Case Study

Simulation Modeling to Secure Environmental Flows in a Diversion Modified Flow Regime

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Abstract: This paper describes the development and application of a spreadsheet model to evaluate effects of water management on diversion modified flow regimes, enabling the exploration of novel ways to meet proposed environmental flow standards. Mill Creek, a northern California river with an altered flow regime that impacts aquatic species, was used as a case study. Test cases examined how water management alternatives, such as groundwater pumping, water rights transfers, and water exchange agreements, can improve environmental flow allocations given irrigation water demands. Four test cases include passage flows for Chinook salmon and steelhead trout, a minimum instream flow, 80% of natural flow, and a spring recession flow with functional flow components. The model identified late October as consistently water-scarce, even in wet years. These analyses suggest that fall shortages for fish migration could be eliminated through a water exchange agreement combined with use of wells. All cases except the minimum fish passage flow case required acquisition of the largest water rights to decrease environmental shortages by over 80%, with a substantial curtailment in irrigation. **DOI: 10.1061/(ASCE)WR.1943-5452.0000694.**

Introduction

Rivers carry only 0.0002% of water globally (Shiklomanov 1993), but support 6% of the world's species (Dudgeon et al. 2006). Biologically functioning freshwater ecosystems provide goods and services for people, such as food production, disposal of industrial and human wastes, and flood control, as well as adaptive capacity for future conditions with climate and other changes (Baron et al. 2002). The transformation of rivers by human structures such as dams, diversions, and flood-control infrastructure has dramatically affected ecosystems and the critical services they provide (Arthington 2012; Dudgeon 2010). As a result, freshwater ecosystems are among the most endangered ecosystems in the world (Sala et al. 2000), and accelerating degradation of freshwater ecosystems (Dudgeon et al. 2006) threatens both human water security and river biodiversity globally (Vorosmarty et al. 2010). There is a need for water management to sustain processes that support freshwater ecosystems.

The ecological integrity of rivers depends on the natural dynamic character of streamflow captured by characteristics of flow patterns: magnitude, frequency, duration, timing, and rates of change. Streamflow is often identified as controlling physical and ecological processes in rivers (Poff et al. 1997), making stream regulation important for environmental management. For example, high-magnitude flows, through sediment erosion and deposition, initiate succession in riparian forests (Rood et al. 2005). Reproductive success of riverine species, such as the foothill yellow-legged frog (*Rana boylii*), depend on the timing and rate of change of the spring snowmelt recession of Mediterranean-montane streams (Yarnell et al. 2010). Altered flow regimes affect aquatic biodiversity in streams and rivers (Bunn and Arthington 2002) and human well-being (Naiman and Dudgeon 2011). Even small, widely distributed reservoirs affect river flow (Deitch et al. 2013) and sediment transport. For freshwater conservation to be viable in the long term, water managers must identify and allocate environmental flows, reconciling human livelihoods, biodiversity conservation, and ecosystem function (Nel et al. 2009).

Environmental flows, characterized by quantity, timing, and quality of water in rivers, are required to sustain freshwater and estuarine ecosystems (Brisbane Declaration 2007). Several approaches to developing environmental flow requirements exist from basic minimum instream flows, to statistical Tennant Methods, ecological limits of hydrologic alteration (ELOHA), percent change from natural flow or a sustainability boundary approach (SBA), and hydraulic modeling approaches (Tharme 2003). One approach to environmental flows is to limit alterations to a natural flow regime or to design flow regimes for specific ecological functions in regulated rivers (Acreman et al. 2014).

Growing water demands, global climate warming, and hydrologic alterations (Vorosmarty et al. 2010) have exacerbated the uncertainty of water availability and conflicts among water users. California's recent major drought (Swain et al. 2014) is forcing difficult decisions on water allocation, such as mandatory reduction of diversions from rivers to provide minimum flows for state-listed and federally-listed anadromous fish (CA State Water Resources Control Board 2015). Decreasing water supply reliability coupled with competing water demands is only increasing the need for tools that enable people to better organize and make management decisions.

While some studies focus on water abstraction restrictions (Acreman et al. 2008) and the effect of small-scale spatially

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distributed water reservoirs (Deitch et al. 2013), many environmental flow studies focus on reservoir reoperation of large centralized water management systems (Jager 2014; Richter and Thomas 2007; Shiau and Wu 2013; Yin et al. 2011). A successful example of reservoir releases for environmental objectives is on Putah Creek and Putah Diversion Dam (Solano County, California) where flow releases that mimicked spring flow pulses increased the proportion of native fish species in reaches previously dominated by alien fish species (Kiernan et al. 2012). However, rivers lacking reservoir storage still face disrupted flow patterns. In these rivers, other management options must be used to meet environmental flow targets, yet few scientific studies focus on these systems. Recent studies have demonstrated the use of nonproportional redistribution rules as well as riparian benefit economic models to generate variable environmental flow releases in rivers with run-of-the-mill hydropower, improving on the standard minimum flow release approach (Gorla and Perona 2013; Perona et al. 2013; Razurel et al. 2016). This research addresses water scarcity in diversion-impacted rivers through the development and application of a decision-support tool for integrated water resources management (IWRM) planning to explore water management alternatives to balance agricultural water supply needs with support of freshwater ecosystems through a range of natural flows.

The model developed in this study explores the following questions:

- Given specific environmental flow objectives, represented as a design hydrograph, when is water insufficient to meet environmental flow needs?
- What are the effects of different water management alternatives on instream environmental flow? and
- How do water management alternatives perform in different water year types?

Water transactions are an emerging management tool for acquiring water for the environment, but there is a need to know when and how much water needs to be transferred to support environmental flows. The first question aims to quantify the timing and quantities of environmental flow needs. A combination of management options such as groundwater pumping, water exchanges, or water transfers will probably be needed to acquire sufficient environmental water, so it is useful to explore how these options may reduce environmental flow shortages. Preferred alternatives for meeting environmental flow targets may change between wet and dry years. For this reason, this study also explores the effect of different water management alternatives during different water year types, defined by the Sacramento Valley Index. As a river system impacted by agricultural diversions that also provides habitat for threatened species of Pacific salmon, Mill Creek, in Tehama County, California is an insightful case study for such an environmental water management planning model.

Study Area

Mill Creek, in Tehama County, California, runs approximately 95 km from the peak of Mount Lassen to the Sacramento River, draining 342 km^2 of watershed (Fig. 1). Due in part to its rugged terrain, the river's middle and upper reaches (>200 m elevation) have remained largely undeveloped. Unlike many other tributaries to the Sacramento River, Mill Creek still supports native fish assemblages and remains largely unimpounded. This enables passage for anadromous fish to headwater stream habitat, making Mill Creek one of three remaining strongholds for two endangered fish, spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*) (California Department of Fish and Wildlife 2015; Moyle 2002; Moyle and Randall 1996; Palmer 2012).

As a Mediterranean-montane river system, the natural flow regime of Mill Creek is characterized by summer low flows, precipitation in winter months with spring snowmelt pulses (Yarnell et al. 2010) (Fig. 2). In the lower gradient reach, prior to flowing through the unincorporated town of Los Molinos and reaching its confluence with the Sacramento River, Mill Creek is subject to two diversions for agricultural users in Los Molinos during the irrigation season, April 1 to October 31. Two stream gauges are located in the lower Mill Creek reach—an upstream gauge [U.S. GS 11382500, hereafter referred to with California Data Exchange Center (CDEC) code MLM standing for Mill at Los Molinos] and a downstream gauge (DWR A004420, hereafter referred to with CDEC code MCH for Mill Creek at Highway 99). Two diversions, Upper Diversion Dam and Ward Dam, support 11 water rights holders in the system, and are operated by the Los Molinos Mutual Water Company with a combined diversion capacity of 4.2 m^3/s (150 ft^3/s). Two of the water rights are held by The Nature Conservancy (TNC), which manages water to support the riverine ecosystem. Water rights on Mill Creek were fully adjudicated by the state in the 1920s (Superior Court of Tehama County 1920), with flows up to 5.7 m^3/s (203 ft^3/s) allocated to water users, which represents most, if not all, summer base flow in Mill Creek and this often leads to dewatering the river downstream of Ward Dam. Recently, in an effort to restore summer in-stream flows for fish migration, an Interagency Water Exchange Agreement was created to exchange groundwater pumping for irrigation in return for decreases in surface water diversions during fish migration seasons (Heiman and Knecht 2010).

Flow regime alterations in this river call for innovative solutions to provide environmental flows and the development of tools to quantitatively evaluate management options, which may more broadly support water management of diversion modified flow regimes.

Methods

Stream Gauge Analysis

Flow exceedance probabilities were computed with available data for the period of record for the two stream gauges. This period of record is restricted by the downstream MCH stream gauge which only has data available for water years (WY) 1999 through 2013.

Model Formulation

A linear programming model of Mill Creek was developed to simulate and evaluate water management alternatives with respect to proposed environmental flow standards. The model focuses on the lower Mill Creek reach, which has multiple diversions and evolving environmental flow requirements. The model operates on a weekly time step. Outflow, O_t, at the downstream end of the river reach, is calculated as

$$O_t = I_t - \sum_{i}^{n} A_{i,t} \tag{1}$$

where I_t = total inflow from upstream (at MLM gage); $A_{i,t}$ = water use of water user i with diversion demands that change with time, t; and n = total number of water diverters (Fig. 3). Diverted water is transported through canals to agricultural users located mostly outside the Mill Creek watershed, so no flows return to Mill Creek. The model also assumes negligible stream accretion due to the

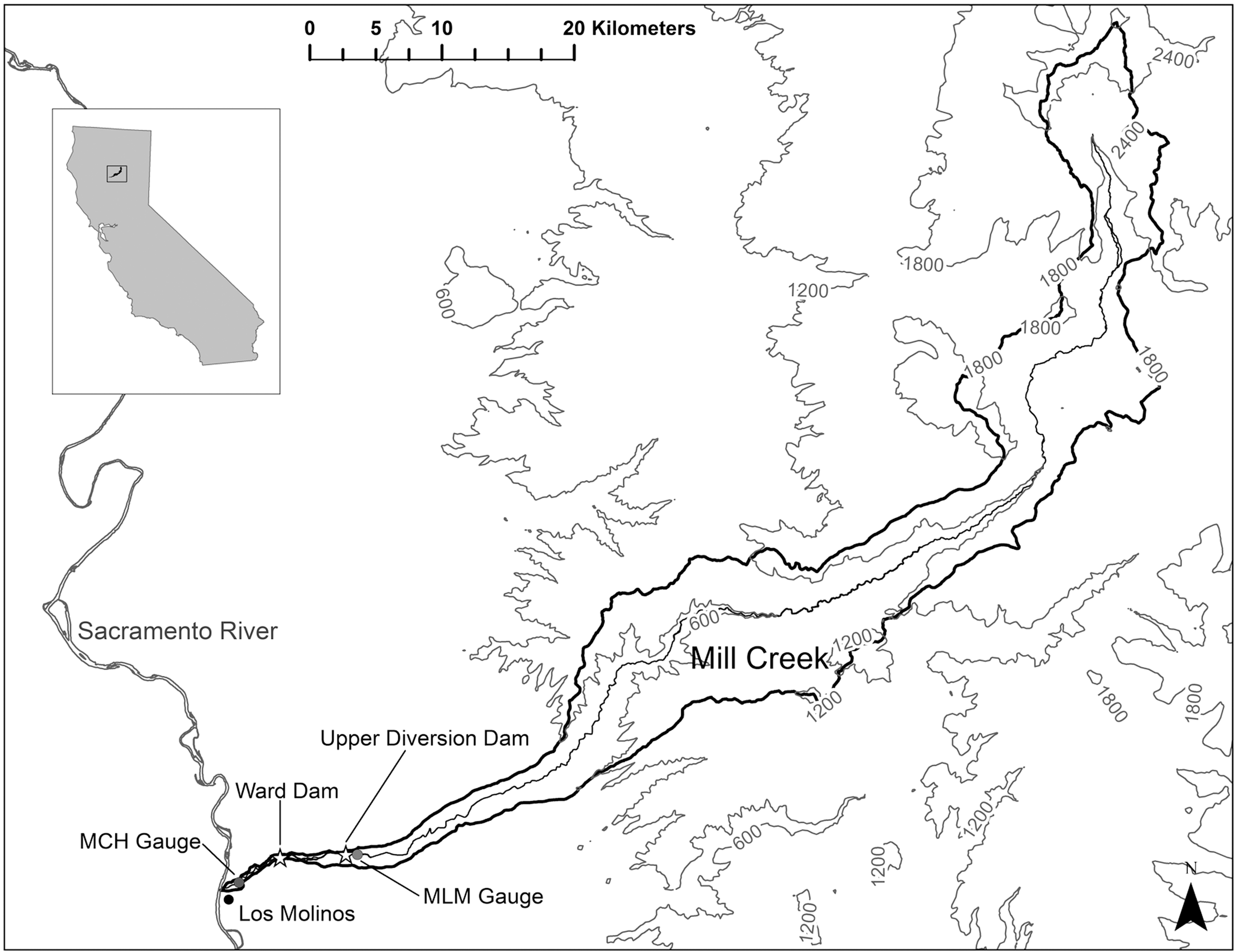

Fig. 1. Map of Mill Creek watershed in Tehama County, California (elevation contours in meters)

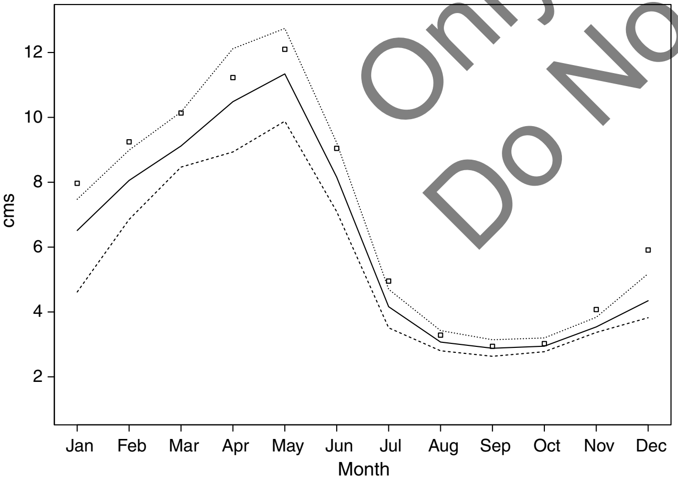

Fig. 2. Mill Creek monthly median (solid line) discharges at MLM gauge with 95% confidence intervals (upper limit = dots; lower limit = dash) and monthly mean discharges (square)

short distance between gauge stations. Environmental flow allocations, $A_{E,t}$, are represented as a water user with flow demands downstream of all diversions, and are not included in the water balance equation [Eq. (1)] because environmental flow allocations remain in the river and are a component of the outflow, O_t. In this model, environmental flow allocations, $A_{E,t}$, are less than or equal to outflow, O_t, which is reasonable for a river system such as Mill Creek, where water diversions often bring river flow below environmental targets.

For the model to allocate water to high-priority water users first, each user (including the environmental flow) is assigned a shortage penalty rate, P. Each user has a time-dependent water demand, $D_{i,t}$. Environmental flow demand, $D_{E,t}$, is set by a design hydrograph developed for meeting environmental flow targets. Decision variables, or the output of the linear programming model, are allocations to all water users, both human ($A_{i,t}$) and environmental ($A_{E,t}$), based on an objective function that minimizes the sum of the penalty-weighted shortages, as follows:

Minimize

$$Z = \sum_{i}^{n} P_{i,t}(D_{i,t} - A_{i,t}) + \sum P_{E,t}(D_{E,t} - A_{E,t}) \qquad (2)$$

Subject to

- No negative diversions

$$A_{i,t} \geq 0, \quad \forall\ i, t \qquad (3)$$

- No negative environmental flow allocations

$$A_{E,t} \geq 0, \quad \forall\ t \qquad (4)$$

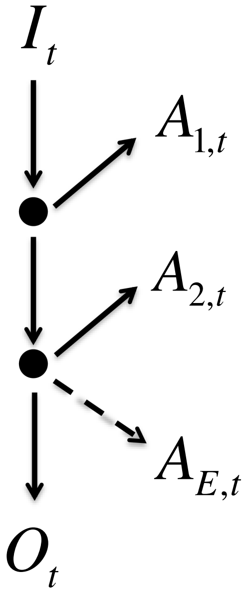

Fig. 3. Model schematic

- Environmental allocations cannot exceed demand

$$A_{E,t} \leq D_{E,t}, \quad \forall\ t \tag{5}$$

- Diversions cannot exceed water demand

$$A_{i,t} \leq D_{i,t}, \quad \forall\ i, t \tag{6}$$

- No negative outflow

$$O_t \geq 0, \quad \forall\ t \tag{7}$$

- Inflow must be greater than or equal to sum of allocations

$$I_t \geq \sum_{i}^{n} A_{i,t} + A_{E,t}, \quad \forall\ i, t \tag{8}$$

The linear programming model was implemented in Microsoft *Excel 2010* with the *OpenSolver 2.6* add-in (Mason 2012). The model inputs required are upstream inflow discharge, downstream outflow discharge, water diversion demands in the system, and a hydrograph representing the environmental flow target of interest. Modeled decisions that can vary to represent different water management alternatives include the irrigation periods for each water right holder, the option to purchase and leave instream individual water rights, and the number, pumping capacity, and use of conjunctive-use wells.

Model Testing

A 1920 Tehama County Superior Court decree designated a table that defines water rights for all water users in the system based on the amount of water in Mill Creek from 5.75 $\mathrm{m^3/s}$ and below (Superior Court of Tehama County 1920). The model uses these water right values for each user and assumes that these amounts will be diverted from the river to simulate river flow for three representative water year types defined by the Sacramento Valley Water Year Index (California Department of Water Resources 2013). Although not all water users will divert all of their water rights, this conservative approach can help guarantee instream environmental flow. Values of the penalty shortage rate, $P_{i,t}$ and $P_{E,t}$, in Eq. (2), were given integer values from 1 through 3 to reflect three water right priorities in Mill Creek. A higher-penalty shortage rate was assigned to higher-priority water rights in order to decrease the shortages to these users in the objective function. Two senior water rights holders were assigned penalty shortage rates of $P_{i,t} = 3$, with the remaining water rights holders assigned $P_{i,t} = 2$. Environmental water use was assigned the lowest penalty shortage rate of $P_{E,t} = 1$ to indicate the lowest priority, which is reasonable for exploring water management options that reduce shortages to environmental flows with the assumption that human water demands are met before environmental flows.

Model evaluation was done by comparing simulated outflows with observed discharge at the downstream MCH gauge through the calculation of Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of root-mean square error to standard deviation of measured data (RSR) as recommended by Moriasi et al. (2007). NSE were computed with the following equation (Moriasi et al. 2007):

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})^2}{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}})^2}\right] \tag{9}$$

where Y_i^{obs} = ith observation of discharge at the MCH gauge; Y_i^{sim} = ith simulated value; Y^{mean} = mean value of observed discharge; and n = total number of observations. A NSE value of 1 indicates a perfect match between modeled and observed discharge. PBIAS was calculated with Eq. (10)

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})(100)}{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}})}\right] \tag{10}$$

Low values of PBIAS indicate model simulation accuracy, with the optimal value equal to zero. RSR was calculated with Eq. (11)

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})^2}}{\sqrt{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}})^2}} \tag{11}$$

Better model performance is indicated by lower RSR values.

Proposed Environmental Flow Targets

Four environmental flow cases were run in the model:

1. Target fish passage flows [Fig. 4(a)] were based on 2014 Volunteer Drought Agreements (Howard 2014) between the National Marine Fisheries Service, the California Department of Fish and Game, and water rights holders to provide minimum flows below Ward Dam (Table 1). Pulse flows mimic natural increases in flow from spring precipitation and snowmelt. The corresponding water volume needed for each 24-h pulse flow was added to the environmental demand in the model's weekly time-step, with the understanding that weekly water allocations would need to be managed to create the daily pulse flows.
2. A second environmental flow case [Fig. 4(a)] was based on preliminary recommendations from the Central Valley Freshwater Needs Assessment conducted by The Nature Conservancy that analyzed data from the upstream Mill Creek MLM gauge using the *Indicators of Hydrologic Alteration* (*IHA*) software (Richter et al. 1996). This study suggests a minimum instream flow (MIF) of 2.55 $\mathrm{m^3/s}$ to match unaltered minimum baseflows to provide conditions that could support a suite of freshwater focal species such as cottonwood (*Populus sp.*), freshwater mussels (*Margaritifera falcata*), western pond turtle (*Actinemys marmorata*), and bank swallow (*Riparia riparia*), as well as Chinook salmon and steelhead and resident native fish.

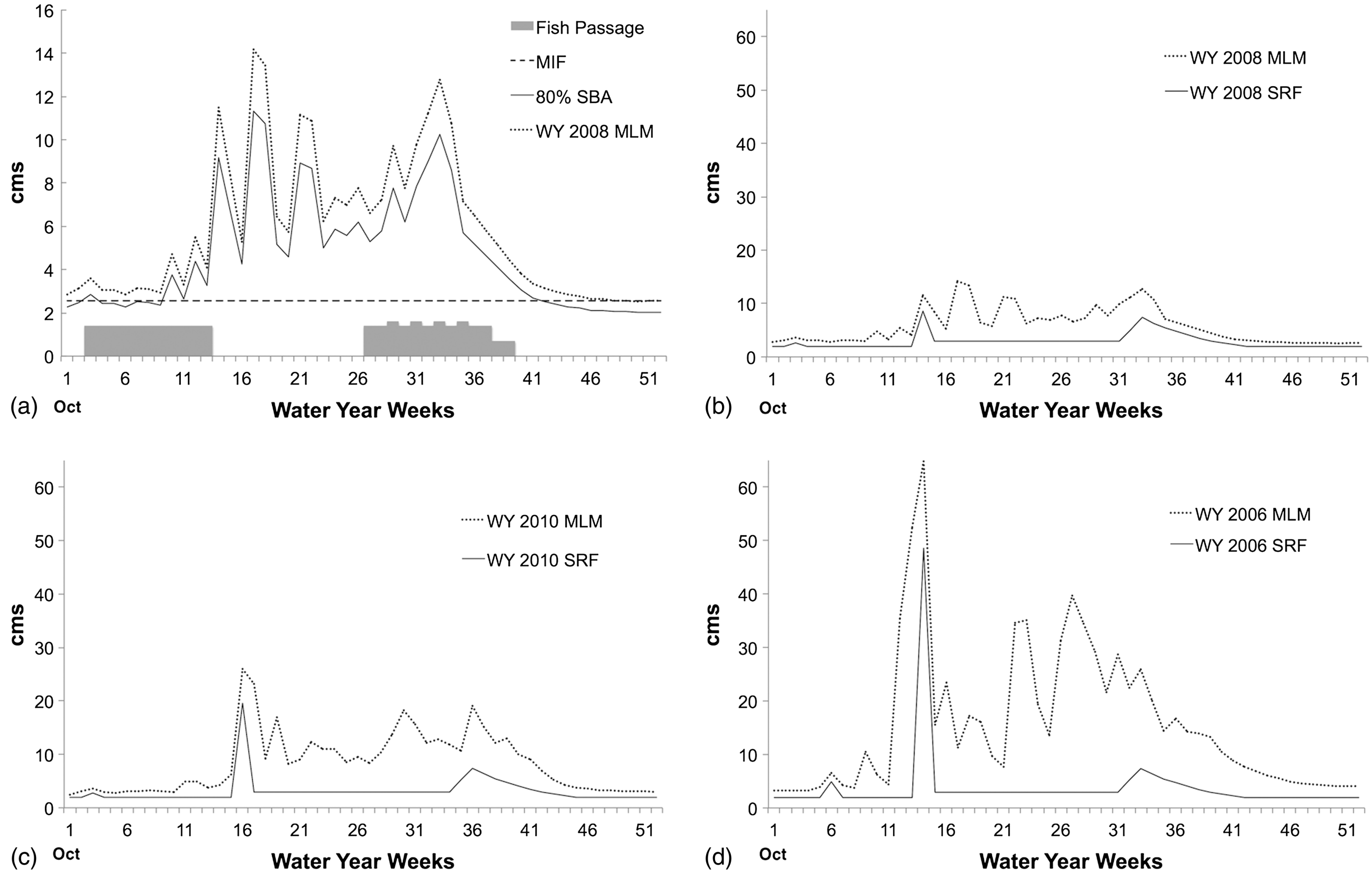

Fig. 4. Environmental flow cases: (a) fish passage flows, 2.55 m^3/s MIF, 80% SBA for WY 2008; (b) SRF for critically dry WY 2008; (c) SRF for below normal WY 2010; (d) SRF for wet WY 2006

Table 1. Fish Passage Flow Targets for Spring-Run Chinook Salmon (SRCS) and Steelhead Trout

Feature	April 1–June 14 (base flow)	April 15–June 14 (pulse flow)	June 15–30 (base flow)	October 15–December 31 (base flow)
Flow	1.42 cms	1.42 cms + base; 24 h, biweekly	0.71 cms	1.42 cms
Fish type	Adult and juvenile SRCS and steelhead	Attract adult SRCS	Juvenile SRCS & steelhead	Out-migrating juvenile SRCS & steelhead, up-migrating adult steelhead

3. A third environmental flow case [Fig. 4(a)] was based on the concept of a sustainability boundary approach (SBA) that defines the extent of hydrologic alteration in the system that is likely to maintain aquatic ecosystem function (Postel and Richter 2003). Here, 80% of full natural flow was proposed as a representation of a sustainability boundary environmental flow target for exploratory purposes.
4. A fourth environmental flow, a spring recession flow (SRF) case, incorporates functional flow components such as a wet-season initiation flow, peak flow, spring recession flow, and dry-season baseflow (Yarnell et al. 2015). Wet-season initiation and peak flow magnitudes are 75% of observed flow for representative water year types [Figs. 4(b–d)]. Spring recession periods are 10 weeks long (decay constant $k = 0.15$). The following representative water year types were selected for model runs: critically dry (2008), below normal (2010), and wet (2006).

Description of Water Management Alternatives

Each environmental flow case was run with a range of water management alternatives (Table 2). The *baseline* option leaves water rights owned by TNC instream year round. The second option, called *4 wells*, expands groundwater use for irrigation to allow stream water to remain instream for environmental flow. Two wells are available with a combined capacity of 0.28 m^3/s. Potential new wells were modeled with individual capacities of 0.14 m^3/s. A third option, called *Agreement*, is a water exchange between TNC and LMMWC, where TNC water rights are available for diversion between July 1 and October 14. In return, LMMWC leaves 0.68 m^3/s (24 ft^3/s) instream after October 15 for 3 weeks to supplement fall fish passage flows.

A fourth option, called *Water Rights A&B*, is to purchase water rights from individual users to leave instream. Of the 11 water right holders in the system, Water Rights A and B have been considered for potential transfers in the model. Water Right C holds the largest water right in the watershed (68% of total water diversion) and was selected as a water transfer option in the simulation called *Water Right C* to quantify its effect on meeting the MIF, SBA, and SRF cases, environmental flow cases that require much more water than the fish passage flow case. Finally, a fifth option is a combination of groundwater wells and water exchange agreements, called

Table 2. Water Management Options Used in Model Runs

Option	Description
Baseline	Irrigation period for all water users: April 1–October 31 TNC water rights left instream year round
4 wells	Four groundwater wells each with a pumping capacity of 0.14 cms (5 cfs)
Agreement	Water exchange agreement: TNC water rights diverted: July 1–October 14, left instream otherwise supplemental instream flows of 24 cfs for 3 weeks (October 15–early November)
Water rights A, B, C	Purchase of Water Rights A, B, or C to leave instream
4 wells & agreement	Combination of 4 wells and water exchange agreement

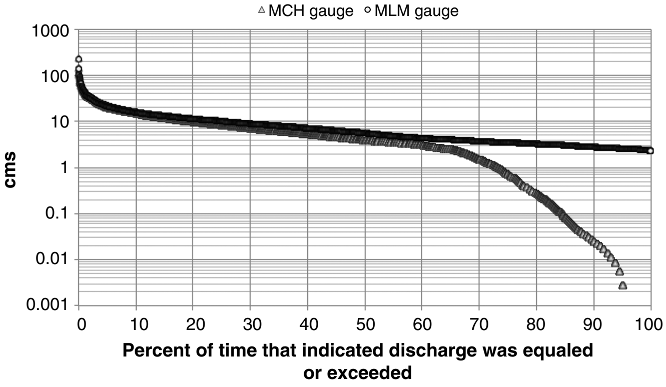

Fig. 5. Flow exceedance probabilities for downstream (MCH) and upstream (MLM) gauges for WYs 1999–2013

4 Wells & Agreement. Likelihood of implementation of these management options depends on relationships among stakeholders in Mill Creek. Since groundwater use in place of surface water already exists and past water exchange agreements have been successfully negotiated, these options are most likely to be implemented or expanded. Purchase of water rights, on the other hand, are hypothetical and require substantial financial investment and trade-offs, so their likelihood of implementation depends on strong stakeholder support.

Each environmental flow case and water management alternative were run with representative water year types based on the Sacramento Valley Index (California Department of Water Resources 2013). The environmental water user was assigned the lowest priority to ensure that agricultural water users are allocated water first.

Results

Water inflow and outflow values in lower Mill Creek were taken from the MLM and MCH stream gauges, respectively. There is a 38–70 million cubic meters (mcm) (31,000–57,000 acre-ft) annual difference in water volume between the upstream and downstream gauges. The impact of diversions is illustrated by the increased frequency of low flow discharges on the downstream MCH gauge (Fig. 5).

The model identified periods of water scarcity, quantified shortages to environmental flow cases, and explored the effects of management alternatives on environmental flows. The modeled water flows were very close to observed values [Critically Dry (2008), NSE = 0.92, PBIAS = 1.05, RSR = 0.29; Below Normal (2010), NSE = 0.87, PBIAS = 11.57, RSR = 0.36; Wet (2006), NSE = 0.98, PBIAS = 6.52, RSR = 0.14].

Fish Passage Case

Under baseline conditions, model results indicate insufficient flow (shortages) for upstream migration passage from October 15 through the first week of November (WY weeks 3–5). Shortages also exist in the spring from mid-to-late June (WY weeks 36–39). Over the critically dry water year 2008, flow shortage for safe fish passage was 3.0 mcm, roughly 2,400 acre-ft (af), over two periods: 2.1 mcm (1,700 af) in fall and 0.9 mcm (700 af) in spring [Fig. 6(a)].

Climate conditions affect the severity of shortages. The predicted annual environmental shortage drops from 3.0 mcm (2,400 af) in critically dry years [Fig. 6(a)] to 2.1 mcm (1,700 af) in below-normal years [Fig. 6(b)] and 2.0 mcm (1,600 af) in wet years [Fig. 6(c)]. The shortage in fall was similar in critically dry and below-normal years (WY weeks 3–5), and fell to 1.7 mcm (1,400 af) for the wet year. The spring shortages (weeks 36–39) in critically dry years are not present in below-normal and wet years.

For meeting fish passage flows (Table 1), transfer of Water Rights A and B were least effective at reducing annual environmental shortage for all water year types (16–31%, Table 3). In contrast, the four conjunctive-use wells reduced environmental shortage by 50–61%, while the water exchange agreement reduced shortage by 41–62% from baseline. Moreover, a combination of four wells and a water exchange agreement nearly eliminated environmental water shortage (94–100%), while still meeting human use demands.

Minimum Instream Flow Case

This environmental flow target, providing baseflows to support other freshwater species, requires more water than the fish passage case, so purchase of the largest water right (C) was included in management options. For critically dry water year 2008, under baseline conditions there is an annual shortage, relative to meeting the minimum flow target of 2.55 m^3/s, of 30.9 mcm (25,000 af) [Fig. 7(a)], and decreases to 20.9 mcm (16,900 af) for below-normal water year 2010 [Fig. 7(b)] and 18.7 mcm (15,200 af) for wet year 2006 [Fig. 7(c)]. Acquiring the largest water right gave the greatest reduction in shortage for all water years with a decrease of 86–99% from baseline (Table 3). The four wells decreased shortages by 26–28% and the well and agreement combined had a 19–24% reduction, with purchase of Water Rights A and B yielding the least reduction of 9–11%. The water exchange increases minimum instream flow (MIF) shortages by 3% for critically dry year, when TNC water rights are diverted for irrigation in the summer.

Sustainability Boundary Approach Case

For critically dry water year 2008, weeks 1 through 5 have a shortage of 6.7 mcm (5,400 af) and a shortage of 43.2 mcm (35,000 af) in weeks 27 through 52, for an annual shortage of 49.9 mcm (40,000 af) [Fig. 8(a)]. Below-normal water year 2010 experiences shortages during the same weeks with a smaller volume, 6.4 mcm (5,200 af) for the fall and 41.9 mcm (34,000 af) for the spring and summer for an annual shortage of 48.3 mcm (39,000 af) [Fig. 8(b)].

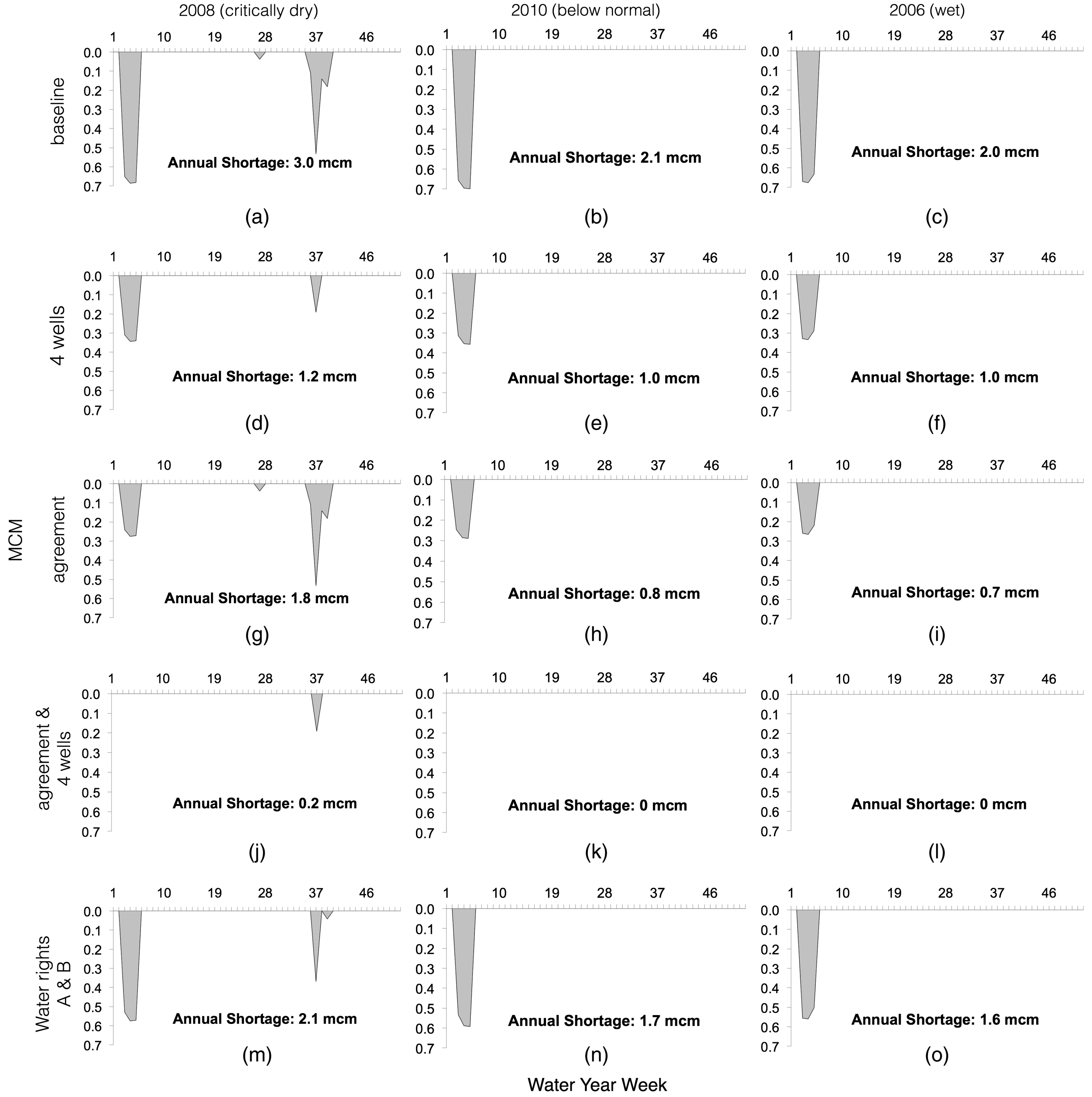

Fig. 6. Fish passage shortages for critically dry (2008), below-normal (2010), and wet (2006) WYTs for five management options: baseline, 4 wells, water agreement, water agreement and 4 wells, and leaving Water Rights A and B instream; *x*-axis is in WY weeks and *y*-axis is water shortages in mcm

Wet year 2006 has shortages during the same weeks 1 through 5 of 7.2 mcm (5,800 af) with spring shortages starting in week 30 through 52 of 35.1 mcm (28,000 af) for an annual shortage of about 42.4 mcm (34,000 af) [Fig. 8(c)].

Effects of different management options in the sustainability boundary approach (SBA) case were similar to the MIF case with little variation between water year types. For critically dry water year 2008, the Water Right C purchase decreases shortage by 97%, with a 21% reduction with the four wells, a 19% reduction with the well and water exchange combination, and an 8% decrease with the purchase of Rights A and B (Table 3). The exchange agreement increases environmental shortage by 2%.

Spring Recession Flow Case

Of the four functional components in this target flow, winter peak flow targets are met during the nonirrigation season for critically dry, below-normal, and wet water years [Figs. 9(a–c)]. Shortages to dry-season baseflows exist regardless of water year type, and the critically dry water year (2008) has shortages to wet-season

Table 3. Annual Environmental Flow Shortage in Million Cubic Meters (% Decrease)

Water year type	Option	Fish passage	2.55 cms MIF	80% SBA	SRF
Critically dry (2008)	Baseline	3.0	30.9	49.9	31.1
	4 wells	1.2 (61%)	22.3 (28%)	39.3 (21%)	21.9 (30%)
	Agreement	1.8 (41%)	31.9 (+3%)	39.3 (+2%)	32.1 (+3%)
	4 wells & agreement	0.2 (94%)	23.3 (24%)	40.4 (19%)	22.9 (26%)
	Water Rights A & B	2.1 (31%)	27.8 (10%)	45.9 (8%)	27.7 (11%)
	Water Right C	—	4.3 (86%)	1.7 (97%)	0.1 (99%)
Below normal (2010)	Baseline	2.1	20.9	48.3	16.4
	4 wells	1.0 (50%)	15.4 (26%)	37.7 (22%)	10.9 (33%)
	Agreement	0.8 (60%)	(6%) 22.1	50.2 (+4%)	17.8 (+8%)
	4 wells & agreement	0.0 (100%)	16.7 (20%)	39.6 (18%)	12.2 (26%)
	Water Rights A & B	1.7 (16%)	18.9 (9%)	43.9 (9%)	14.5 (12%)
	Water Right C	—	1.8 (92%)	1.1 (98%)	0.1 (99%)
Wet (2006)	Baseline	2.0	18.7	42.4	12.9
	4 wells	1.0 (52%)	13.5 (28%)	33.4 (21%)	7.9 (38%)
	Agreement	0.7 (62%)	20.6 (11%)	45.0 (+6%)	14.5 (+13%)
	4 wells & agreement	0.0 (100%)	15.2 (19%)	36.0 (15%)	9.4 (27%)
	Water Rights A & B	1.6 (18%)	16.6 (11%)	38.5 (9%)	10.8 (16%)
	Water Right C	—	0.2 (99%)	0.7 (98%)	0 (100%)

initiation flows and spring recession flows [Fig. 9(a)]. The situation is similar to the MIF and SBA cases in which acquisition of the largest water right is needed to most effectively address shortages [Figs. 9(p–r)].

Discussion

These model runs identify late October (WY weeks 3–5) as a critical period of water scarcity in lower Mill Creek, with insufficient natural flow for all agricultural irrigation and fish passage demands. Increased competition for water during this period challenges water managers to find solutions that ensure sufficient flows for up-migrating adult steelhead and out-migrating juvenile spring-run Chinook salmon and steelhead. Since fall shortages occur during the last few weeks of irrigation, potential solutions include deficit irrigation, offstream storage ponds filled during winter or spring, or foregoing one or more late-season irrigations, though feasibility is limited by nut crops in the region (Fereres and Soriano 2007). Results also indicate that a water exchange agreement coupled with four wells could decrease fish passage flow shortages by 94–100% (Table 3) with no curtailment to irrigation water deliveries. With this information, managers can develop and select water management options suitable for each water year condition, which is important given that the frequency of change is likely to increase throughout the region, increasing the likelihood of environmental flow targets going unmet (Null and Viers 2013). Furthermore, changing hydroclimatic conditions indicate more precipitation as rain and less as snow, which will increase winter flows, limit snowmelt runoff, and increase low-flow duration. This is likely to exacerbate environmental flow shortages during late summer, a period with consistent unmet environmental demands.

The MIF, SBA, and spring recession flow (SRF) cases show that the only water management alternative able to decrease the environmental flow shortages by more than 80% baseline is the entire purchase of the largest water right, which is 68% of all water rights in the system. Given the current water allocations in the system, substantial curtailment of irrigation would be needed to meet these environmental flow objectives.

Uncertainty can be due to inherent variability in a system (ontological) or due to imperfect knowledge of a system (epistemic) (van der Keur et al. 2008). From Mill Creek stream gauge records, the highest variability in natural flow is during wet winter and spring months (December through May) (Fig. 2). In contrast, summer and early fall low flow months show less variation in natural stream flow. These more regular months have greater water scarcity. Therefore, it is likely ontological uncertainty due to natural flow variability may not play a major role for water management. On the other hand, epistemic uncertainty is reflected in the nature of water control infrastructure on Mill Creek. The gates that control the flux of water diverted from the stream consists of boards lifted to allow flow of water. Unless flow meters are used in conjunction, precise diversions of specific discharges of river water will be challenging. Since the water management options considered rely on diversions or withholding of diversions, uncertainty in water flow measurement would likely affect alternatives similarly and not have a large impact on choice of alternative.

While model results identified critical water scarcity periods and the effects of potential water management options in this case study, some limitations are important to note. The model developed runs on a weekly time step, but many flow components are better resolved at daily or even hourly time steps, which would require more-detailed hydrodynamic modeling of flows. Water quality parameters such as temperature are critical in supporting freshwater fish. The survival of migrating fish depends on having not only sufficient water quantity to traverse riffles but also water with temperature ranges appropriate for their physiology. While instream flows affect stream temperature, this work focused primarily on water volume, and future work should address potential effects of water transfers on water quality for freshwater fish species (Willis et al. 2015). For a more-comprehensive approach to conservation in the region, habitat quality and suitability assessments are needed (Viers 2008). Additionally, future work on loss in agricultural revenue from water transfers can provide insights on the economic costs of environmental flows in diversion-impacted rivers and inform the design of incentive programs to compensate farmers. The alluvial nature of the lower Mill Creek will likely involve interaction of groundwater and surface water in the system. While groundwater surface water interactions are beyond the scope of this study, future research that characterizes spatial and temporal relationships between water in local aquifers with stream flow may suggest the feasibility of managed aquifer recharge during wet seasons to augment dry season base flows.

The general nature of this modeling approach allows the user to define the environmental flow target. In this case study, the authors

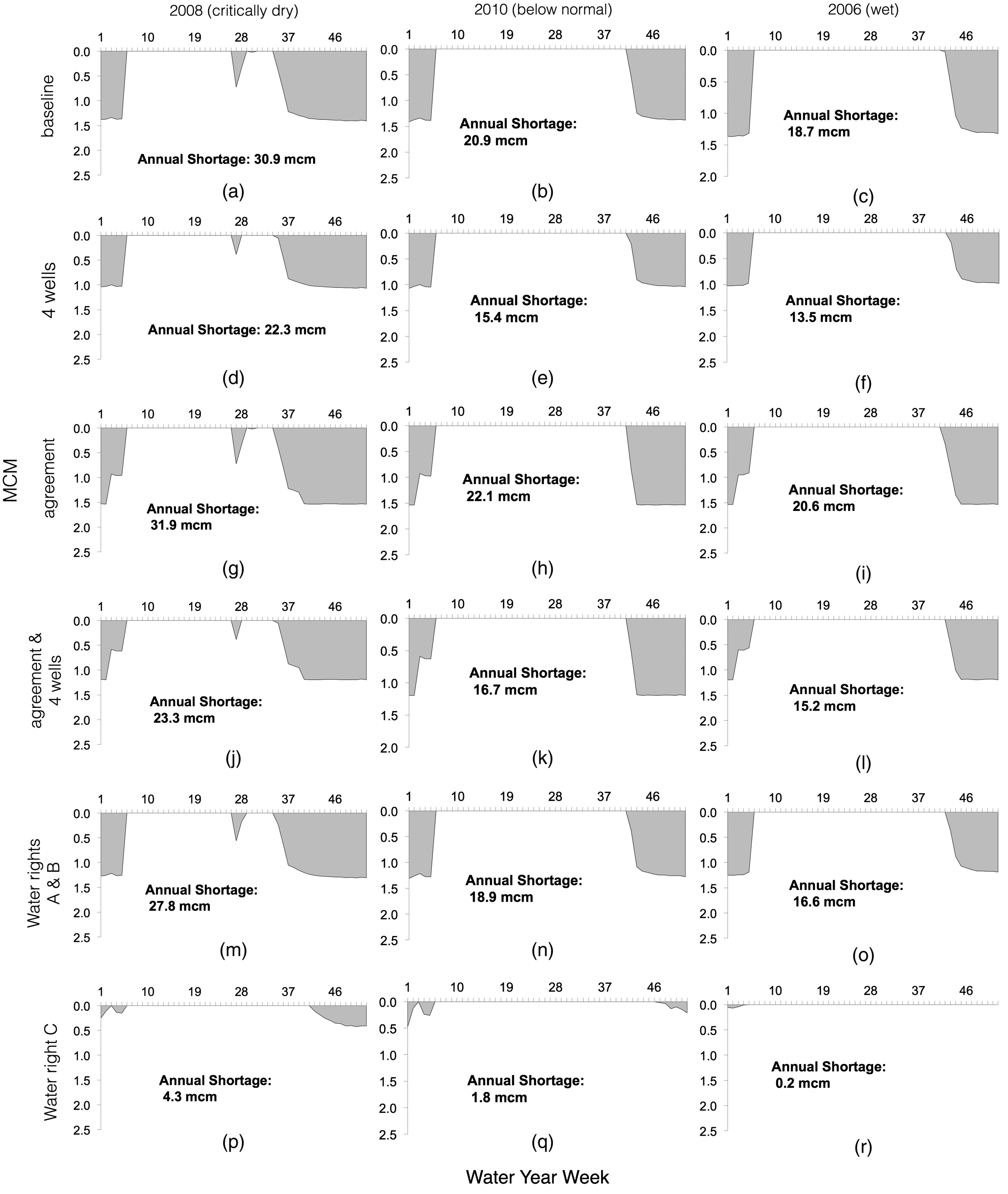

Fig. 7. MIF shortages for critically dry (2008), below-normal (2010), and wet (2006) WYs for baseline, 4 wells, water exchange agreement, agreement and 4 wells, Water Rights A & B, or C left instream; *x*-axis is WY weeks and *y*-axis is shortage in mcm

explored a reasonable range of environmental flow targets from minimum instream flows, to a fixed percentage of inflow, and more varied functional flows. Future work can implement other approaches to environmental flow target design such as the use of economic models to design variable flows that are economically optimal or the use of novel redistribution rules (Perona et al. 2013; Razurel et al. 2016).

The transparency of a linear programming model implemented as a spreadsheet tool lends itself to be readily adapted for use in other rivers with diversion modified flow regimes and would

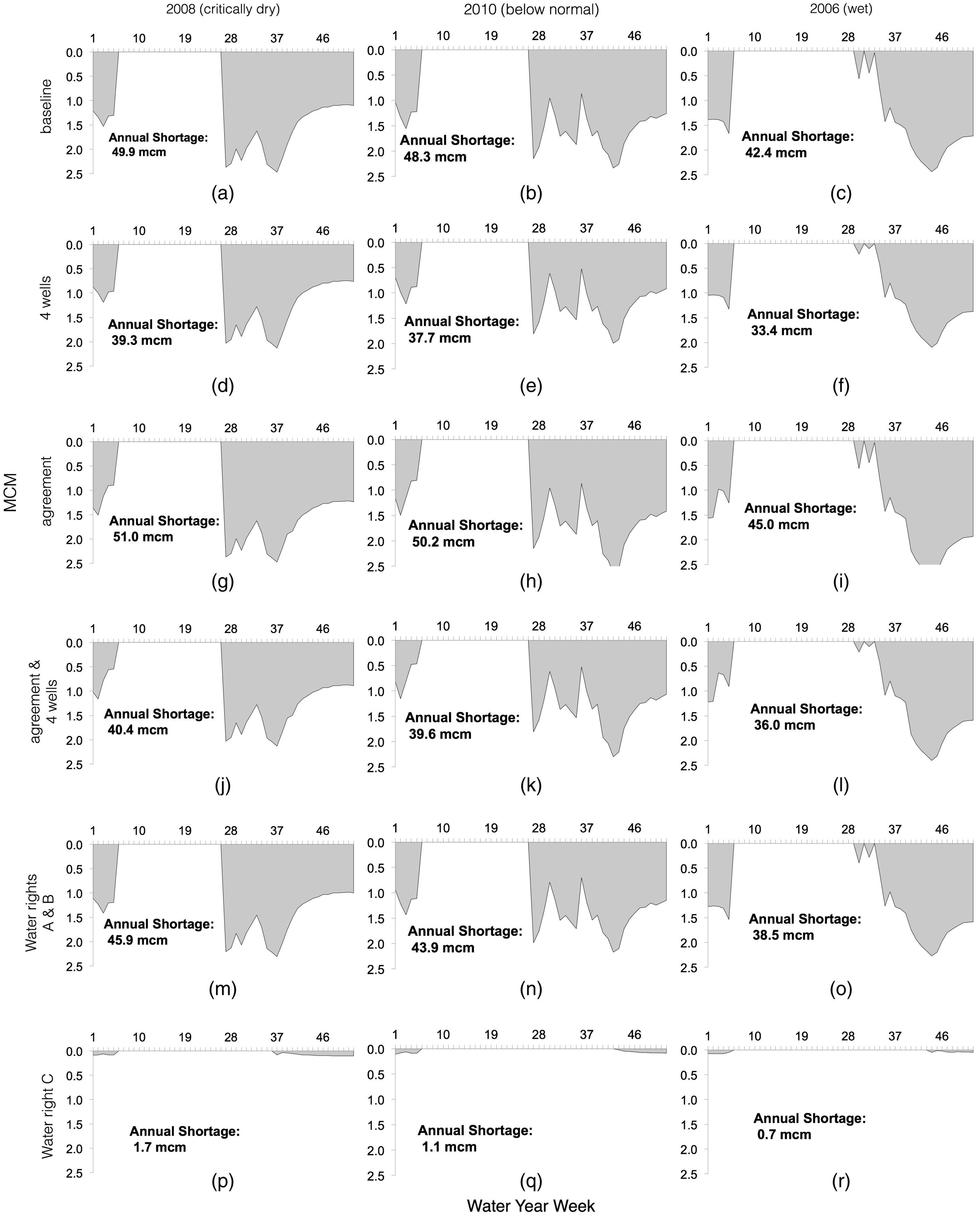

Fig. 8. SBA shortages for critically dry (2008), below-normal (2010), and wet (2006) WYs for baseline, 4 wells, agreement, agreement and 4 wells, and Water Rights A & B, or C left instream; *x*-axis is WY weeks and *y*-axis is shortage in mcm

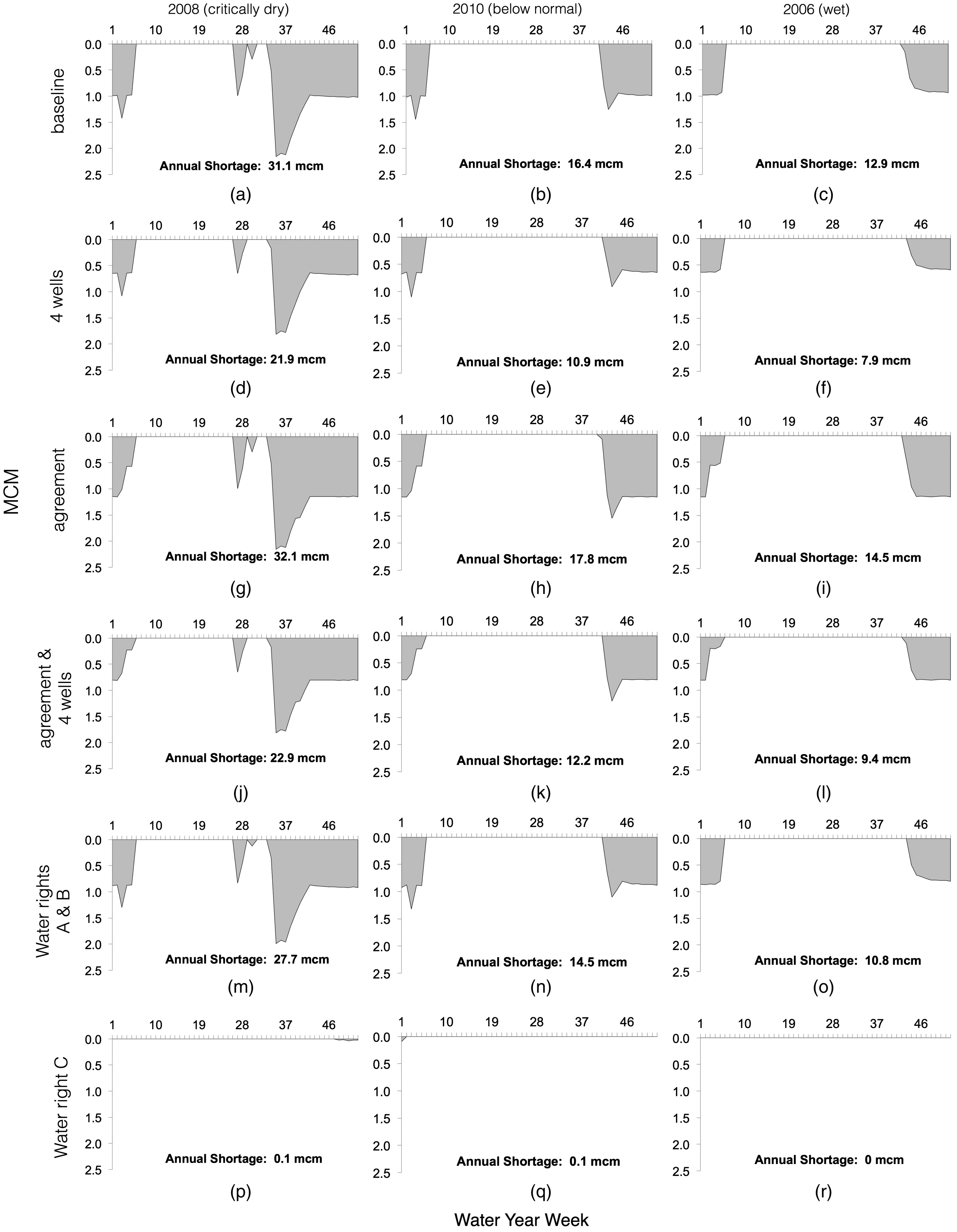

Fig. 9. Environmental flow shortages for SRF case for critically dry (2008), below-normal (2010), and wet (2006) WYs; the *x*-axis is in WY weeks and the *y*-axis is water shortage in mcm

facilitate communication between stakeholders in the Integrated Water Resources Management planning process. With growing water scarcity, water managers are faced with the challenge of finding ways to manage water that meets competing demands. The methodology developed and demonstrated in this paper enables exploration of potential effects of novel water exchange agreements to meet environmental flow targets.

Conclusion

The modeling described here suggests opportunities to strategically manage water systems through creative water practices to meet ecological flow needs during different water year types. Its linear programming approach to managing ecological flow needs in the water-stressed system of Mill Creek demonstrates the efficacy of a simple model to quantitatively explore potential solutions. This work can be extended to a broader range of riparian species or ecosystem processes as well as the adoption of novel water resource infrastructure or irrigation methods. The model developed can be modified and applied to other river systems with flow regimes impaired by water abstractions, such as other watersheds in the Mount Lassen foothills such as Deer Creek as well as coastal rivers in northern California subject to flow-regime impairment through small diversions.

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