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HYDROLOGIC IMPACTS OF SMALL-SCALE INSTREAM DIVERSIONS FOR FROST AND HEAT PROTECTION IN THE CALIFORNIA WINE COUNTRY

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ABSTRACT

Though many river studies have documented the impacts of large water projects on stream hydrology, few have described the effects of dispersed, small-scale water projects on streamflow or aquatic ecosystems. We used streamflow and air temperature data collected in the northern California wine country to characterize the influence of small instream diversions on streamflow. On cold spring mornings when air temperatures approached 0°C, flow in streams draining catchments with upstream vineyards receded abruptly, by as much as 95% over hours, corresponding to times when water is used to protect grape buds from freezing; flow rose to near previous levels following periods of water need. Streams with no upstream vineyards showed no such changes in flow. Flow was also depressed in reaches below vineyards on hot summer days, when grape growers commonly use water for heat protection. Our results demonstrate that the changes in flow caused by dispersed small instream diversions may be brief in duration, requiring continuous short-interval monitoring to adequately describe how such diversions affect the flow regime. Depending on the timing and abundance of such diversions in a drainage network, the changes in streamflow they cause may be an important limiting factor to valued biotic resources throughout the region. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: small diversions; natural flow regime; intermittent streamflow; human water abstraction; temperature thresholds

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INTRODUCTION

The methods through which humans acquire water supply can fundamentally alter stream ecosystems. Aquatic scientists across many disciplines have demonstrated that centralized water projects operating on or near major rivers, including dams and large instream and groundwater diversions, can change the flow regime (describing the magnitudes, durations, timing, rate of change and other characteristics of runoff patterns, Poff *et al*., 1997) of that river system (Kondolf *et al*., 1987; Wilcock *et al*., 1995; Cowell and Stoudt, 2002; Grams and Schmidt, 2002; Glennon, 2002; Nislow *et al*., 2002; Magilligan and Nislow, 2005; Page *et al*., 2005; Claessens *et al*., 2006). Along with these changes in flow regime, large centralized projects also alter the dynamics of sediment (Ligon *et al*., 1995; Sear, 1995; Brandt, 2000; Grams and Schmidt, 2002) and reduce hydrologic connectivity (Ward and Stanford, 1995; Pringle, 2003), both upon which aquatic organisms depend (Poff and Ward, 1989; Bunn and Arthington, 2002; Lytle and Poff, 2004). Through a number of mechanisms, changes in the natural flow regime as a result of flow manipulation below large water projects can cause a shift in the composition and function of instream communities (Power *et al*., 1996; Pringle *et al*., 2000; Marchetti and Moyle, 2001; Osmundson *et al*., 2002; Downes *et al*., 2003; Cowley, 2006) as well as those in adjacent riparian zones (Johnson, 2002; Nilsson and Svedmark, 2002; Elderd, 2003; Lytle and Merritt, 2004).

Because of these ecological consequences, and for a number of social, political and economic ones as well, water resource managers are searching for less hydrologically manipulative ways to meet future water needs (Scudder, 2005; Potter, 2006). As an alternative, water users may meet water needs individually through small-scale water projects (e.g. Mathooko, 2001; Liebe *et al*., 2005, *The Economist*, 2007), including direct instream diversions and surface reservoir storage in small headwater tributaries. The decentralized nature of small-scale projects is believed

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to mitigate pressures on stream ecosystems (Potter, 2006); because they serve only one or a few users, small projects retain smaller volumes and employ lower pumping rates than large centralized projects designed to meet the needs of many water users. Additionally, the distribution of small projects spatially and temporally lessens the hydrologic impairment at any one location or at any time within a drainage network.

Though such small-scale water projects may not be individually capable of influencing streamflow like large dams, the cumulative effect of several projects may have potential to impair ecologically relevant flow regime characteristics in other ways (Pringle, 2000; Stillwater Sciences and Dietrich, 2002; Spina *et al*., 2006). Such concerns may be especially pertinent in regions where decentralized water projects are the primary means to meet human water needs, such as in the wine country of northern California (including Napa, Sonoma and Mendocino Counties), where virtually all agricultural water needs are met individually and locally. Despite that wine grapes require lower volumes of water per area than most other crops grown in California, virtually no precipitation occurs during the summer growing season, so irrigation is regarded as often necessary for successful wine grape production (Smith *et al*., 2004). In addition to irrigation, vineyard operators spray water aerially to protect crops from frost in spring and from heat in summer, which can threaten grape survival and sugar quality, respectively. Records describing water rights indicate that grape growers throughout the California wine country depend upon surface water abstraction to meet these water needs (SWRCB, 1997; Deitch, 2006).

The pressures that surface water abstractions place on streamflow in the California wine country depend on how water is acquired to meet various needs, and different needs may be met through different mechanisms. Vineyard irrigation, for example, requires low volumes of water periodically through the dry summer. Irrigation needs may be met through diverting low volumes of water from streams briefly and periodically through the growing season, or through pumping groundwater where such sources are available. In addition to requiring lower volumes of water, crops are not irrigated constantly through the growing season, so the effects of water abstraction for irrigation on streamflow may be temporally dispersed. Other uses, such as springtime frost protection and summer heat protection, require high volumes of water over a short duration. Groundwater pumping may not yield sufficient water volumes (especially from low-yield aquifers common in the region) so surface water in the form of streamflow may be especially attractive for meeting such water needs. Because frost and heat protection are linked to particular climatic conditions, growers who employ such practices likely all require water at the same time. Depending on the magnitude of individual diversions relative to streamflow and the number that occur in a drainage network, small-scale instream diversions may have potential to cause changes in flow regime having consequences to stream biota that depend on particular flow characteristics.

Though literature has recently begun to explore the ecological impacts of small instream diversions on aquatic ecosystem communities (e.g. McIntosh *et al*., 2002; McKay and King, 2006; Wills *et al*., 2006), few studies have described how surface water abstraction practices under a decentralized management regime affect flow regime. Characterizing how water management affects flow regime is an important step for understanding how human development may affect aquatic ecosystems (Richter *et al*., 1996); it provides the foundation for understanding how detected changes in biotic community composition may occur, and can be used for directing changes in management practices to mitigate those ecological consequences. Here we present data describing streamflow in two tributaries to the Russian River in Sonoma County, California, to illustrate how small-scale diversions alter the natural flow regime when certain water need thresholds are reached (indicating need for frost or heat protection) and distinguish these alterations from those commonly described from large water projects, both relative to the natural flow regime and to the spatial extent of the drainage network.

METHODS

Site description

We monitored streamflow in water years 2004 and 2005 at seven locations within the Maacama Creek and Franz Creek drainages in eastern Sonoma County, California. Maacama Creek is one of the five principal tributaries to the Russian River (3800 km^2) and Franz Creek is the tributary to Maacama just upstream of its confluence with the Russian River (Figure 1), at the southern end of the Alexander Valley grape-growing region. At their confluence, the Maacama and Franz Creek catchments drain 118 km^2 and 62 km^2, respectively. The flow regime of both streams

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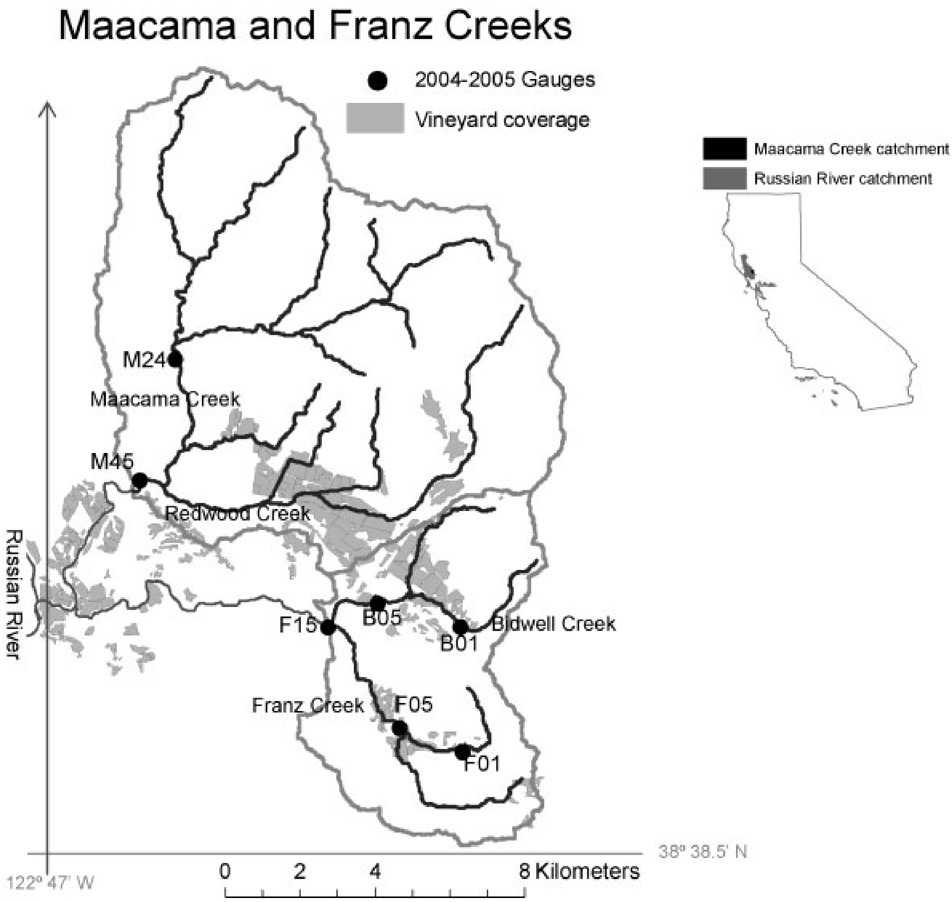

Figure 1. Maacama and Franz Creek channel networks, with gauges 45-Maacama (M45), 24-Maacama (M24), 15-Franz (F15), 05-Franz (F05), 05-Bidwell (B05), 01-Franz (F01) and 01-Bidwell (B01); and vineyards present in 2004

reflects the Mediterranean climate of coastal California; virtually all precipitation occurs as rainfall during the wet half of the year, so streamflow recedes gradually through spring and approaches intermittence by the end of summer (Conacher and Conacher, 1998; Gasith and Resh, 1999).

To monitor flow at each of the seven locations, we attached Global Water WL15 pressure transducers encased in high-pressure flexible PVC hose to solid substrate and operated each instrument as a streamflow gauge according to standard USGS methods (Rantz, 1982). We measured flow using Price Mini and AA current meters biweekly to monthly to develop rating curves; instruments recorded stage at 10-min intervals from November 2003 to September 2005. Gauge locations in the Maacama and Franz drainage networks varied with upstream catchment area and vineyard coverage (Table I). Franz Creek was gauged in a nested design (Figure 1). Gauges 01-Bidwell and 01-Franz each measured flow from 2.6 km^2 headwater catchments (1 mi^2; number designations corresponded to catchment area normalized by smallest basin size) with less than 1% of each catchment developed in vineyards; 05-Franz and 05-Bidwell gauges each measured flow from 14 km^2 (5 mi^2) catchments with 5% and 14% of the catchment in vineyards, respectively. The most downstream 15-Franz gauge measured flow immediately below the Bidwell-Franz Creek confluence, with 10% of its 40 km^2 catchment in vineyards. Maacama Creek gauges were installed upstream of the Maacama-Franz confluence. The more downstream 45-Maacama gauge recorded flow from a 112 km^2 catchment with 6.0% of its area in vineyards; and the upstream 24-Maacama gauge recorded flow from a 61 km^2 catchment with no upstream vineyard development. Almost all of the vineyards above 45-Maacama are in the Redwood Creek subcatchment, which is the other major tributary above the 45-Maacama gauge (Figure 1). We also identified the vineyard area in each basin on land parcels abutting streams (termed ‘riparian parcels’), indicating the potential for wine grape growers on those parcels to use streamflow as a water source.

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Table I. Characteristics of streamflow gauges and upstream catchments in the Franz Creek and Maacama Creek drainage networks

Gauge (map ID)	Period of record	Catchment area, km^2	Upstream vineyard, ha (% of catchment)	Upstream vineyard on 'riparian' parcels, ha
15-Franz (F15)	2004, 2005	40.4	407 (10%)	276
05-Franz (F05)	2004, 2005	13.7	69 (5.0%)	64
05-Bidwell (B05)	2004, 2005	13.6	193 (14%)	158
01-Franz (F01)	2004, 2005	2.6	0.7 (0.3%)	0
01-Bidwell (B01)	2004, 2005	2.6	2.4 (0.9%)	0
45-Maacama (M45)	2005	112.0	674 (6.0%)	582
24-Maacama (M24)	2005	60.7	0	0

Detecting changes in flow: frost protection

In the Franz Creek drainage, we identified frost protection impacts as sudden changes in streamflow on days when temperatures dropped to near 0°C recorded at a nearby California Irrigation Management Information System weather station at Santa Rosa (weather data were available through the internet at www.cimis.ca.gov). We measured the maximum change in flow as the difference between flow at the beginning of each irregular recession and the minimum flow recorded during the recession period, and the duration as the time from when flow first receded irregularly to the time when flow rose back to near previous levels. We also calculated the total abstraction volume for each irregular flow recession, which we define as the total volume of water extracted from the stream at each gauge over each period of depressed flow, as the difference between the discharge that would occur under an estimated natural flow recession and the actual discharge that occurred over the period of irregular flow recession. In addition, we created a statistic to express flow alteration in a flow regime context. Because flow in Franz Creek recedes naturally through spring and summer, and flow rose to near previous levels following need for frost protection, the minimum flow caused by diversion for frost protection will occur again later in the context of natural flow recession. We measured the number of days before the diversion-induced minimum flow occurred again in the natural recession, a variable we term as the dry-season acceleration.

We used different methods to assess impacts of frost protection in the Maacama Creek basin because we had no gauges on Redwood Creek, where vineyard development is concentrated; we thus could not simply measure flow changes as we did in Franz Creek. Instead, we used a mass-balance approach to determine how the relationship between the two Maacama gauges (24-Maacama representing the undeveloped half of the basin and 45-Maacama representing the entire basin) changed when water would likely be diverted for frost protection. We estimated flow in the ungauged Redwood Creek basin as the difference between the flow at 24-Maacama and flow at 45-Maacama below the confluence of the two forks (Figure 1), and identified the occurrence of frost protection impacts as irregular deviations in the relationship between the flow at 24-Maacama and 45-Maacama that occurred on days when air temperatures were near or below freezing.

Detecting changes in flow: heat protection

We used similar approaches to identify effects of diversions for heat protection on summer base flow as changes in streamflow that occurred on hot days in summers 2004 and 2005. We obtained maximum air temperature data from California Irrigation Management Information System weather station records measured at Santa Rosa and Bennett Valley, California. We used mean daily flows rather than hourly because daily averages dampened the within-day fluctuations from local and catchment-scale evapotranspiration. In the Franz drainage, we focused on changes in flow at 05-Franz and 15-Franz gauges (05-Bidwell became intermittent in early summer, so it was not included in this analysis); for both, we plotted mean daily flow and daily maximum air temperature together to identify whether flow receded similarly at two sites with upstream vineyard development. Unlike our frost protection analyses, we did not attempt to quantify changes in flow magnitude attributed to heat protection: streamflow was very low during summer, increasing the difficulty to distinguish between impacts of instream

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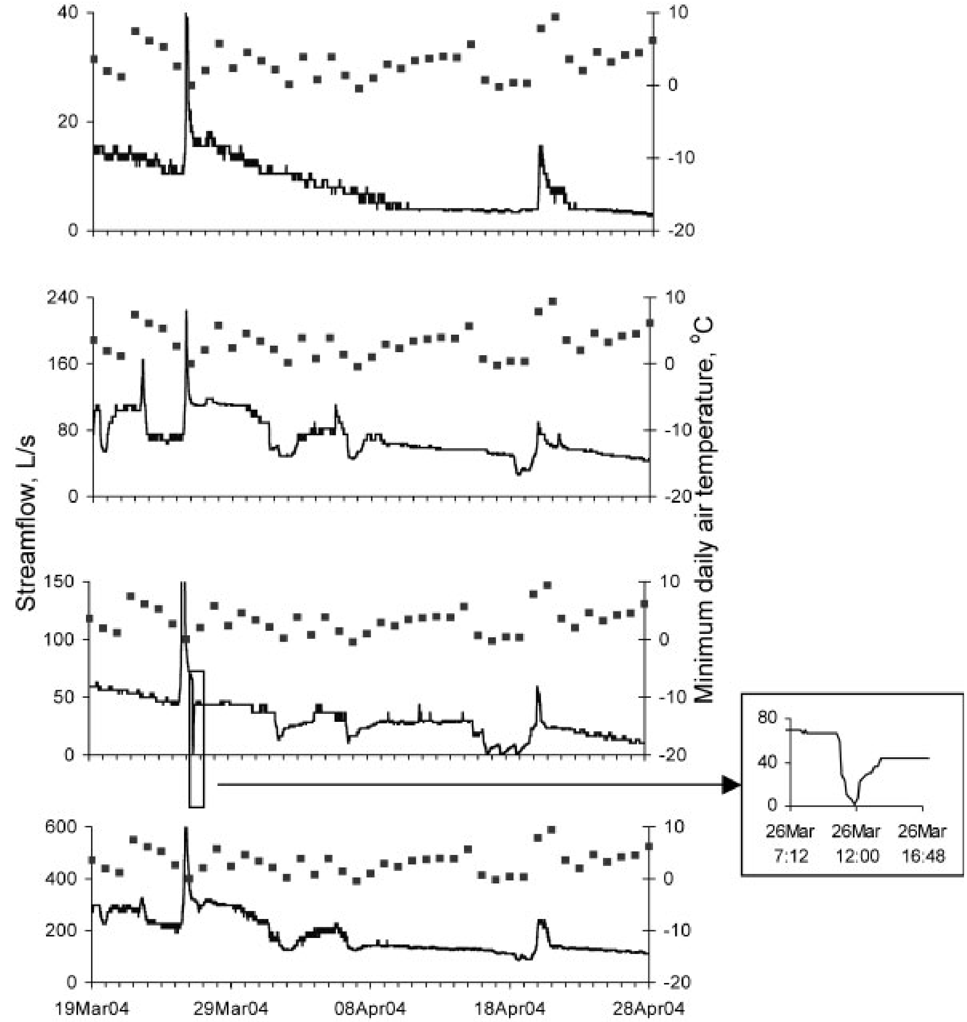

Figure 2. Streamflow hydrographs in the Franz Creek basin in water year 2004, from top to bottom: 01-Franz, 05-Bidwell, 05-Franz and 15-Franz; and minimum daily air temperature recorded in Santa Rosa (southeastern Sonoma County)

diversions and evapotranspiration. For Maacama sites, we plotted mean daily flow at 24-Maacama and 45-Maacama along with daily maximum air temperature to identify whether streamflow receded on days with particularly high temperatures only at the site with upstream vineyard development. In this case, 24-Maacama served as a baseline; with no vineyards in the catchment, flow changes at 24-Maacama could be attributed to natural processes associated with evapotranspiration. Flow changes occurring at 45-Maacama but not at 24-Maacama on very hot days could be attributed to water demand for heat protection.

RESULTS: EFFECTS OF MANAGEMENT PRACTICES ON STREAMFLOW

Frost protection, Franz Creek

No abrupt changes in flow occurred in reaches without upstream vineyard development (e.g. 01-Franz; Figure 2), but streamflow in reaches draining vineyards abruptly receded on spring days when air temperature dropped to near freezing. On 19 March 2004, when minimum daily air temperature fell below 2°C, flow at 05-Bidwell receded by nearly 50% over 12 h, while flow returned to previous levels over the following 18 h (Figure 2; Table II). Flow at this

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Table II. Changes in streamflow and abstraction volumes on freezing or near-freezing mornings in the Franz Creek drainage network, spring 2004 and 2005

Event date	Site	Change in flow, L/s		Magnitude of change	Percent change	Duration, hours	Total volume, m^3
		Initial	Minimum				
19–20 March 2004	05-Bidwell	110	55	55	50	30	3300
	05-Franz	(No change)		0	0	—	0
	15-Franz	300	225	75	25	24	2400
22–25 March 2004	05-Bidwell	110	70	40	36	72	9100
	05-Franz	(No change)		0	0	—	0
	15-Franz	300	210	90	30	70	14 000
26 March 2004	05-Bidwell	(No change)		0	0	—	0
	05-Franz	65	2	63	97	8	300
	15-Franz	310	270	40	13	6	1200
31 March–04 April 2004	05-Bidwell	90	50	40	44	72	7900
	05-Franz	45	15	30	67	90	2900
	15-Franz	240	125	115	48	80	14 000
06–07 April 2004	05-Bidwell	75	45	30	40	36	2400
	05-Franz	40	15	25	63	54	1600
	15-Franz	175	125	50	29	30	2400
14–20 April 2004	05-Bidwell	55	25	30	55	84	3800
	05-Franz	30	1	29	97	110	7700
	15-Franz	125	85	40	32	72	4600
24 March 2005	05-Bidwell	650	570	80	12	10	1200
	05-Franz	840	670	170	20	12	1100
	15-Franz	1750	1580	170	10	4	1700
25 March 2005	05-Bidwell	545	465	80	15	12	1200
	05-Franz	600	70	530	88	12	8800
	15-Franz	1580	1360	220	14	10	5100
30 March 2005	Bidwell	420	320	100	24	14	1900
	05-Franz	510	280	230	45	10	5300
	15-Franz	1280	1160	120	9	10	2400
31 March 2005	05-Bidwell	(No change)		0	0	—	0
	05-Franz	410	165	245	60	6	3000
	15-Franz	1220	1035	185	15	7	1900
12 April 2005	05-Bidwell	270	150	120	44	97	20 000*
	05-Franz	205	45	160	78	14	3100
	15-Franz	470	400	70	15	14	1600
13 April 2005	05-Bidwell	—		—	—	—	*
	05-Franz	165	35	130	78	16	5100
	15-Franz	420	340	80	19	16	5500
14–16 April 2005	05-Bidwell	—	—	—	—	—	*
	05-Franz	160	35	125	78	30	6700
	15-Franz	395	320	75	19	36	14 000

*Hydrograph depression at 05-Bidwell on 12 April 2005 was sustained until 16 April 2005.

site changed similarly when temperature approached freezing from 22 March 2004 through 19 April 2004, receding irregularly when minimum daily air temperature approached zero and rose in the days following; the artificially depressed flows lasted from 1.5 to 3.5 days (Table II), corresponding with the number of consecutive days with minimum daily air temperatures near 0°C. Surface water abstraction volumes over these periods ranged from 2400 to 9100 m^3, corresponding to in between 1000 and 3000 m^3 per morning of depressed flows (i.e. for each instance when water would have been used for frost protection).

Other gauges showed similar patterns of irregular changes in flow on mornings when minimum daily air temperature was near freezing. Data at 05-Franz first indicated irregular flow recession on 26 March 2004 (minimum temperature 0°C), when flow fell from 65 L/s (0.065 m^3/s) to near zero in 2 h; flow rose again to previous levels during the following 3 h (Figure 2). Flow recessions over the following weeks more closely resembled the

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changes in nearby Bidwell Creek in terms of magnitude and duration (Table II), with the exception of alteration from 14 April 2004 to 19 April 2004 (during which minimum daily air temperature ranged from 0°C to 1°C on four consecutive mornings), when flow receded from 30 L/s to 0 L/s and then remained depressed for 3 days before rising back gradually to 30 L/s. Over the three intervals when frost protection impacts were detected, total abstraction volume at 05-Franz ranged from 300 m^3 to 7700 m^3 (corresponding to between 300 m^3 and 1900 m^3 per morning of depressed flow).

Changes in streamflow at the 15-Franz gauge mirrored the changes upstream. Flow at 15-Franz decreased by 75 L/s and 90 L/s on 19 March 2004 and 22 March 2004, respectively, exceeding the magnitude of flow change recorded at 05-Bidwell (i.e. when flow was not affected at 05-Franz; Table II). Flow at 15-Franz fell by as much as the sum of 05-Franz and 05-Bidwell on 06 April 2004, and by more than the sum of 05-Bidwell and 05-Franz from 01 April 2004 to 03 April 2004 (Figure 2; Table II), suggesting that additional water was drawn from the Franz Creek drainage downstream of the 05-Bidwell and 05-Franz gauges on the latter period. Flow at 15-Franz receded from 16 April 2004 to 19 April 2004, less than the sum of the recession detected at 05-Bidwell and 05-Franz. Abstraction volumes detected at 15-Franz also varied from event to event, ranging from 1200 m^3 to 14 000 m^3 (corresponding to between 1200 m^3 and 4800 m^3 per morning of depressed flow). These total abstractions measured at 15-Franz were also frequently less than the sum of abstraction detected at the two upstream gauges.

Similar irregular recessions occurred through the Franz drainage network in spring 2005. Streamflow was higher throughout the drainage as a result of late-spring rainfall, but changes in streamflow on days with low temperatures occurred over similar duration at 05-Franz, 05-Bidwell and 15-Franz (Figure 3, Table II). The most dramatic change was detected at 05-Franz, where flow on 24 March 2005 fell from 600 L/s to 70 L/s over a few hours, and rose to previous levels by the end of the day (Figure 3). At all sites, changes in flow on cold mornings were greater in magnitude and duration than the previous year, but because of higher spring flows in 2005, the relative magnitude of flow recession was less. Abstraction volumes over each instance of frost protection need were also greater than the previous year, but their impacts on overall discharge were also tempered by higher discharge in spring 2005.

Frost protection, Maacama Creek

Data in the Maacama drainage indicates that flows in Redwood Creek changed abruptly as a result of extractions for frost protection as well. Streamflow at 45-Maacama was 1.8–2 times the flow at 24-Maacama through the winter until late March when this discharge relationship changed systematically during the two periods. Following rainfall on 26 March 2005, streamflow in 45-Maacama receded to approximately equal flow at 24-Maacama; minimum air temperature on 26 March 2005 was 0°C (Figure 4). A high-flow event following rainfall on 27 March 2005 raised flow at 45-Maacama again to approximately two times that at 24-Maacama; but flow receded in the days following to again equal to 24-Maacama from 30 March 2005 to 03 April 2005 and from 04 April 2005 to 08 April 2005. Each instance corresponded to minimum air temperatures near 0°C. According to the mass-balance relationship described above, when flow at 24-Maacama equalled flow at 45-Maacama, flow from Redwood Creek was zero. Streamflow at 45-Maacama rose again to approximately two times the flow at 24-Maacama following the occurrence of minimum daily air temperatures near 0°C.

Heat protection, Franz Creek

Streamflow at 05-Franz and 15-Franz changed systematically in summer 2004 and 2005 in patterns suggesting that water was diverted from streams for heat protection on very warm days. Flow at 15-Franz receded to intermittence during the third week of July 2004, corresponding to a period when daily maximum air temperatures exceeded 32°C (Figure 5). Flow then rose when maximum temperatures were lower in late July, but receded again when maximum temperatures exceeded 32°C in early August. Flow rose briefly in mid-August but fell when maximum temperatures again exceeded 32°C; 15-Franz remained intermittent until late September. During sustained intermittence from late August to late September, stage continued to fall when maximum daily air temperatures were high and rise when temperatures were cooler (Figure 6). Streamflow at 05-Franz showed some but not all of the patterns illustrated at 15-Franz; flow receded abnormally with high air temperatures in early and mid-August, and rose again afterward (Figure 5). In summer 2005, streamflow at 15-Franz and 05-Franz did not change as frequently with high temperatures. Flow at 05-Franz receded gradually throughout summer 2005, falling

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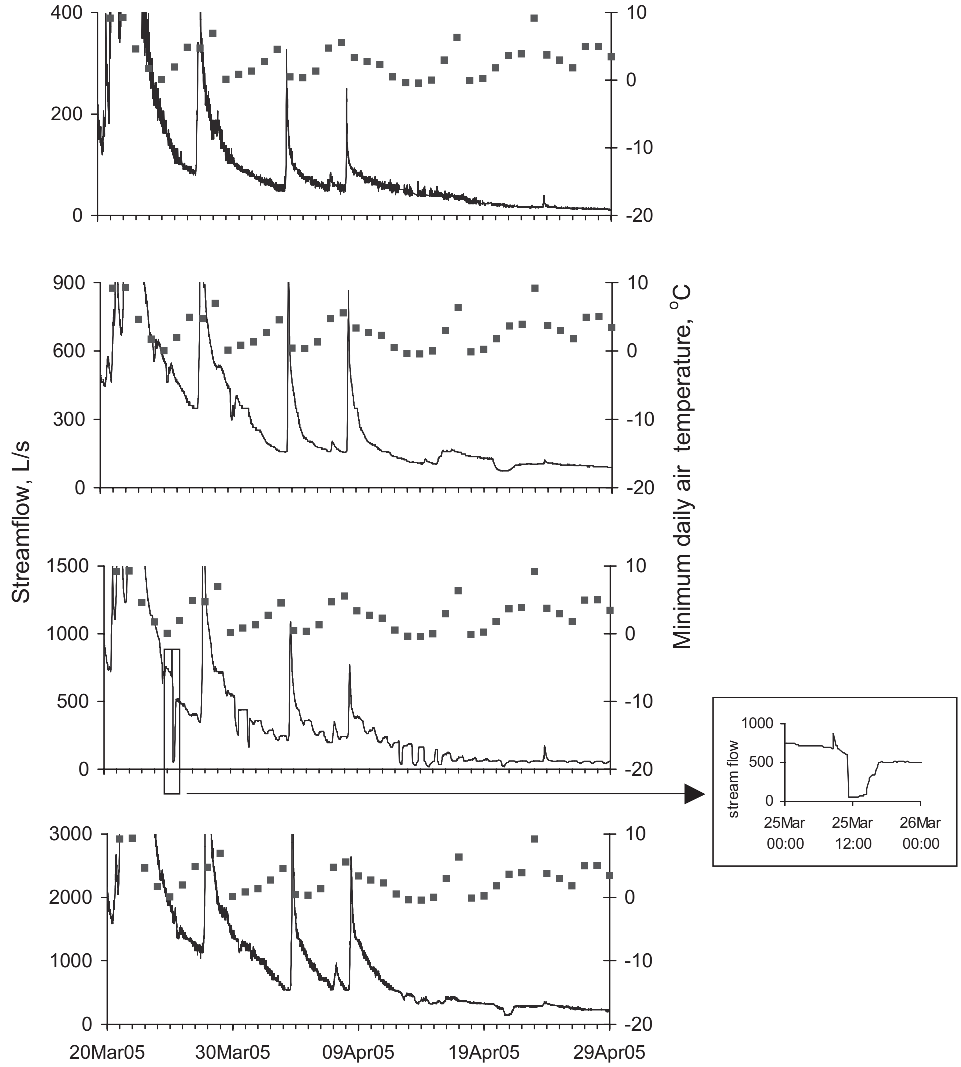

Figure 3. Streamflow hydrographs in the Franz Creek basin in water year 2005, from top to bottom: 01-Franz, 05-Bidwell, 05-Franz and 15-Franz; and minimum daily air temperature recorded in Santa Rosa (southeastern Sonoma County)

only once during a period with temperatures above 32°C in mid-July (Figure 5); flow at 15-Franz also fell during the same period. At both sites, flow rose when maximum air temperatures were lower in the days that followed, and receded gradually through the remainder of the summer.

Heat protection, Maacama Creek

Changes in streamflow at 45-Maacama also suggested that water was diverted for heat protection on very warm days. Streamflow receded more quickly on days when maximum temperature exceeded 32°C and then rose when maximum daily air temperatures were lower in June and early July 2004, and again in August and September 2004 (Figure 7). The same sustained period of maximum daily air temperatures above 32°C that caused flow to cease at 15-Franz caused flow to cease at 45-Maacama as well. At 24-Maacama, where no vineyards exist upstream, flow receded regularly until early August, then rose slightly and remained steady throughout the remainder of summer 2004 (including the period of sustained high temperature in early September). Similar to fluctuations at 15-Franz, flow at 45-Maacama changed abnormally in mid-July 2005 during a period of high maximum daily temperature,

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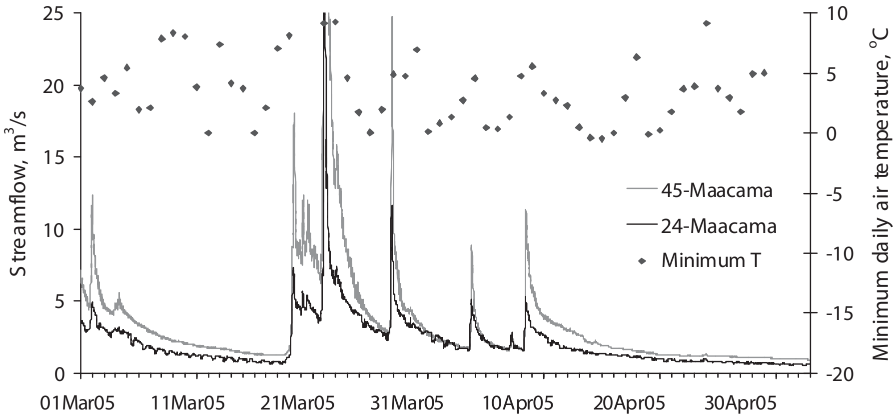

Figure 4. Streamflow at 45-Maacama and 24-Maacama, and minimum daily air temperatures (recorded at Santa Rosa, CA), spring 2005

and then rose in the days following (Figure 7). Flow at 24-Maacama, with no upstream vineyards, receded regularly through summer 2005.

Dry-season acceleration

The irregular changes in flow in spring 2004 can be used to illustrate how water demand for frost protection in the Franz Creek drainage network causes flow recession to accelerate. Diversions caused flow at 05-Bidwell fall to

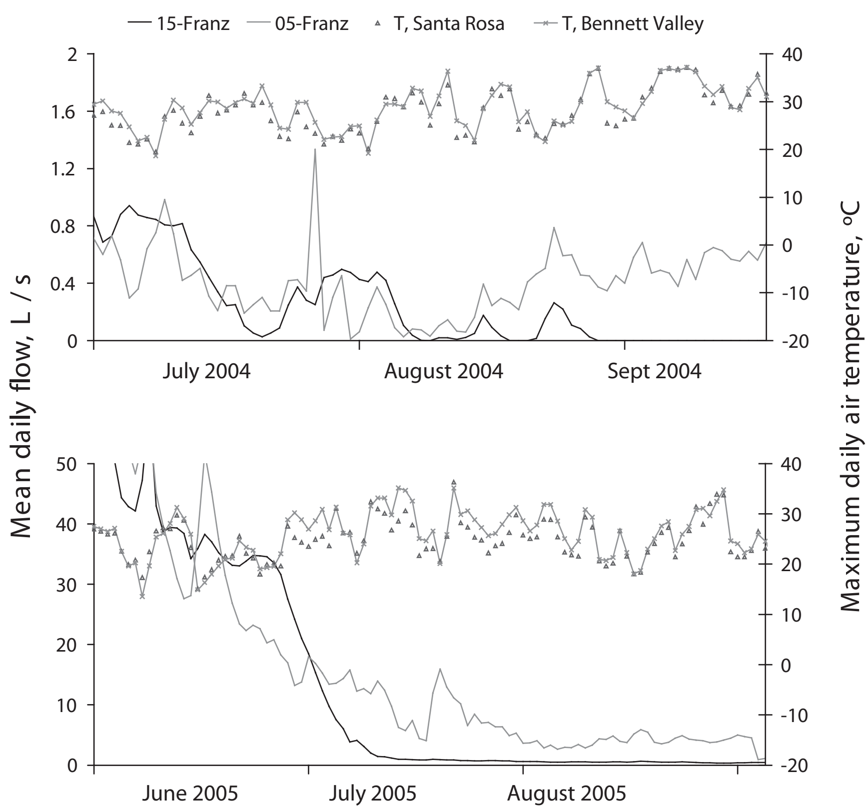

Figure 5. Maximum daily air temperatures at Santa Rosa and Bennett Valley (eastern Sonoma County) and streamflow in Franz Creek, summer 2004 and 2005

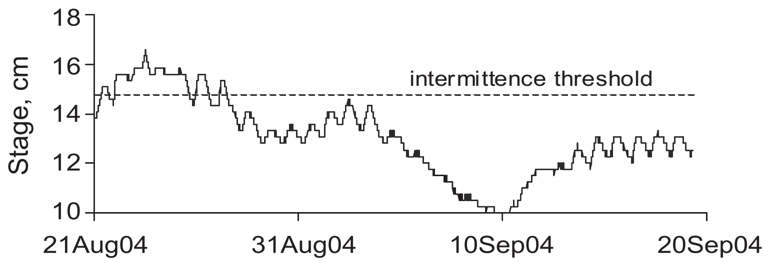

Figure 6. Surface water stage recorded at 15-Franz after surface flow ceased, summer 2004; irregular flow recession occurred within the context of natural diurnal fluctuations in flow

60 L/s on 19 March 2004; flow then rose to the previous level in the days that followed, when minimum daily air temperatures were above freezing. Following a more natural flow regime, flow at 05-Bidwell receded gradually and remained above 60 L/s until 12 April 2004 (Figure 2). This difference in time between the 60 L/s flow magnitude caused by diversion and its occurrence under natural flow recession is 24 days; thus diversions for frost protection at 05-Bidwell on 19 March 2004 accelerated the summer drought by 24 days. Similarly, diversions caused flow at 05-Franz to fall to 16 L/s on 01 April 2004; when minimum daily air temperatures were again above zero, flow returned to its previous level. Under a natural recession, flow did not reach 16 L/s until 24 April 2004; again, the summer drought was accelerated by 24 days. Flow at 05-Franz became nearly intermittent on 16 April 2004, and then rose when diversions ceased; flows did not recede to near intermittency naturally until July. In this case, frost protection accelerated the dry season by over 2 months. Similarly, diversions for frost protection accelerated the dry season in the Maacama Creek drainage. Equal flow at 24-Maacama and 45-Maacama indicated that flow from Redwood Creek ceased over two 4-day periods in April 2005; summer flow hydrographs show that flow from Redwood Creek continued for the remainder of summer 2005 (Figure 7).

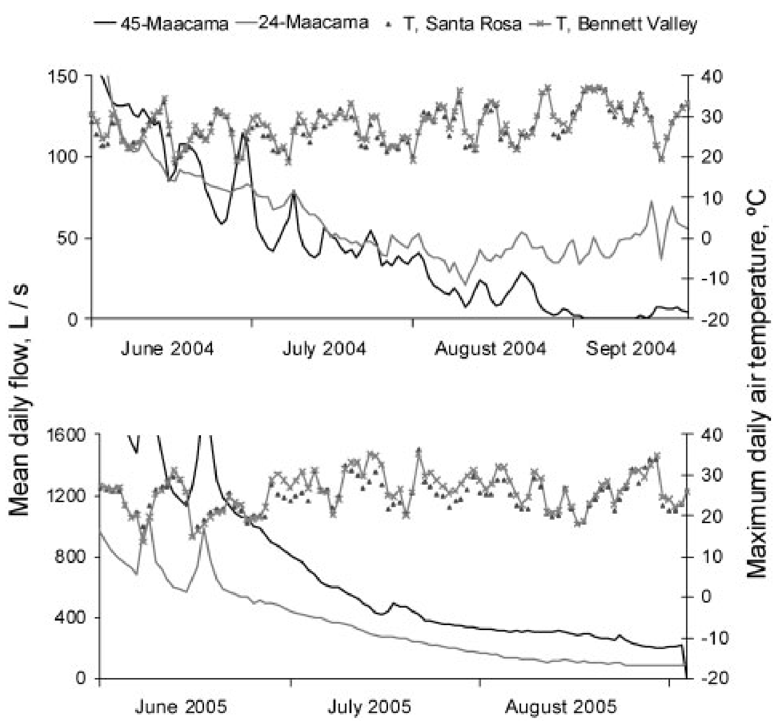

Figure 7. Maximum daily air temperatures at Santa Rosa and Bennett Valley (eastern Sonoma County) and streamflow in Maacama Creek, summer 2004 and 2005

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DISCUSSION

Natural catchment processes are insufficient to explain the irregular changes in streamflow in Franz and Maacama Creeks documented above that occurred when particular temperature thresholds were crossed. In spring, sudden decreases occurred only on days when temperatures were near freezing, when water was needed for frost protection; changes were only detected at gauges with vineyard development upstream. The causes of flow alteration on hot summer days are less straightforward, as it is conceivable that there could be some characteristics of soil, topography and/or vegetation in the catchments of 05-Franz, 15-Franz and 45-Maacama that caused ET to abruptly increase when air temperature exceeded 32°C. Evapotranspiration is one factor that may reduce streamflow, especially in semi-arid environments (Mwakalila *et al.*, 2002; Lundquist and Cayan, 2002); it seems less plausible, however, that such processes would only be activated beyond particular temperature thresholds. The relatively abrupt declines in discharge that we attribute to diversions for heat protection occurred when air temperatures exceeded 32°C, and only in catchments with vineyard development. The declines were followed by increased discharge in subsequent days.

Though results above indicate that irregular flow recession occurred repeatedly at particular temperature thresholds at sites with vineyard development upstream, the changes in streamflow magnitude and total volumes of abstraction were not always consistent from one occurrence of water need to the next. The magnitude of flow alteration at the Franz Creek gauges, for example, varied throughout water years 2004 and 2005; in only a few cases the maximum magnitude of change at a site will ever be the same (Table II). The total volume of abstraction also frequently varied at the same site from one instance to the next (Table II). Such variations may partly reflect irregularities that are characteristic of water management in the wine country. Wine grape growers tend only to apply water for frost protection as needed. Aerial spraying only occurs when temperatures reach certain thresholds, and the durations of these temperature thresholds may vary from one instance of need to the next. The total volume of water abstraction for a given need reflects the amount of time over which water was diverted. Additionally, geographic analyses of land parcel data in Sonoma County indicate that at least six different land owners with property abutting the streams above the 05-Franz and 05-Bidwell gauges have vineyards planted on their property (Figure 8). Because water in this region is managed on the individual level, each grape grower may have a different temperature threshold at which water is initially applied to crops, and each grower who diverts from the stream to meet water needs may do so with a different pumping rate than a neighbour upstream or downstream. These management variations, along with temperature variability across space, can contribute to the differences in abstraction volume and magnitude of flow alteration each time air temperatures approached freezing. Similar variations likely occurred during the summer heat protection season as well.

The data presented in this study document another important discrepancy related to the impacts of decentralized water management in the region. In a few instances when water was needed for frost protection, the maximum magnitude of diversion and total abstraction volume at the downstream 15-Franz gauge is greater than or equal to the sum of diversion magnitudes and total volumes extracted at the upstream 05-Franz and 05-Bidwell gauges. Such results could be expected: impacts of diversion in headwaters, both as a maximum rate and total abstraction, could propagate downstream in a cumulative fashion (additional vineyards between the upstream and downstream gauges could account for greater diversion rates and total abstractions at the downstream gauge than the two upstream gauges combined). However, for the majority of instances when water is diverted from the Franz Creek drainage for frost protection, the maximum change in flow rate and total estimated abstraction was greater at one of the upstream sites than at the downstream 15-Franz site. Our detection of greater change in flow and greater overall abstraction detected upstream than downstream may seem counterintuitive to basic principles of stream hydrology. Streamflow at any point is a product of an upstream drainage network, so an abstraction that occurs in headwaters should appear in lower reaches as well. One possible explanation for this detected phenomenon may be the means by which we calculated maximum diversion rates and abstraction volumes. For each apparent frost protection occurrence, we selected an arbitrary point where diversion began based on irregular hydrograph changes, and selected the end point as the maximum flow following the rise in discharge after apparent water need had ended; we may have incorrectly identified when management actions began and ended.

The greater detected abstraction at upper than lower reaches of Franz Creek may also be attributed to the complexities of hydrological processes that influence streamflow. During base flow periods, streamflow may be

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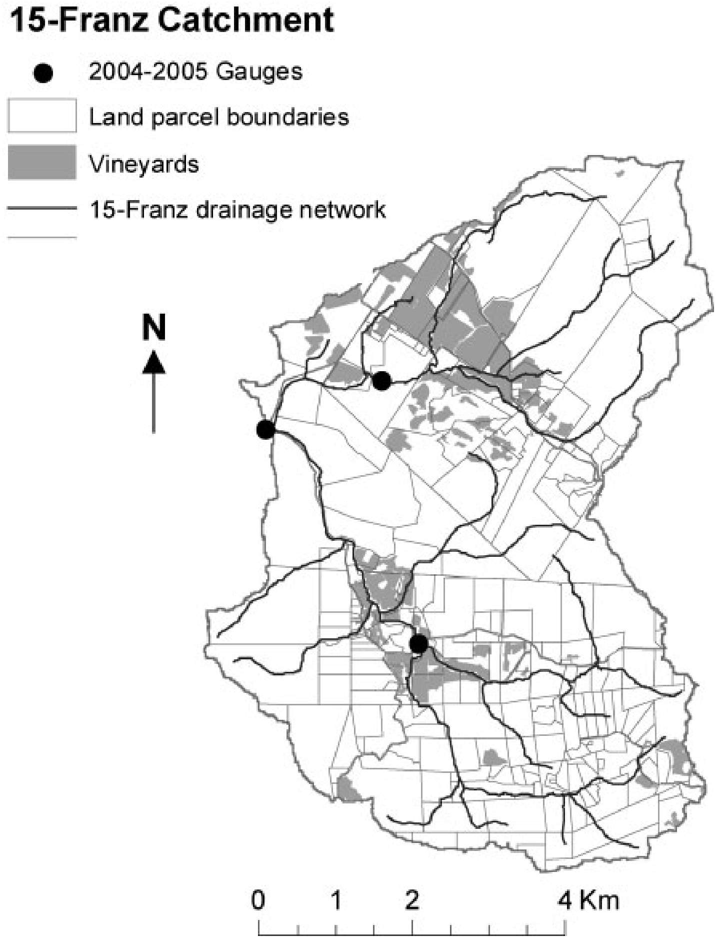

Figure 8. Land parcel data and vineyard coverage in the 15-Franz drainage basin, Sonoma County, California

derived from headwater drainages and adjacent shallow aquifers alike; the water level in the stream is often interpreted as the surface exposure of the shallow groundwater table (Dunne and Leopold, 1978; Ward and Trimble, 2004). If a volume of water diverted at an upstream reach causes a sudden depression of the surface water level, shallow groundwater could supplement streamflow so that surface water and shallow groundwater levels are equal once again. As a result, the impact of abstraction would appear less downstream. If this process were occurring in Franz Creek between headwater and downstream gauges, it appears that the rate at which groundwater can supplement streamflow is less than the rate at which water is diverted from the stream because there is some abstraction detected at the 15-Franz gauge. Though the abstraction may not fully manifest itself at 15-Franz through surface flow, the gap in water caused by upstream abstractions may instead accelerate the recession of shallow groundwater table between gauges. It would be inappropriate to attribute this mitigated flow impact to ‘return flow’, (the process whereby water applied to a crop percolates through soil and returns to the stream); return flow would return to the stream above the 05-Franz gauge where water was removed, and thus would not appear in the 05-Franz hydrograph. These unexpected differences in abstraction at upper and lower reaches highlight an important point regarding assessments of cumulative effects at the catchment scale. Local hydrologic impacts may manifest themselves differently at a different location in the drainage network. Impacts of changes to streamflow in the upstream catchment may not be accurately depicted by abstractions or changes in flow detected downstream.

Despite the differences in abstraction volumes at the same site and among different sites along the same drainage, the abstractions from Franz and Bidwell Creek correspond to reasonable estimates of water need if a fraction of the vineyard operators in each basin divert from the stream for a particular instance of frost protection in each basin. Regional vineyard extension specialists indicate that frost protection requires approximately 1000 m^3 of water per

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hectare of vineyard in a given year to be used over six events (Smith *et al*., 2004), corresponding to 166 m^3 per hectare for each frost protection event. Given the total vineyard area on riparian properties in the 05-Franz catchment, the total water need for 1 day of frost protection above the 05-Franz gauge is 10 600 m^3 per event. Even the highest calculated abstraction for a single day (8800 m^3) is less than the total water need among all potential upstream diverters. Water need versus abstraction above 05-Bidwell and 15-Franz compare similarly. Volumes of abstraction for each day indicate that only a fraction of water needed for frost protection for each event is met through direct instream diversion.

Small- versus large-scale water management projects

As small-scale water projects are increasingly developed to meet individual water needs, the potential local-scale and cumulative catchment-scale impacts of such projects on flow must be better understood (Potter, 2006). It may be most useful to frame these impacts through a comparison of our results described above to the hydrologic effects of larger projects. Magilligan and Nislow (2005) reported the greatest changes to the natural regime among 21 river systems with large-scale dams as reduced high-flow magnitudes, a point that was reiterated consistently in case studies (Ligon *et al*., 1995; Richter *et al*., 1996; Batalla *et al*., 2004; Grams and Schmidt, 2002; Marston *et al*., 2005; Page *et al*., 2005). In addition, large water projects commonly alter the rate of change of peak flows. Magilligan and Nislow (2005) describe more gradual rises in the rising limb of flood hydrographs in dammed river systems, and Wilcock *et al*. (1995) describe longer persistence of elevated flows than would occur naturally; Page *et al*. (2005) describe both higher and lower peak flow durations in a series of nested large dams.

These changes in peak flow characteristics reflect the capacity for large projects to regulate discharge for purposes such as flood protection and storage for uses during other periods, a characteristic that is absent among small-scale diversions in this study. Small diversions from Franz and Maacama Creeks did not reduce peak flow magnitude, timing or duration in winter or spring; peaks at 15-Franz in March and April, for example, occur at the same time and with the same duration as at upstream sites without diversions (Figure 3); and peaks at 45-Maacama occur with similar timing, duration and relative magnitude as at 24-Maacama (Figure 4). Although the small diversions did not reduce peak flows, they affected spring and summer base flows. In most cases, the magnitudes of spring and summer flows caused by diversion are not lower than what would typically occur at some point during the dry season, but diversions alter the rate of flow recession and cause low flows to occur earlier in the year. In contrast, large dams frequently augment base flow during the growing season by releasing more water to provide for conjunctive uses (e.g. Batalla *et al*., 2004; Grams and Schmidt, 2002; Magilligan and Nislow, 2005; Marston *et al*., 2005). Effects of small-scale water projects more closely resemble alterations caused by large-scale groundwater pumping. Kondolf *et al*. (1987) and Zariello and Reis (2000) both describe groundwater pumping as causing long-term reductions to streamflow during base flow periods by lowering groundwater tables. Unlike large-scale groundwater pumping, however, impacts caused by small-scale projects are not sustained; flows fall and then rise again even in summer, suggesting that a depleted groundwater table is not the cause of changes in spring and summer flows in Franz and Maacama Creeks.

In addition to different hydrograph impacts, small-scale water projects also have different spatial implications relative to centralized projects. Small projects in Franz and Maacama Creek, and throughout the northern California wine country, are distributed through the drainage network, and thus have potential to alter base flow dynamics wherever they operate. Franz Creek data indicate that diversions appear to have greatest influence locally and upstream in the drainage network; diversions above the 05-Franz gauge caused large local-scale changes in flow, and comprised a greater fraction of discharge than at 15-Franz (partly because flows were less in headwater reaches than further downstream). Several diversions in a catchment can depress flow throughout the drainage network, rather than at one location. Franz Creek data also illustrate the importance of measuring impacts locally over extrapolating to predict upstream impacts based on downstream measurements; local upstream changes in flow were frequently of greater magnitude than downstream gauge indicated.

Ecological consequences of small-scale water management

Because small water diversions have different hydrologic impacts than larger projects, they likely have different ecological effects as well. Small diversions are unlikely to significantly alter the magnitude and timing of high

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flows, which are critical to maintaining channel form and gravel bed texture and composition (Kondolf and Wilcock, 1996; Power *et al*., 1996), and thus are unlikely to cause changes to riparian and aquatic ecology commonly attributed to large storage projects. Preserving the timing of peak flows also maintains the biological signals and energy transport that high-flows provide (Ward and Stanford, 1995; Puckridge *et al*., 1998). In addition to altering peak flows, large water projects frequently augment summer base flows, which can benefit exotic (often predatory) fish populations (Marchetti and Moyle, 2001); small instream diversions have no capacity to increase base flows, and instead cause base flows to drop abruptly to unseasonably low levels earlier in the year. These changes in base flows may alter macroinvertebrate and fish community composition (McIntosh *et al*., 2002; McKay and King, 2006; Wllis *et al*., 2006). The hydrologic effects of small instream diversions more closely resemble those of large-scale groundwater pumping, but groundwater pumping also has different ecological consequences than small instream diversions. By lowering shallow aquifers, groundwater overdraft frequently causes loss of riparian vegetation that can no longer reach shallow aquifers (Shafroth *et al*., 2000; Naumburg *et al*., 2005). The rise of streamflow in Maacama and Franz Creeks immediately following periods of water demand, and the persistence of flow at most sites through summer, suggests that adjacent groundwater tables are not impaired by surface diversions to the extent that riparian vegetation would likely be unaffected under this management regime.

The potential ecological consequences of small instream diversions in the California wine country may be best described in the context of dry-season acceleration. Diversions in 2004 caused streamflow to resemble natural discharge 4 weeks later. Dry-season acceleration by up to 4 weeks in Franz Creek means that the depressed flows in late April more closely resembled those that occurred in late May; as a result, processes dependent on April flow conditions may not persist under depressed April flows. Even in Mediterranean-climate ecosystems where biota are adapted to a prolonged dry season each year, drought is considered a major ecosystem stressor (Gasith and Resh, 1999); instream processes dependent on a more gradual flow recession may be truncated if low-flow conditions occur prematurely. In Mediterranean climate streams in coastal California, longer or more intense drought can lead to different aquatic community organization, either resulting in lower overall numbers of certain organisms (e.g. Fawcett *et al*., 2003) or community composition more closely resembling lentic communities rather than lotic ones (Beche *et al*., 2006).

Though it is impossible to know for certain how small-scale water projects affect stream biota without a thorough analysis of how accelerated drought conditions affect instream resources, the changes that small instream diversions cause in the flow regime may be sufficient to change conditions that valued biota such as *anadromous salmonids* depend upon for persistence in a given stream. Anadromous salmonids, those fishes including steelhead trout (*Oncorhynchus mykiss)* and coho salmon (*Oncorhynchus kisutch*) that live as juveniles in freshwater streams and adults in the ocean, use tributaries such as Franz and Maacama Creeks for reproductive spawning and nursery habitat (SWRCB, 1997; Marcus and Associates, 2004). Their migration from the ocean to freshwater streams to complete their life cycle begins at the onset of the rainy season in late fall and early winter, and may occur throughout winter months. After redd construction and egg fertilization, water must pass over redds so that eggs remain oxygenated for between 40 and 60 days before fry emerge (Moyle, 2002). Changes in streamflow as a result of instream diversion can cause portions of riffles to be exposed (Spina *et al*., 2006); if flow conditions in March or April are manipulated to resemble those in late April or May, riffle exposure could cause egg mortality among redds laid as early as late January. Irregular flow recession in late spring may also adversely affect recently hatched juvenile salmonids by causing a loss of steady food supply via downstream drift, and by reducing long-term macroinvertebrate food supply (depending on the mobility of macroinvertebrates to regions that remain wetted), which provide important energy resources through summer (Suttle *et al*., 2004). In the Russian River catchment, hundreds of small diversions have the potential to impair spring and summer flows throughout the drainage network (Deitch, 2006). Because of their potential impacts on low flows and ubiquity throughout the northern California wine country, small instream diversions may threaten the survival of salmonids throughout the region.

CONCLUSIONS

Small instream diversions operating under a decentralized management regime may not impair the high flows as documented for large water projects, but instead deplete streamflow over short durations when water is needed for

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specific uses. Flow in subcatchments of Maacama and Franz Creeks with vineyards dropped abruptly as air temperatures approached 0°C and 32°C due to multiple, simultaneous small diversions, for frost and heat protection, respectively. The changes in flow at our gauges indicated that impacts of small projects tended to occur over brief periods and during base flow, a significant departure from the impacts of large water projects; the dispersed nature of these diversions means these flow regime alterations may occur throughout the catchment where such practices are prevalent.

Small-scale water projects may, as Potter (2006) implies, play an important role in alleviating the pressures of human water needs on aquatic ecosystems, but small projects as currently operated in Franz and Maacama Creeks do not achieve this objective. Instream diversions such as those in the Franz and Maacama catchments withdraw water when needed; this tends to occur during periods when streamflow is naturally low. Stable summer base flow is increasingly scrutinized as an essential factor for the persistence of anadromous salmonids in the region (RWQCB, 2005); if small instream diversions have similar effects throughout the northern California wine country, the changes that small water projects cause to the natural flow regime may play a principal role in limiting valued ecological resources such as anadromous salmonids throughout the region.

Just as the data presented here illustrate the impacts that these diversions may cause, they also may play a role in directing how future management can alleviate such pressures. Water needs for wine grapes are low relative to most crops, so if water needs could be satisfied through other methods of abstraction, then ecologically sustainable water management in California may still be achieved. Efforts to meet human needs while protecting instream values may be best addressed, not by altering how water may be diverted, but rather by changing when such diversions may occur. In this context, the natural flow regime of Mediterranean-climate rivers in coastal California can serve as a guide; the abundance of discharge that occurs during the wet winters may provide ample resources to meet all needs.

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