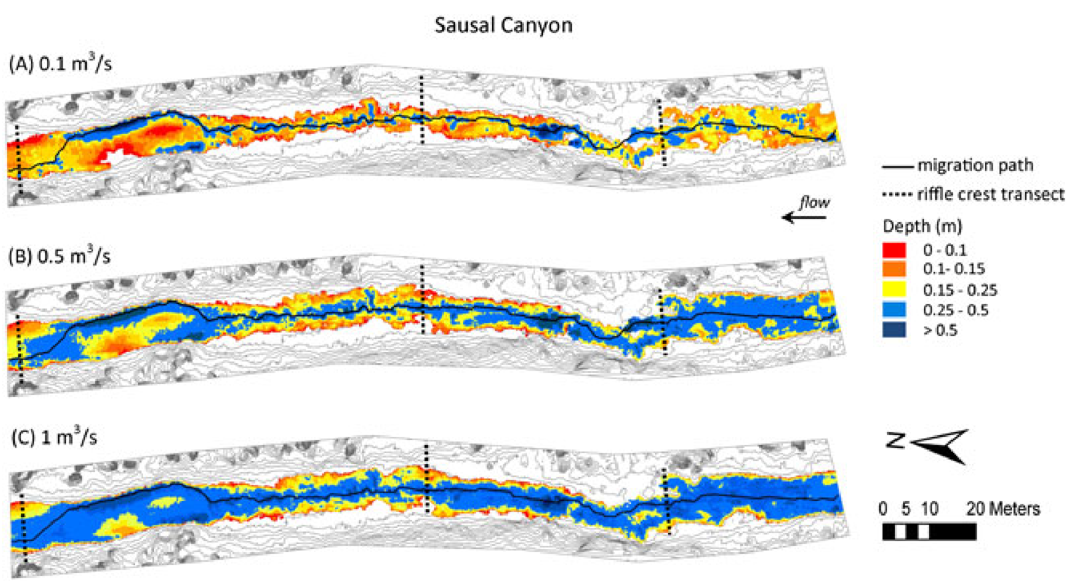

Figure 8. Simulated depths for the Sausal Canyon reach at (A) 0.1 $m^3 \cdot s^{-1}$ (B) 0.5 $m^3 \cdot s^{-1}$ and (C) 1 $m^3 \cdot s^{-1}$, indicating deepest potential migration path and riffle-crest transects. Cells in blue are at or above the 0.25-m depth criteria for fish passage. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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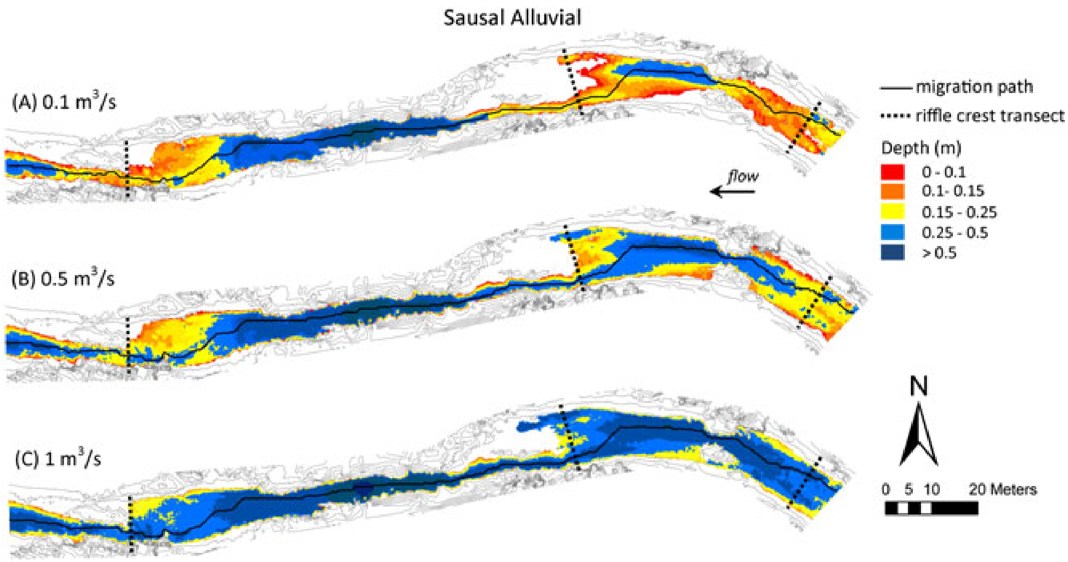

Figure 9. Simulated depths for the Sausal Alluvial reach at (A) $0.1\,m^3 \cdot s^{-1}$, (B) $0.5\,m^3 \cdot s^{-1}$ and (C) $1\,m^3 \cdot s^{-1}$, indicating deepest potential migration path and riffle-crest transects. Cells in blue are at or above the 0.25-m depth criteria for fish passage. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

bed features that are larger than one-half the water depth (Waddle, 2010). Furthermore, small absolute differences in shallow stream depth correspond to relatively large relative per cent errors. Thus, mean prediction error of 0.05–0.07 m for depths is acceptable model performance. Error in velocity was substantially higher and suggests that 2D models may not be well suited for applications in which accurate predictions of velocity fields in shallow streams are required. However, the significant correlation of modelled and observed velocity values suggest that error in velocity predictions is acceptable for this application, which is focused on the simulations of stream depths.

There are several sources of error that likely contributed to model prediction uncertainty. These have been discussed in detail in previous studies (e.g. Crowder and Diplas, 2000; Kondolf *et al*., 2000; Waddle, 2010) but briefly relate to various sources of field measurement, model formulation and model discretization error. Measurement errors result from operator mistakes, faulty equipment and inherent limitations to measurement precision. Errors associated with model formation refer to the governing equations, simplifying assumptions and numerical methods used to represent fluid dynamics. For example, 2D models are designed to estimate velocity in the cross-stream and downstream direction but neglect vertical velocity and acceleration and give only depth-averaged values. As a consequence, 2D models often do not perform well in predicting velocity fields around submerged boulders and other obstructions where near-bed flow structures can include reverse, upward and downward velocities (Shen and Diplas, 2008). For the shallow streamflows modelled at the study sites, the assumed vertical velocity profile is probably not valid, nor do the point measurements of average velocity accurately capture the variability in flow structures. Thus, both the model formulation and measurement technique likely contributed to the large observed errors in velocity predictions. Finally, model discretization error originates from the way the channel topography is represented in the model and is influenced by both field measurements (e.g. topographic mapping) and specification of the model grid (e.g. node spacing).

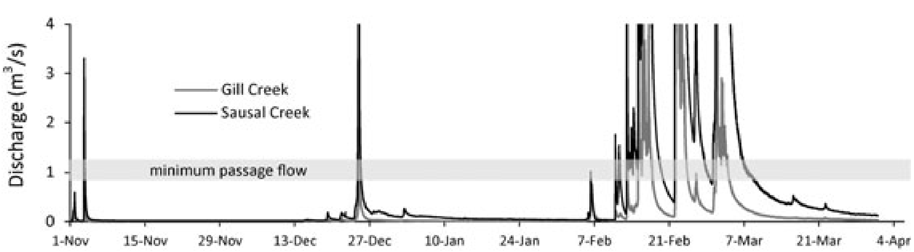

Figure 10. Winter hydrograph (1 November 2008 to 31 March 2009) of Gill Creek and Sausal Creek. Shaded bar indicates the range of flow requirements for fish passage at the three study sites, based on the 2D model-derived estimates of passage flow connectivity

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Table IV. Passage flow frequency and duration statistics for measured 2009 discharge and modelled long-term discharge (1961–1981)

Site	Passage flow criteria ($m^3 \cdot s^{-1}$)	Frequency (no. of spells)[a,b]	Mean duration (days)	SD duration (days)	Min. duration (h)[c]	Max. duration (days)	Total Duration (days)
Gill Canyon	1.3	5 (5.4)	1.2 (19.6)	1.1 (13.3)	0.7 (0)	2.2 (43)	6.2
Sausal Canyon	1.1	6 (5.9)	3.1 (31.8)	3.1 (21.6)	3.5 (0)	6.1 (80)	18.9
Sausal Alluvial	0.9	7 (5.9)	3.2 (45.0)	5.2 (24.8)	1.8 (0)	13.7 (101)	22.5

[a]Statistics based on 10-min flow data from 2009 and simulated mean daily flow for 20-year record (1961–1981), shown in parentheses.
[b]Spells are defined as instantaneous flow exceeding the minimum passage flow criterion, separated from by at least 12 h for 2009 records or 1 day for long-term records.
[c]In 1977, the minimum passage flow was not exceeded.

Although the measurement and model formulation error can be minimized through proper field techniques and appropriate model selection/specification, respectively, the accuracy and resolution of channel topography surveys, in practice, is generally the most important constraint to 2D model performance (Pasternack *et al.*, 2006; Legleiter *et al.*, 2011). In this study, a terrestrial LiDAR scanner was used to collect topographic data at densities of ≥ 20 points per square metre, which is substantially greater than minimum point densities commonly used to characterize alluvial (Brasington *et al.*, 2000; Pasternack *et al.*, 2006) and confined river channels (Valle and Pasternack, 2006). Thus, the observed error in depth and velocity predictions likely would have been substantially greater had a lower density of survey points been used to represent stream channel topography. Nevertheless, even with node spacing of 0.2 m, subgrid scale topographic features probably contributed to observed differences between spatially averaged depth predictions at the node-scale and local point measurements. Terrestrial LiDAR surveys of stream channels are limited by the inability to penetrate water and are not suited for surveying areas with dense riparian vegetation. However, laser scanning may be superior to traditional methods (e.g. total station) for surveying intermittently flowing streams that can be mapped in the dry season when the entire channel is exposed.

Spatial and temporal variation in passage flow connectivity

The hydraulic modelling simulations indicated that the discharge required to provide a continuous path of suitable passage depths was 1.30 $m^3 \cdot s^{-1}$ in the Gill Canyon reach, 0.90 $m^3 \cdot s^{-1}$ in Sausal Canyon and 1.10 $m^3 \cdot s^{-1}$ in Sausal Alluvial. Below these discharges, shallow water encountered along the migration path has the potential to restrict upstream movement of adult steelhead. Estimates of passage flow connectivity were fairly sensitive to uncertainty in depth predictions. However, simulated depths within the range of error obtained in direct measurement (or estimation based on measurement) and overall error in the 2D modelling approach is probably typical of field-based methods for fish passage assessments. Although the sensitivity analysis performed in this study assumed a spatially uniform error field for all nodes, spatial stochastic simulations of depth prediction errors could provide a more robust approach for quantifying model uncertainty (e.g. Legleiter *et al.*, 2011) and lead to an improved understanding of the influence of model prediction error on passage flow connectivity metrics.

The site-specific estimates of passage flow connectivity thresholds were dependent on unique channel properties of each site, yet differences between the confined and alluvial reaches did not follow expected patterns. Confined, canyon reaches have narrower channels and thus tend to have relatively deeper flow depths than the broader, alluvial channels at the same discharge. However, the Sausal Canyon reach required higher discharge than Sausal Alluvial to maintain passage flow connectivity. This could be because the Sausal Alluvial reach has been modified to some extent by bank stabilization structures, resulting in channel incision and a more restricted cross-section profile than is typical for a gravel-dominated, gently sloped reach. In addition to the

Table V. Comparison of passage flow assessment methods

	Gill Canyon		Sausal Canyon		Sausal Alluvial	
Method	Min. passage flow ($m^3 \cdot s^{-1}$)	% Connectivity[b]	Min. passage flow ($m^3 \cdot s^{-1}$)	% Connectivity[b]	Min. passage flow ($m^3 \cdot s^{-1}$)	% Connectivity[b]
$Q_{connectivity}$[a]	1.30	100	1.10	100	0.90	100
$Q_{riffle\ crest}$	0.75	90	0.25	75	0.50	91
$Q_{regional}$	1.24	99	1.77	100	1.76	100

[a]Passage flow connectivity estimate from predicted migration path through modelled reach.
[b]Per cent of cells along predicted migration path that meet or exceed 0.25-m depth.

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spatial configuration of flow connectivity, the results highlight the importance of temporal flow variability for assessing fish passage flows. Based on the calculated passage requirements for each reach, passage flows occurred fewer than seven times at all sites during the 2009 winter season. Furthermore, the long-term hydrographs modelled for each site indicate that the total duration of passage flows ranges from 13 to 25 days in most years. Because passage flow connectivity occur with relatively low frequency and duration, standards to protect passage flows through the regulation of upstream water users appear warranted. The large variation in passage flow days also suggests that flexibility should be incorporated in environmental flow regulations. The ecological consequences of temporarily impairing passage are likely to be more significant in years with few passage flow days than in years with many opportunities for fish passage, so regulations should be more restrictive in dry than in wet years. It also is important to consider that the more protective regulations are of passage flows, the less frequently flows will exceed the minimum threshold, thus providing fewer opportunities for water users to abstract and store water in the winter. Therefore, the potential threats to human water security must be considered when formulating policy thresholds that determine when water users are entitled to divert flows from streams (Grantham *et al.*, 2010). Regardless of the specific flow criteria selected, consideration of the seasonal and interannual dynamics of passage connectivity will be critical to developing effective flow management strategies in small streams (Stalnaker *et al.*, 1996; Fullerton *et al.*, 2010).

Comparison to alternative passage flow assessment methods

Although the regional approach for defining passage flow needs yielded comparable or higher flow values than indicated by the hydraulic model simulations, the method was not sensitive to changes in channel morphology that occur over relatively short river lengths. For example, predictions for minimum passage flows by the regional method were similar for Sausal Canyon and Sausal Alluvial, which have similar drainage areas despite their distinct differences in channel width, slope and sediment sizes (Table 1; Figure 2). This is because the minimum passage flow derived from the regional equation is based only on drainage area and mean annual flow. Although the simplicity of the regional approach makes it an attractive tool for management and decision making, potential improvements to the formula could be made by incorporating a variable that accounts for changes in channel morphology associated with geologic transitions (e.g. bedrock-dominated confined to gravel-dominated alluvial reaches) or anthropogenic influences (e.g. channel stabilization and incision). In comparison to the hydraulic modelling method, the riffle-crest approach consistently underestimated minimum flow requirements because shallow-water barriers persisted within riffles, even when minimum passage depths were exceeded at riffle crests. Although a comprehensive investigation of stage-discharge relationships at riffle crests would typically use more channel transects (e.g. 15–20) than evaluated in this study, the results suggest that the riffle-crest approach may be insufficient for assessing local passage flow requirements in streams. However, field-based assessments of passage flows based on channel transects could be improved by focusing on shallow-water areas within riffles, in addition to riffle crests.

Uncertainty in the relationships between river flows and biological responses is a persistent challenge that must be dealt with in all ecological flow assessments (Castleberry *et al.*, 1996; Railsback, 1999; Poff and Zimmerman, 2010). In this study, fish passage is assumed to be constrained by segments of shallow water along the migration path. This is clearly a simplification of fish behaviour because adult salmon have been observed working their way upstream over shallow riffles with a significant proportion of their bodies exposed above the water surface (Carlson and Quinn, 2007). Thus, the hydraulic factors that influence the probability of fish passage relates not only to the local depths but also to the lengths of shallow water flow that occur within the stream channel. Furthermore, the body size and swimming ability of an individual fish will also be important for determining the likelihood of successful passage. Linking calibrated hydraulic model predictions with detailed observations of fish passage behaviour would be highly informative for quantifying how flow depths, velocities and spatial configurations of shallow-water habitats interact to influence fish passage success. Nevertheless, the spatially explicit characterization of stream hydraulic habitats is a critical first step to establishing mechanistic ecological-flow relationships (Souchon *et al.*, 2008).

CONCLUSIONS

The maintenance of hydrologic connectivity is an important principle for managing salmon populations and restoring riverine ecosystem integrity, yet in practice, connectivity in river networks has been a challenging property to measure and directly apply in conservation planning (Fullerton *et al.*, 2010; Hermoso *et al.*, 2011). The hydraulic modelling approach presented here yields a quantitative metric of hydrologic connectivity and accounts for the temporal and spatial connectivity of fish passage flows. Recognizing the uncertainties and limitations associated with all environmental flow assessment methods, 2D models appear well suited for simulating flows in support of fish passage investigations. Although the effort required to initialize and calibrate flow simulations places practical constraints on the spatial extent to which the approach can be applied, high-resolution 2D hydraulic modelling offers a promising means

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for relating ecological processes to hydrologic controls in rivers. The spatially explicit simulation of flow depths and velocities produced by hydraulic modelling also make 2D models a useful management tool for visualizing and communicating the relationships between flow regimes, stream hydraulics and habitat suitability. Finally, the 2D hydraulic modelling approach may be particularly valuable for testing the assumptions behind alternative environmental-flow assessment methods and for evaluating habitat-flow relationships in stream reaches of particular importance, such as critical habitat for threatened species or sites subject to potential alterations from water projects.

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