Public Comment TUC
Sonoma Co. Water Agency
Deadline: 4/24/09 by 5:00 p.m.

**From:** Alan Levine <alevine@mcn.org>
**To:** <commentletters@waterboards.ca.gov>
**CC:** <DRice@waterboards.ca.gov>, <TDoduc@waterboards.ca.gov>, <Choppin@waterb...
**Date:** Thursday, April 09, 2009 5:06 PM
**Subject:** : Frost and Flows Comments Russian River
**Attachments:** FROST COMMENTS.doc; Deitch_Kondolf_Merenlender_surfacewater_balance_AQC In Press 20081.pdf; Deitch_Kondolf_Merenlender_diversions_impacts_paper_RRA_in press 20081.pdf

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SWRCB EXECUTIVE

State Water Quality Control Board

These Comments are on the Frost Protection and other Russian River Flows Issues.

Coast Action Group has lengthy comments on file with the SWRCB regard State Policy (Draft Policy) for Maintaining Flows in Northern California Streams and the Trout Unlimited Peregrine Audubon Petition. CAG also has attended meetings with Ms Whitney on these issue and the issue of un-permitted/un-licensed diversions on the Russian River.

We believe that the Frost Protection issue is related, part and parcel, to the need for the State Board to express its authority and regulate both permitted and un-permitted diversion and use of water in the Russian River Basin.

CAG's recommendation(s) include application of the NMFS/DFG 2002 Joint Guidelines for Maintaining Flows in North Coast Streams and removal of un-permitted impoundment structures that are blocking stream habitat. With these actions by the SWRCB to occur immediately.

The SWRCB has been dawdling of making decisions on this issue for too long. The result is now a mess with Order WR 2009-0027-DWR - SWRCB mandatory Flow Reductions that will complicate issues of maintianing sufficient flows for fish and supplies for urban areas and agriculture in the Russian River. While attempting to grapple with supply issues and drought, the cumulative diversion by illegal and illegal agricultural use is an unmeasured obstacle confounding the whole issue. With the issue of agricultural use, illegal and legal; how will compliance assurance occur for Condition #15
- voluntary/cooperative compliance will be secured for withdrawal reduction target of 25 % in Sonoma County and 50% in Mendocino County from Ag and Municipal Users? Who will be monitoring Ag compliance? Will there be numbers attached.? Or - is this all going to rest on Sonoma County Water Agency flow modeling, that is unverified and inaccurate?

It should be obvious that sort of half way addressing the issue, without dealing with important constituent aspects, the problem will become uncontrollable and/or damaging to all parties. And, if periods of low rainfall continue, beneficial uses will not be maintained.

Attached is some scientific data, that you may have already, on the subject.

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**April 9, 2009**

**State Water Resources Control Board**
**Division of Water Rights**
***California Environmental Protection Agency***
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**And Linda Adams, Secretary for Environmental Protection**

**Russian River Frost Protection Workshop**

Re: Comments of Frost Protection Activities and Fish Kills; Inadequate Time to respond to Frost Protection Request for Comments

Thank you for the opportunity to comment on the above described important policy issue. Although a highly significant issue for many Russian River activists and volunteers working with agencies to forestall the extinction of steelhead trout and Coho and Chinook salmon in the basin, the public was only given 10 days - March 23, 2009 to April 2, 2009, to review and to respond to a request for comments. This is an unreasonable amount of time to expect volunteers - only able to devote a portion of their day to reading and responding to requests for comments from local and state agencies in a meaningful and substantive manner. I respectfully request that these comments be accepted and that the comment period be officially extended to allow an additional ten days for interested volunteer organizations to prepare comments.

I write to ensure that your office is aware of the studies conducted by Berkeley scientists that provide direct site specific data and analysis on the issue of the impacts of frost protection activities on wildlife, residents, and watersheds. Your policy discussions will very much be advanced by these.

> "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 18 m3/s) to near **zero** in two hours;" (*Hydrologic Impacts of Small Scale Diversions*, 2007; page 10; emphasis added)

I hereby incorporate by referencethe studies cited below and attached to these email transmission.

1. *Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian River basin, California, USA* 2007 by Merelender, Deitch, and Kondolf

2. *Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country* Matthew J. Deitch1, G. Mathias Kondolf, and Adina M. Merenlender1 Department of Environmental Science, Policy, and Management

These studies demonstrate that saving wine grapes from the cold often starnds and kills rare populations of listed commercial and sport fish. This spring time pumping and diversion of large amounts of ground and surface water, in the context of survival of listed species, is counter indicated by the facts. The facts militate against even small diversions. The steelhead and salmon are already struggling to survive huge odds including extreme low flows, high water temperatures, sedimentation, stranding, predation, and pollution. The listing of the several fish species under the Endangered Species Act is by definition a aggravated circumstance raising the threshold for what constitutes an acceptable impact to their critical habitat. That threshold does not include aerial spraying scarce abd critically important water on thousands of acres of wine grapes that can be "protected" by way of numerous other frost avoiding strategies.

The following are a representative sample of statements contained in the scientific studies attached hereto. These speak directly to the issues of many small diversions, frost protection, and extreme low flows.

Based upon conservative estimates of current demand, the surface water balance study conducted in 2006-2007 states that, " [i]n the streams studied here, sufficient flows do **not** exist to meet human demands during **spring** and summer, but winter discharge may be sufficient to meet human needs later in the year (*Surface water balance to evaluate the hydrological* *impacts of small instream diversions and application to the Russian River basin, California, USA 2007 by Merelender, Deitch, and Kondolf;*emphasis added*)*. The authors go on to explain that , "[t]he classic water balance as commonly applied is not useful for exploring impacts of **human water use** relative to flow regime because the time scale over which it typically operates is not congruent with streamflow." *Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian River*

"Empirical data collected in Maacama and Franz Creeks indicate that streamflow recedes quickly when water is needed for frost or heat protection at magnitudes approximately equal to the demand hydrographs presented here." (Supra Deitch, *2006 cited in 2007*). In addition, "[t]he model indicates that existing diversions have little capacity to influence peak or base flows during the rainy winter season, but may reduce streamflow during spring by 20% in one- third of all the study streams; and have potential to accelerate summer intermittence in 80% of the streams included in this study."

Regulatory agencies - lead, trustee, and responsible, have many tools at their disposal to prevent further loss of populations of species struggling to survive. Action and fortitude is demanded. Given what is known, what has been observed, measured, and predicted, and what additional water usurping projects have been planned, strict regulation is overdue. Diverters have not held up their end of the bargain and seek only to delay the time when either the fish as re gone and thus no longer protectable or the agencies miss the opportunity to be heroes and save the fish. The general public eagerly awaits the day when an agency determines that it will NOT be on its watch that listed species, counting on it, perished.

Although politically uncomfortable, an immediate prohibition on pumping for frost protection of non food or non essential crops would be appropriate, as well as institution of metering, monitoring, and additional moratoriums. To do less is to actively decide to abdicate local, state and federal responsibility to protect critical habitat and listed species.

And finally, "[r]iver restoration tends to emphasize physical channel rehabilitation (Palmer et al., 2005; Wohl et al., 2005), but such actions can be beneficial to biota only if streamflow is sufficient to support the necessary ecological processes (Richter et al., 1998; Arthington et al., 2006; Stromberg et al., 2007). Management and restoration practitioners can use the surface water balance to evaluate the extent to which water management practices may limit streamflow necessary for important ecological processes." As the scientist affirm, maintaining year round stream flows must be the top priority.

Thank you for considering my comments, and I wish you well in your important efforts to restore a healthy fishery and reliable instream flow regime for all.

Kimberly Burr

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Accepted: Aquatic Conservation: Marine and Freshwater Ecosystems

# Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian River basin, California, USA

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## Abstract

1. Small streams are increasingly under pressures to meet water needs associated with expanding human development, but their hydrologic and ecological effects are not commonly described in scientific literature.

2. To evaluate the potential effects that surface water abstraction can have on flow regime, scientists and resource managers require tools that compare abstraction to streamflow at ecologically relevant time scales.

3. We adapted the classic water balance model to evaluate how small instream diversions can affect catchment streamflow; our adapted model maintains the basic mass balance concept, but limits the parameters and considers surface water data at an appropriate time scale.

4. We applied this surface water balance to evaluate how recognized diversions can affect streamflow in twenty Russian River tributaries in north-central California.

5. The model indicates that existing diversions have little capacity to influence peak or base flows during the rainy winter season, but may reduce streamflow during spring by 20% in one-third of all the study streams; and have potential to accelerate summer intermittence in 80% of the streams included in this study.

## Introduction

The methods through which humans meet water needs frequently alter aquatic ecosystems. Manipulations caused by large centralized water projects have been well-documented: large dams and diversions can change the magnitude, frequency, duration, timing, and rates of change of peak flows and base flows (Cowell and Stroudt, 2002, Nislow *et al.,* 2002; Magilligan and Nislow, 2005; Page *et al.,* 2005; Marston et al., 2005; Singer; 2007), which may in turn change the sediment regime, disturbance regime, and biogeochemical processes upon which instream and riparian biota are dependent (Poff *et al.,* 1997; Whiting 2002; Bunn and Arthington 2002; Lytle & Poff 2004; Doyle et al. 2005). Ecohydrologists and stream ecologists frequently focus aquatic ecosystem management and restoration efforts on mitigating the impacts of large-scale water projects on major rivers (Baron *et al.,* 2002; Tharme, 2003; Fitzhugh and Richter, 2004; Arthington *et al.,* 2006; Richter and Thomas, 2007), whereby the natural flow regime serves as a reference for ameliorating those impacts (Postel and Richter, 2003; Suen and Eheart, 2006; Wohl *et al.,* 2005). Where data are available to illustrate pre- or post-dam streamflow conditions, managers use tools (e.g., Indicators of Hydrologic Alteration or IHA, Richter *et al.,* 1996; Dundee Hydrologic Regime Assessment Method or DHRAM, Black *et al.,* 2005) can explore how these projects affect discharge and direct management operations to more closely match a natural flow regime.

As an alternative to large-scale projects, water users are increasingly turning to smaller-scale projects, including small surface reservoirs and low-volume diversions, to meet water needs (SWRCB, 1997; Mathooko, 2001; Liebe *et al.*, 2005; *Economist,* 2007). Small-scale water projects are attractive from an ecosystem management perspective because they entail less abstraction and tend to be distributed in the catchment, thus spreading their impacts throughout the drainage network (Potter, 2006). However, the uncertainty regarding the impacts of small water projects on streamflow both locally and cumulatively and their growing numbers in many regions across the globe have caused concern among managers and scientists over their potential effects on stream hydrology and aquatic ecosystems (Pringle, 2000; Malmqvist and Rundle, 2002; Spina *et al.,* 2006). Recent literature has attributed changes in aquatic macroinvertebrate and fish communities to the operation of small diversions and reservoirs in the upstream drainage network (Rader and Belish, 1999; McIntosh *et al.,* 2002; McKay and King, 2006; Willis *et al.,* 2006). Despite these concerns, however, no clear frameworks have been presented in literature to evaluate or predict the effects of small projects on streamflow.

Tools designed to make ecologically meaningful evaluations of small-scale water projects on streamflow must consider potential interactions of two factors, flow regime and management regime (describing the means through which users acquire water from the ecosystem), over ecologically relevant timescales. Whereas streamflow gauges operating below large-scale water projects provide the resources necessary to evaluate the impairments they cause, fewer resources exist to characterize the changes to stream of small projects on streamflow. In the research that follows, we present a tool for ecologists and water resource managers based on the classic water balance (Thornthwaite and Mather, 1959; Dunne and Leopold, 1978) that can be used to predict the impacts of small decentralized water diversions on catchment discharge. We then demonstrate this tool to evaluate the impacts of small instream diversions on streamflow in the major tributaries to the 3800 km$^2$ Russian River catchment in the northern California wine country, and extrapolate to predict the potential effects that these projects may have on anadromous salmonids that use these tributaries for a large part of their life cycle.

## Study area and methods

Water users have used small-scale water projects to meet water needs in the Russian River basin in northern coastal California for over 100 years (SWRCB, 1997; Deitch, 2006). The regional climate is Mediterranean: virtually all of the annual precipitation occurs as rainfall between November and April, so water users cannot rely on precipitation for agricultural or domestic uses for several months each year. Instead, users frequently divert water directly from streams as needed. The climate also places pressures on aquatic ecosystems: streamflow recedes gradually through spring and summer to approach (and frequently reach) intermittence in the dry season, forcing aquatic ecosystems to persist through the annual drought each summer until precipitation returns the following winter. Impacts of diversion for human water needs may thus be greatest on stream hydrology and aquatic ecosystems during the spring and summer growing season: naturally low flows may be further depressed by diversions for agricultural uses such as frost protection, heat protection, and irrigation.

State and federal agencies have grown concerned about the increasing number of small-scale water projects in far upland watersheds, hillslopes, and hilltops of the Russian River catchment because of the potential impacts to environmental flows necessary for native anadromous salmonids (namely, federally protected coho salmon *Oncorhynchus kisutch* and steelhead trout *Oncorhynchus mykiss*) (SWRCB, 1997). The life cycle of these fishes is well-adjusted to regional streamflow patterns, but alterations to streamflow at particularly sensitive times may disrupt important ecological processes. Adult salmonids migrate into freshwater streams throughout the rainy winter, so winter flows must be high enough to allow salmonid passage and spawning, and keep redds submerged through incubation (which may last as long as 60 days). Juveniles must remain in streams through summer until the rainy season begins again in late fall; many juvenile salmonids remain in freshwater streams for more than one year before migrating back to the ocean (Moyle, 2002). Base flows during spring must keep redds submerged over adequate duration to complete incubation and supply energy to juvenile salmonids via downstream drift; and water levels in summer must be sufficient to maintain adequate habitat and energy supply as streams approach intermittence through summer. Streamflow alterations during this dry season may be a primary consideration to the conservation of salmonid populations in this region: the persistence of appropriate low-flow conditions is frequently a limiting factor for the survival of organisms adapted to seasonal environments (Gasith and Resh, 1999; Marchetti and Moyle, 2001; Lake, 2003).

## Model description and rationale

Hydrologists and resource managers frequently use the water balance as a foundation for exploring the effects of human water demand on river discharge (Dunne and Leopold, 1978; Ward and Trimble, 2004). The water balance uses a mass balance design (where output from a system equals input minus the change in storage, or $O = I \pm \Delta S$) to quantify water in various forms within a catchment. Input occurs via precipitation; output may occur as runoff, evaporation, plant transpiration, and/or groundwater flow (depending on its purpose or data availability); and change in storage may include plant water uptake and change in deep or shallow groundwater storage (also variable with data availability and purpose). Water balances can be expressed mathematically as

$$0 = P - Q - ET \pm \Delta G \pm \Delta \theta - U \qquad (1)$$

where P is precipitation, Q is stream discharge, ET is evapotranspiration (a combination of plant transpiration and surface evaporation), Δ G is change in groundwater storage, Δ θ is change in soil water storage, and U is plant uptake (Ward and Trimble, 2004).

The water balance has found many applications in contemporary applied hydrology. In ecology, it is used most commonly to project the changes in discharge under a managed change in catchment vegetation (often termed "water yield," reviewed by Bosch and Hewlett, 1982; Stednick, 1996; and Brown *et al.*, 2005), where changes in discharge are attributed to altered catchment evaporation and transpiration. Water balances have also been used along with new modeling techniques to predict how land management decisions that alter catchment processes affect discharge (*e.g.*, de Roo *et al*, 2001; Fohrer *et al.*, 2001; Wegehenkel, 2003; Vaze *et al.*, 2004; Ott and Uhlenbrook, 2004). Other recent applications include informing water budgeting and water management on a regional or national scale (*e.g.*, Hatton *et al.*, 1993; Yin and Nicholson, 1998; Habets *et al.*, 1999; Shankar *et al.*, 2004) and projecting impacts of climate change on stream discharge (*e.g.*, Strzepek and Yates, 1997; Middelkoop *et al.*, 2001; Walter *et al.*, 2004).

The classic water balance as commonly applied is not useful for exploring impacts of human water use relative to flow regime because the time scale over which it typically operates is not congruent with streamflow. Water balances employ data at annual or monthly scales, partly because of the scales over which certain trends may be illustrated, and partly because of level of detail over which certain components may be available. Though data at monthly and annual scales are useful for illustrating broad-scale changes in discharge over time for many common management objectives, such time scales are insufficient for characterizing streamflow, which ultimately dictates the timing and duration of ecological processes. Streamflow fluctuates naturally over finer scales such as daily or sub-daily (Poff, 1996; Deitch, 2006); aquatic organisms are exposed to water constantly; and human-caused changes to streamflow may be short-term, as brief as hours (Deitch *et al., submitted*).

To evaluate the potential impacts of small water projects on catchment discharge at ecologically meaningful time scales, we have modified the classic water balance by retaining the mass-balance concept and considering only the interactions between streamflow already in the drainage network and the diversions from that drainage. We define input ($I$) as the sum of surface water contributed to the stream from the upstream drainage network, described by streamflow measured at a defined point in the watershed. Change in storage ($\Delta S$) is defined by diversions from the drainage network upstream of that point. Output ($O$) is defined as the flow from the drainage network that leaves the catchment, reflecting that which is not removed by upstream diversions. Conceptually, our surface water balance can be described as:

$$O \text{ (catchment discharge)} = I \text{ (sum of upstream flow)} - \Delta S \text{ (sum of upstream diversions)} \quad (2)$$

Each component of the water balance describes flow over a per-second time interval, thus expressing the impacts of instream diversions on streamflow at appropriate time scales.

## Application

We first used publicly available data to define input and change in storage for seven historically gauged Russian River tributaries in rural Sonoma and Mendocino County, California (A through G, Figure 1): the upper Russian River, Feliz Creek, Pena Creek, Maacama Creek, Franz Creek, Santa Rosa Creek, and Austin Creek (Table 1). Streamflow data provided the temporal resolution necessary for our intended purpose (i.e., volume per second); all streams were unimpaired by large dams or hydroelectric projects at the time of collection and depicted streamflow under low development, thus representing a more natural flow regime than current discharge measurements would express. For six streams gauged in the 1960s, we chose streamflow measured in water year 1966 as input data: 1966 was the year with median annual discharge among four of the six gauges and with median annual precipitation at a central location in the Russian River basin (Healdsburg, California) from 1950 to 2000. The underlying assumption in choosing median-discharge year 1966 as the input is that the 1966 flows depict normal-year streamflow characteristics, so the water balances we depict here illustrate potential changes in flow through an annual cycle in a typical year. For Pena Creek, which operated in the 1980s, we chose streamflow from median annual discharge year 1981 for input.

Change in storage (i.e., maximum allowable water removal) in each study drainage was determined from surface water rights applications, which include the proposed rate of diversion (in volume per second), period of year for diversion (e.g., 1 May to 30 September), and drainage in which the diversion operates. We gathered water rights data for each study stream and summed the approved pumping rates over the period of permitted diversion to calculate a daily maximum rate of diversion for all users in each drainage (unapproved appropriative requests were not included). For the two streams where only the headwaters were gauged (upper Santa Rosa and Upper Russian), only those diversions upstream of the gauge were included. For the other five stream gauges, which were all located near confluences with the Russian River, we used all catchment diversions and adjusted daily streamflow as a ratio of total- to gauged-catchment areas to estimate total catchment flow (e.g., daily streamflow from Maacama Creek was multiplied by [total catchment area / gauged catchment area], or [118 $km^2$ / 112 $km^2$] to estimate total catchment mean daily flow).

We depicted surface water balances by plotting input and change in storage for each stream on the same graph. Streamflow hydrographs illustrated input (I) as described above. To graphically depict instantaneous water demand ($\Delta S$), we plotted the daily maximum rate of diversion on each day as derived from water rights records, which we call a *demand hydrograph.* The demand hydrograph expresses the maximum impact that diversions can have on total catchment discharge at any time. Projected output (*O*) can be for each day can be calculated or conceptualized as the difference between I and $\Delta S$.

## Water balance expansion to ungauged catchments

For our second analysis, we created surface water balances for all other Russian River tributaries fourth-order and greater to more thoroughly explore the potential impacts of diversions on streamflow in the Russian River drainage network (1 through 13, Figure 1). We used records of all registered diversions in each drainage to calculate the daily maximum rate of diversion ($\Delta S$) from each; the two largest streams, Dry Creek and Mark West Creek, were broken up into sub-catchments (Dry into Mill Creek and Pena Creeks; and Mark West into upper Mark West, Windsor, and Santa Rosa Creeks) and each was evaluated separately. We estimated input (I) by converting flow from each gauged stream in Part 1 to flow-per-area (L / s / $km^2$); we then ranked each day's flow values to create a high, median, and low-flow estimate for a Russian River tributary in a typical year. These flow estimates represent three stream-type scenarios, capturing the variability in catchment properties and precipitation in the Russian River basin that could be expected in a typical year. Because our initial low-flow estimate did not depict the natural flow regime (illustrating no peak flow events, atypical even among dry-type streams in a normal year), we instead used median-year flow data from Pena Creek, which had lowest per-area annual discharge and dried the earliest among gauged streams, to depict dry-type conditions. We depicted water balances for ungauged streams through similar methods as the seven gauged streams above: demand hydrographs were plotted along with the wet-type, median-type, and dry-type streamflow estimates to illustrate how diversions could impair normal-year streamflow.

## Results

### Historically gauged streams

Surface water balances were best illustrated graphically on a logarithmic scale because magnitudes of diversion and dry-season flow were orders of magnitude less than flow during winter. All gauged streams show similar flow regime characteristics of high-flow and base flow timing through winter and steady flow recession through spring and summer (Figure 2). Demand from each stream, however, varies considerably from one stream to the next: Maacama Creek and Franz Creek are subject to many surface water diversions, while few diversions have been approved on the upper Russian River and upper Santa Rosa Creek (Table 1). Pena Creek has no formal requests for surface water from its catchment, indicating that its flow is unaffected by approved small-scale water projects.

For those streams with upstream surface water demand, seasonal demand hydrograph trends are similar: demand is lowest in winter, rises during spring and early summer, and recedes in late summer and fall. Peak flows during winter exceed basin demand by over two orders of magnitude in all cases. Also, winter base flows are consistently an order of magnitude greater than winter demand in most drainages (Figure 2; the exceptions being the upper Russian River and Maacama Creek gauges, though only for brief durations in December). In spring, this trend begins to shift. Demand in early April (marking the beginning of the growing season) equals 13% and 26% of normal-year flow in Franz and Maacama Creeks, respectively; by mid-May, demand equals 33% of flow in Franz Creek, 20% of flow in Feliz Creek, and 87% of flow in Maacama Creek (Table 2). By mid-July, surface water demand exceeds flow from the Upper Russian River, Feliz Creek, Franz Creek, and Maacama Creek catchments. Demand is greatest in the Maacama Creek catchment: demand exceeds flow in early June, threatening flow persistence that lasts through September in a normal year. The potential impact of registered diversions is low in Santa Rosa and Austin Creek, comprising less than 10% of flow until late September.

### Ungauged streams

Each of the three estimated input conditions for ungauged stream water balances illustrate high peak flows in winter and receding base flows through spring and summer; but they differ in peak flow magnitudes (8000 L / s / $km^2$ in the wet-type and 2400 L / s / $km^2$ in the dry-type streams) and base flow magnitudes. They also differ with respect to the point at which they become intermittent in summer: the wet-type streamflow approaches intermittency but retains low flow through summer months, while the normal-type stream becomes intermittent in early August and the dry-type stream in early June (Figure 3).

Similar to gauged streams, the potential impact of demand on streamflow in ungauged streams varies with season. Winter demand among all ungauged streams comprises less than 2% of peak flows throughout winter, even relative to flow in the dry-type stream (Figure 3). In most cases, winter base flow is also unimpaired, though demand from two of the 13 ungauged streams exceeds the dry-type winter base flow in early winter and equals more than 10% of median-type base flow later in winter (Table 3).

The potential impact of demand is more variable among ungauged streams during spring. In early April, demand comprises more than 10% of the dry-type streamflow in seven of the 13 streams, and 10% of the wet-type streamflow among five of those (Table 3). As flow recedes through spring, the potential impact of demand becomes greater. By mid-May, demand equals more than 10% of dry-type spring base flow from 12 of the 13 ungauged catchments, and exceeds dry-type flows in five of those 13. The potential impact of demand in summer is not as variable as on spring and winter discharge. By 15 July, demand exceeds dry-type flow in all of the 13 ungauged streams; and exceeds even the wet-type flow in seven of these (Table 3). Also, similar to the gauged streams, the time during summer when demand exceeds discharge varies among catchments. Demand exceeds median-type discharge in two streams as early as May, while demand exceeds median-type discharge in most streams by the end of June (median-type discharge would typically persist until early August).

## Discussion

### Potential effects to flow and ecological consequences

The surface water balances for the 20 major Russian River tributaries described above provide important insights for understanding how regional surface water management practices may affect aquatic resources through the year. Because of the interest in conserving and restoring anadromous salmonids in the region, it may be most useful to compare the impacts of small diversions to environmental flows necessary for salmonid persistence. Flushing flows, which prevent vegetation encroachment and maintain channel form and gravel size distribution for salmonid spawning (Wilcock *et al.,* 1996; Kondolf and Wilcock, 1996), are likely unimpaired by small instream diversions in this region because peak flows are much higher than cumulative demand in all streams studied. Additionally, instantaneous demand comprises less than 10% of base flow over most of the winter in all streams, suggesting that processes dependent upon winter base flows such as spawning and upstream passage are unimpaired by approved instream diversions in these streams for most of the winter.

Instream diversions from Russian River tributaries have greater potential to impair ecological processes through spring and summer because the steady flow recession corresponds with increasing demand during the agricultural growing season. Surface water balances predict that flow may be impaired during spring in almost all of the Russian River tributaries studied here; diversions that depress spring base flow may leave parts of riffles desiccated, which may reduce egg viability and downstream energy drift for juvenile salmonids (Spina *et al.,* 2006). Though most of the gauged streams become intermittent by August under natural conditions (Figure 2), surface water balances suggest that this intermittence may occur as early as June in more than half of the streams studied here. Given their historical distribution throughout central coastal California (Leidy *et al.,* 2005), salmonids native to this region can likely withstand some intermittence; but an accelerated intermittence by as much as 6 weeks could reduce downstream energy drift, essential for juvenile salmonid survivorship in this region (Suttle *et al.,* 2004). Additionally, prolonged isolation of pools may disrupt natural biochemical regimes (e.g., dissolved oxygen, nitrogen), potentially threatening juvenile survivorship (Carter, 2005); and observations and empirical evidence suggest that late summer diversions may continue to deplete pools even where surface flow has ceased (Fawcett *et al.*, 2002; Deitch, *2006*). The imbalance between streamflow and demand in nearly all study streams suggests that summer water demand may be a primary limitation to the persistence of anadromous salmonids throughout this region.

## Model assumptions and strengths

Like any model, the surface water balance described here makes assumptions that may cause inaccurate depictions of interactions among components of interest (here, streamflow and water demand). Most notably, the cumulative catchment demand (reflected here by the demand hydrograph) may not always depict the actual effect of diversions on catchment discharge. The demand hydrograph expresses the pumping rate of all users in a catchment, but all users likely do not operate their diversions continuously or simultaneously through most of the year. Grape growers may need water only for part of the day and for a few days a week, so the sum of all registered diversions over-predicts the impacts to streamflow for most of the spring and summer. At times, however, conditions may occur when all users in a catchment need water simultaneously for the same purpose. For example, on spring mornings when temperatures are below freezing, water is sprayed aerially to prevent recently emerged grape buds from freezing; and on particularly hot summer days, water is sprayed aerially to prevent changes in crop quality associated with high temperatures. Empirical data collected in Maacama and Franz Creeks indicate that streamflow recedes quickly when water is needed for frost or heat protection at magnitudes approximately equal to the demand hydrographs presented here (Deitch, *2006*).

The physical simplification of watershed processes may also constrain the ability of the surface water balance to depict actual diversion impacts. Our model neglects many of the components commonly incorporated into water balances such as catchment evapotranspiration and loss to subsurface aquifers, both of which are important components of the hydrologic cycle. These components may alter the impact of a diversion on catchment discharge from that depicted in our demand hydrograph, but most catchment processes (e.g., evapotranspiration and loss to groundwater) would already be incorporated into discharge. Input already considers these factors. Perhaps more importantly, the surface water balance evaluates discharge and diversion impacts at a catchment scale, and thus does not address the distribution of diversions in the drainage network. It instead projects catchment output based on inputs from upstream and total change in storage throughout the drainage network. Demand may have a larger effect locally near a point of diversion, or a lesser effect on catchment output depending on the distribution of diversions in the drainage network if streamflow can be supplemented by shallow aquifers.

Despite these drawbacks, the surface water balance incorporates some important strengths. The most important feature of our model is the use of data at a temporal scale sufficient for characterizing flow regime: here, input is depicted as mean daily flow, and change in storage is defined by the basinwide demand for surface water each day through the year. Both express changes in volume over per-second time intervals. Similar conceptual comparisons of discharge and appropriation are used in California to determine whether a stream is categorized as "fully appropriated," but the evaluations are performed at an annual scale as volumes per year (SWRCB, 2004); the surface water balance provides a framework to evaluate whether streams are fully appropriated at a daily scale, which is more important for evaluating impacts relative to ecological processes.

Additionally, simple adaptations to the input parameters can allow managers to create surface water balances under a variety of conditions. We used streamflow data from a median-type year as an input, but flow data from a typically dry-type year could illustrate how demand would impair streamflow under a low-flow scenario. Such analyses may be useful to evaluate impacts of instream diversions when systems are under hydrological stresses typically imposed by a regional climate. Our analyses have also demonstrated that the surface water balance can be created quickly to compare interactions between streamflow and management regimes for many streams, and can provide a framework for rapid visual interpretation of these streams as well.

## Conclusions

Because of its ease to create and interpret, the surface water balance tool described here can have many applications in regional water management and restoration prioritization. River restoration tends to emphasize physical channel rehabilitation (Palmer *et al.*, 2005; Wohl *et al.*, 2005), but such actions can be beneficial to biota only if streamflow is sufficient to support the necessary ecological processes (Richter *et al.*, 1998; Arthington *et al.*, 2006; Stromberg *et al.*, 2007). Management and restoration practitioners can use the surface water balance to evaluate the extent to which water management practices may limit streamflow necessary for important ecological processes. Though managers and restoration ecologists frequently emphasize physical channel rehabilitation (Kondolf *et al.*, 2006), the data presented here indicate that water availability in summer months may also play an important role in limiting salmonid persistence throughout the Russian River basin. For many of these tributaries to serve as viable over-summering habitat for juvenile salmonids, changes in water management strategies may be necessary so that small diversions do not impair spring and summer flow regime characteristics.

Just as the surface water balances above illustrate potential problems with small-scale water management, they also can point to possible solutions. In the streams studied here, sufficient flows do not exist to meet human demands during spring and summer, but winter discharge may be sufficient to meet human needs later in the year. The surface water balance illustrates how winter flows in a normal year may be removed from the stream in a way that will not impede the natural flow regime, and thus ameliorate pressures on aquatic organisms that depend on spring and summer flows. Once goals for water management are established, small-scale water projects may operate in strategic ways to maintain the needs of both humans and aquatic biota; but such management will likely require careful planning and may require additional expenses. Without acknowledging the effects of small-scale instream diversions over fine temporal scales, ecologically sustainable water management cannot be achieved.

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Table 1. Gauged Russian River tributaries used in the surface water balance application: streamflow gauge and watershed properties.

| Stream | USGS gauge number | Total area, km$^2$ (letter, Fig. 1) | Period of record (water years) | Number of diversions | Intermittence date, Figure 2 |
|---|---|---|---|---|---|
| Pena | 11465150 | 58.8 (F) | 1979-1990 | 0 | 06 June |
| Santa Rosa | 11465800 | 32.4 (D) | 1960-1970 | 1 | 29 September |
| Austin | 11467200 | 181 (E) | 1960-1966 | 16 | (perennial) |
| Upper Russian | 11460940 | 36.5 (A) | 1964-1968 | 1 | 13 July |
| Franz | 11463940 | 62.1 (C) | 1964-1968 | 10 | 23 July |
| Feliz | 11462700 | 109 (G) | 1959-1966 | 5 | 17 July |
| Maacama | 11463900 | 118 (B) | 1961-1980 | 32 | (perennial) |

Table 2. Comparison of catchment streamflow and upstream catchment demand among gauged study streams at various times through the water year, representing different seasonal flows: winter base flow (26 January), early spring base flow (01 April), late spring base flow (15 May), and mid-summer base flow (15 July).

| Stream | Surface water balance, 26 Jan | | Surface water balance, 01 April | | Surface water balance, 15 May | | Surface water balance, 15 July | |
|---|---|---|---|---|---|---|---|---|
| | Flow, L/s | Demand, L/s | Flow, L/s | Demand, L/s | Flow, L/s | Demand, L/s | Flow, L/s | Demand, L/s |
| Pena | 2400 | 0 | 1100 | 0 | 82 | 0 | 0 | 0 |
| Santa Rosa | 260 | 0.37 | 190 | 0.37 | 6 | 0.37 | 6 | 0.37 |
| Austin | 2700 | 11 | 2200 | 11 | 820 | 11 | 100 | 11 |
| Upper Russian | 270 | 4.0 | 280 | 4.0 | 71 | 4.0 | 0 | 4.0 |
| Franz | 400 | 19 | 250 | 31.6 | 120 | 40 | 4 | 21 |
| Feliz | 500 | 12 | 690 | 13.3 | 140 | 27 | 4 | 27 |
| Maacama | 1200 | 120 | 790 | 205 | 340 | 290 | 80 | 270 |

Table 3. Ungauged Russian River study tributaries used in the surface water balance application: catchment properties, and catchment demand as a percent of streamflow under the *high* flow regime and *low* flow regime estimates, at periods of winter base flow (26 January), early spring base flow (01 April), late spring base flow (15 May), and mid-summer base flow (15 July; **low flow regime flow estimate is 0 L/s).

| Stream | Area, km$^2$ (Num., fig. 2) | Number diversions | Demand as % of flow, 26 Jan | | Demand as % of flow, 01 April | | Demand as % of flow, 15 May | | Demand as % of flow, 15 July | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | High est. | Low est. | High est. | Low est. | High est. | Low est. | High est. | Low est. |
| Dooley | 40.6 (2) | 9 | 11 | 64 | 46 | 92 | 200 | 560 | 660 | ** |
| Ackerman | 51.6 (11) | 4 | 12 | 68 | 34 | 69 | 140 | 400 | 710 | ** |
| York | 30.0 (12) | 4 | 0.0 | 0.0 | 28 | 57 | 120 | 350 | 530 | ** |
| McClure | 44.8 (1) | 6 | 0.0 | 0.0 | 26 | 53 | 110 | 320 | 500 | ** |
| Pieta | 98.2 (3) | 3 | 0.0 | 0.0 | 14 | 29 | 29 | 83 | 190 | ** |
| Mark West | 134 (6) | 20 | 0.0 | 0.1 | 6.6 | 13 | 35 | 100 | 200 | ** |
| Windsor | 69.4 (5) | 4 | 0.0 | 0.0 | 8.9 | 18 | 19 | 54 | 120 | ** |
| Robinson | 67.3 (10) | 8 | 0.0 | 0.0 | 1.3 | 2.7 | 19 | 54 | 82 | ** |
| Forsythe | 125 (13) | 18 | 0.1 | 0.4 | 3.4 | 6.9 | 17 | 48 | 18 | ** |
| Green Valley | 98.6 (8) | 9 | 0.1 | 0.3 | 0.8 | 1.6 | 7.5 | 21 | 50 | ** |
| Mill | 60.0 (9) | 19 | 0.1 | 0.4 | 0.9 | 1.9 | 5.6 | 16 | 44 | ** |
| Santa Rosa | 203 (7) | 8 | 0.0 | 0.0 | 0.5 | 1.0 | 4.2 | 12 | 25 | ** |
| Brooks | 21.0 (4) | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | ** |

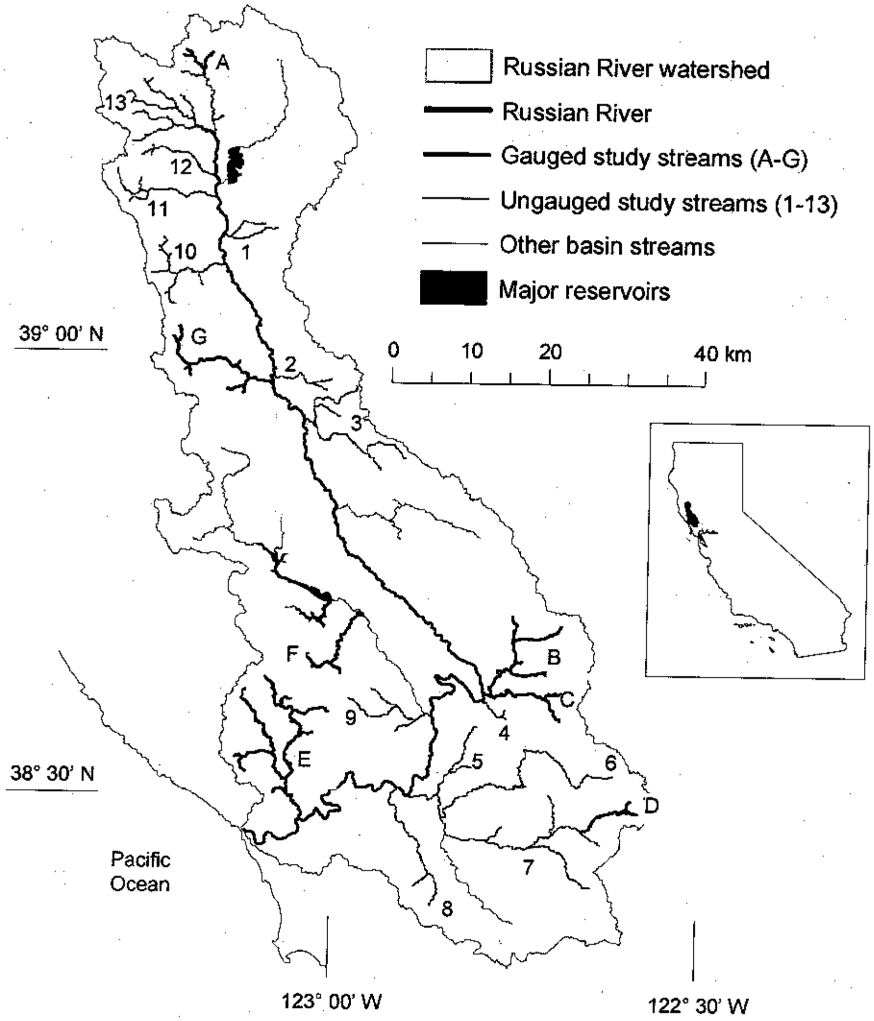


Figure 1. Study streams, tributaries to the Russian River, gauged (A through F) and ungauged (1 through 13). Identifiers correspond to letters and numbers in Tables 1 and 3.

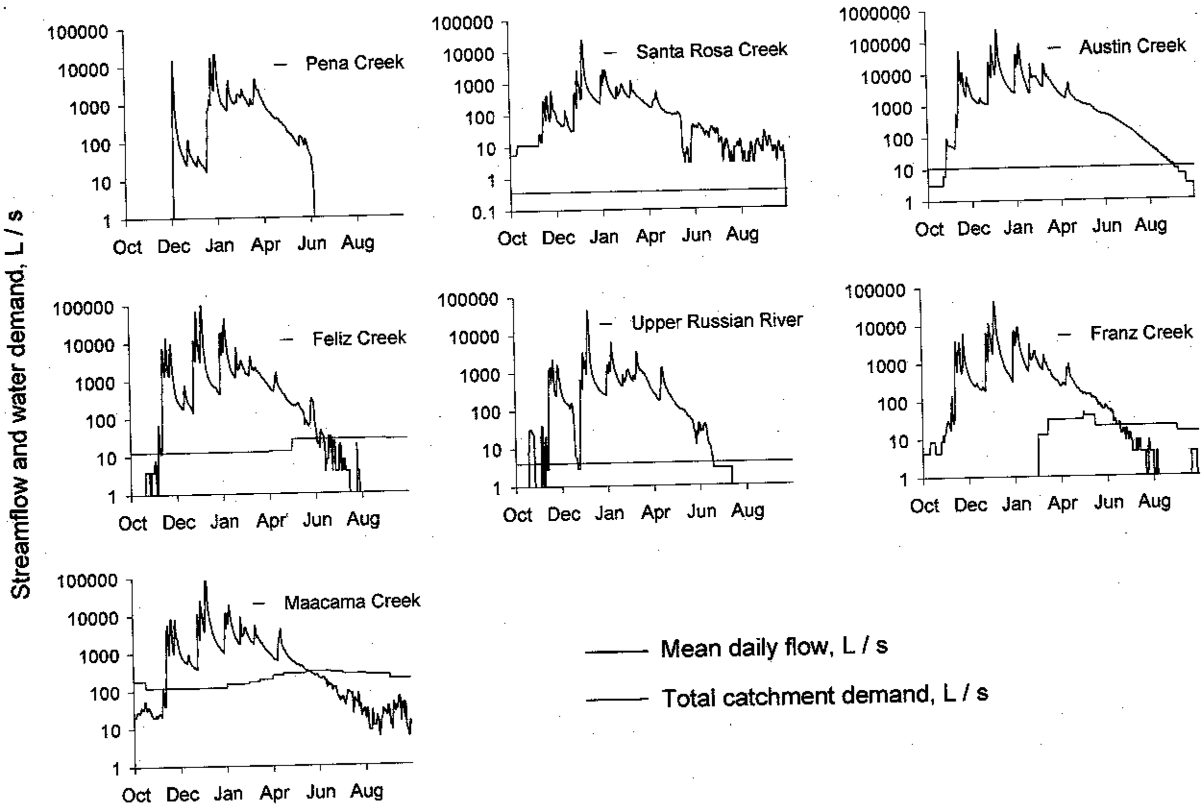
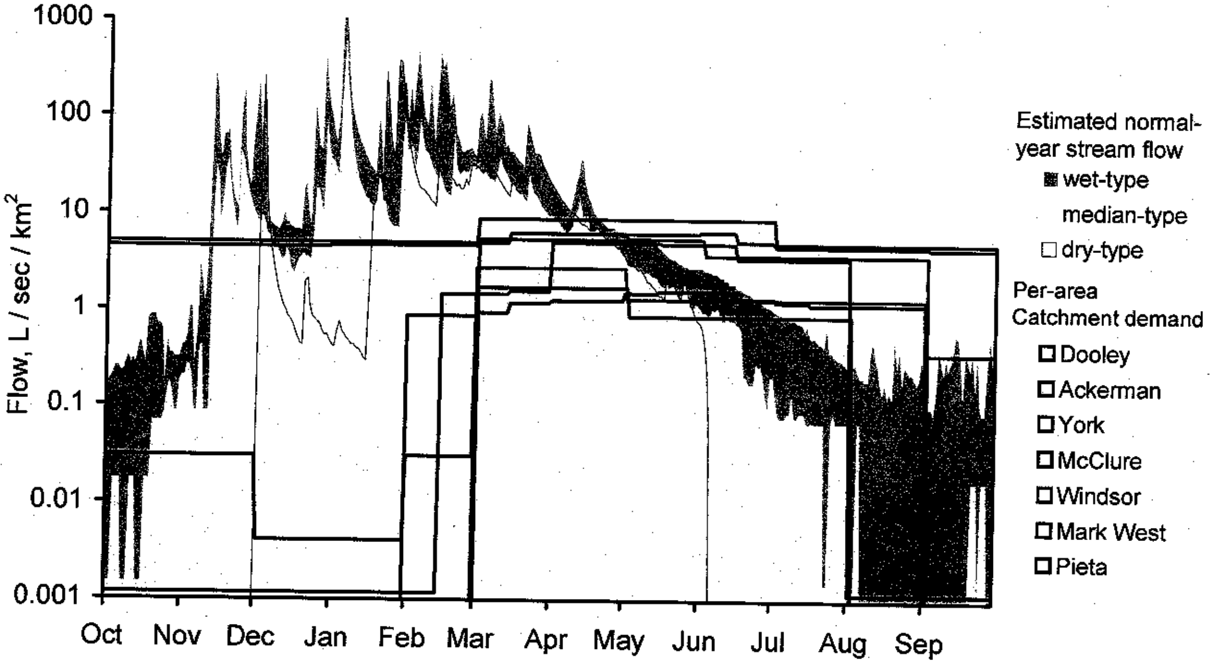


Figure 2. Log-scale plots of surface water balances through a typical water year (based on historical streamflow data) for seven gauged Russian River tributaries, Mendocino and Sonoma Counties, California, USA.



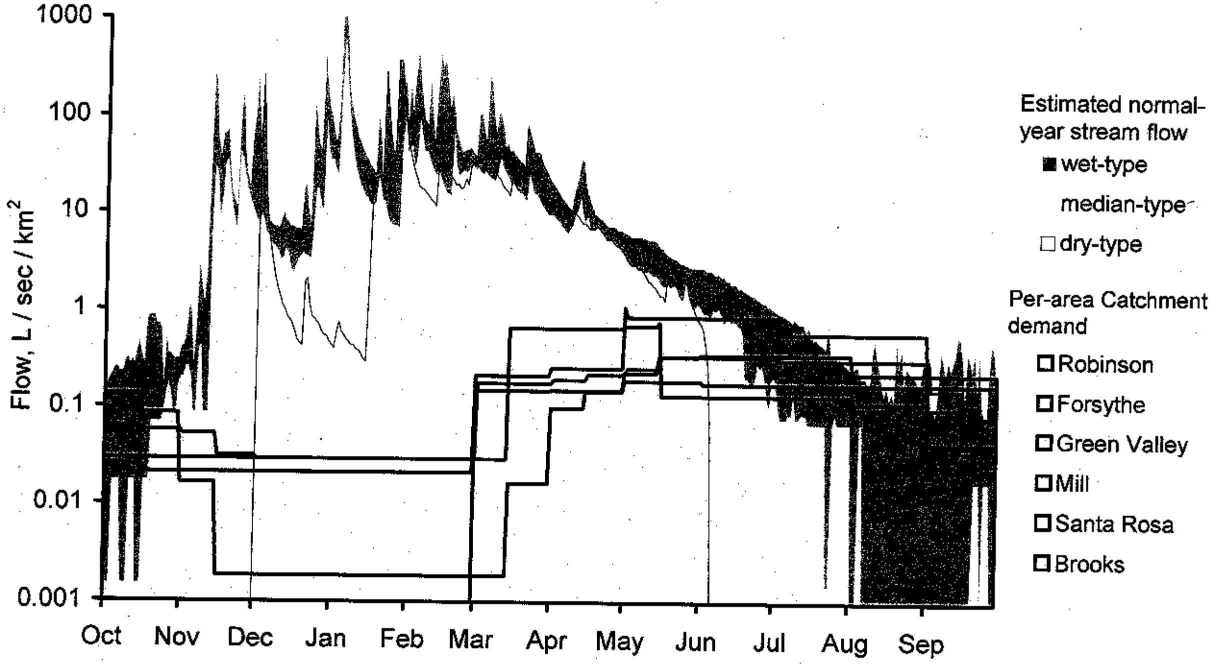


Figure 3. Surface water balances through a water year for the thirteen ungauged Russian River tributaries used in this study: estimates of normal-year flow under a wet-type, middle-type, and dry-type flow regime, and surface water demand from each catchment, both as L/sec/km$^2$ (plotted on a logarithmic scale). Streams were split between two graphs for visual purposes, grouped as higher and lower demand based on demand during spring and summer (Brooks Creek demand is less than 0.001 L/sec/km$^2$ throughout the year).

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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.

## 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 (Wilcock *et al.,* 1995; Cowell and Stroudt, 2001; Nislow *et al.,* 2002; Grams and Schmidt, 2002; Magilligan and Nislow, 2005; Page *et al.,* 2005; Kondolf *et al.,* 1987; Claessens *et al.,* 2006; Glennon, 2003). Along with these changes in flow regime, large centralized projects also alter the dynamics of sediment (Ligon *et al.,* 1995; Sear, 1995; Brandt, 2001; 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; Osmundson *et al.,* 2002; Pringle *et al.,* 2000; Marchetti and Moyle, 2001; Downes e*t al.,* 2003; Cowley, 2006) as well as those in adjacent riparian zones (Nilssen and Svedmark, 2002; Lytle and Merritt, 2004; Johnson, 2002; Elderd *et al.,* 2003).

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., Levite *et al.*, 2003; Mathooko, 2001; Dole and Neimi, 2004), including direct instream diversions and surface reservoir storage in small headwater tributaries. The decentralized nature of small-scale projects is believed 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 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 stream flow 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; McCay and King, 2006; Willis *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 five principal tributaries to the Russian River (3800 km$^2$) and Franz Creek is 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 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, 1999; 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 ten-minute 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 1). 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.

## 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 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 2), and identified the occurrence frost protection impacts as irregular deviations in the relationship between 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 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 hours; flow returned to previous levels over the following 18 hours (Figure 2; Table 2). Flow at this 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 rising in the days following; the artificially depressed flows lasted from 1.5 to 3.5 days (Table 2), 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 between 1000 to 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 two hours; flow rose again to previous levels during the following three hours (Figure 2). Flow recessions over the following weeks more closely resembled the changes in nearby Bidwell Creek in terms of magnitude and duration (Table 2), with the exception of alteration from 14 April 2004 to 19 April 2004 (during which minimum daily air temperature ranged from 0 to 1°C on four consecutive mornings), when flow receded from 30 L/s to 0 L/s and then remained depressed for three 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 to 7700 m$^3$ (corresponding to between 300 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 2). 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 2), 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 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 2). 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 also were 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 to 2 times the flow at 24-Maacama through the winter until late March, when this discharge relationship changed systematically during 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 2005raised flow at 45-Maacama again to approximately two times that at 24-Maacama; but flow receded in the days following to again equal 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 equaled 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 6). 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 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.

### <u>Heat protection, Maacama Creek</u>

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 through 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, 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 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 3). 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 two 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 four-day periods in April 2005; summer flow hydrographs show that flow from Redwood Creek continued for the remainder of summer 2005 (Figure 7).

## 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 T exceeded 32 degrees. 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 is the maximum magnitude of change at a site ever the same (Table 2). The total volume of abstraction also frequently varied at the same site from one instance to the next (Table 2). 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 6 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 neighbor 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 hydrological processes that influence streamflow. During base flow periods, streamflow may be 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 in an effort to make the surface water and shallow groundwater levels 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 the 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 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 one 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 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 (Page *et al.*, 2005; Grams and Schmidt, 2002; Ligon *et al.*,1995; Marston *et al.*, 2005; Batalla *et al.*, 2004; Richter *et al.*, 1996). 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 5). 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; Marston *et al.*, 2005; Magilligan and Nislow, 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 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; Willis *et al.*, 2006; McKay *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; Naumberg *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 four weeks later;. Dry-season acceleration by up to four 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 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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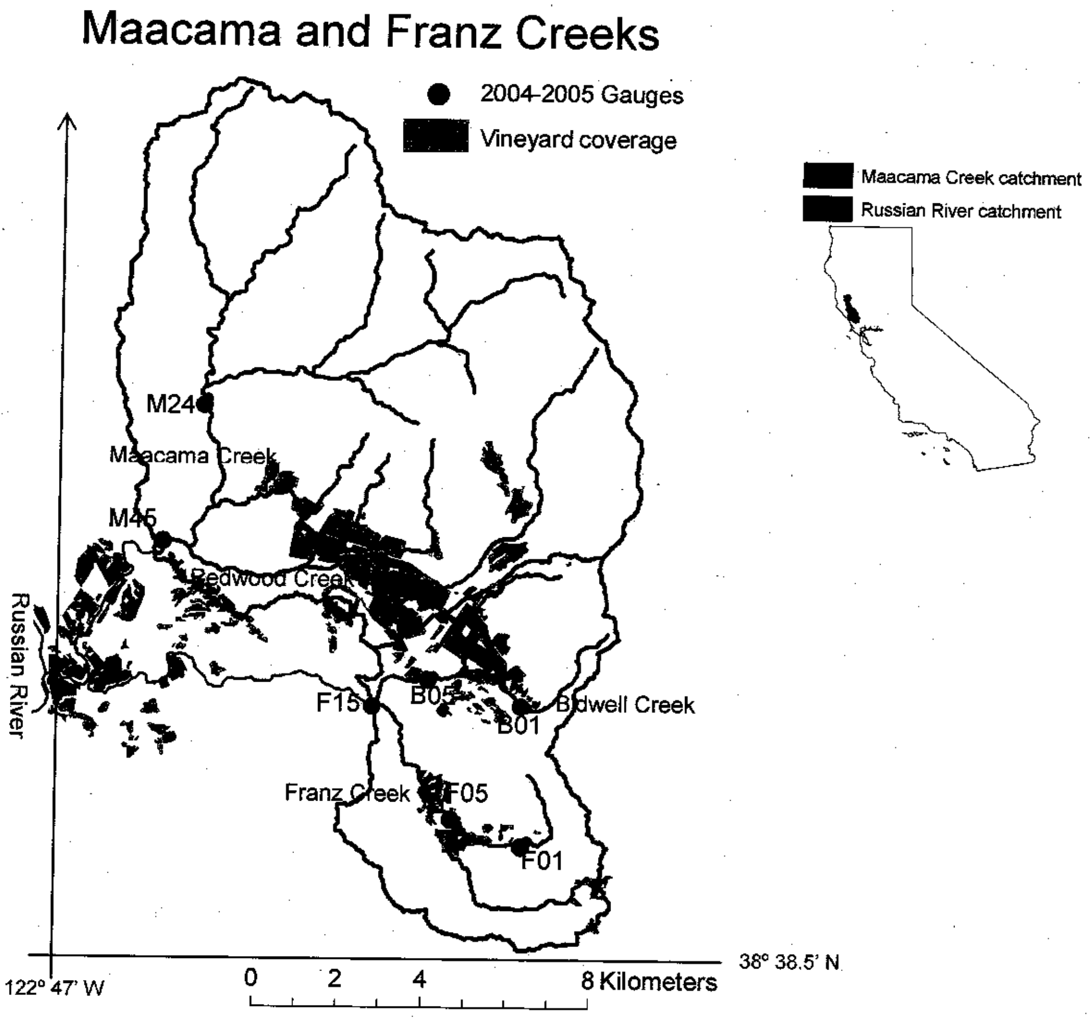
Table 1. Characteristics of streamflow gauges and upstream catchments in the Franz Creek and Maacama Creek drainage networks.

| 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 |

Table 2. Changes in streamflow and abstraction volumes on freezing or near-freezing mornings in the Franz Creek drainage network, spring 2004 and 2005. (** hydrograph depression at 05-Bidwell on 12 April 2005 was sustained until 16 April 2005.)

| Event Date | Site | Change in flow, L/sec |  | Magnitude of change | Percent change | Duration, hours | Total volume, m$^3$ |
|---|---|---|---|---|---|---|---|
|  |  | Initial | minimum |  |  |  |  |
| 19 March 2004 - 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 March 2004 - 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 2004 - 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 April 2004 - 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 April 2004 - 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 |

| Event Date | Site | Change in flow, L/sec |  | Magnitude of change | Percent change | Duration, hours | Total volume, m$^3$ |
|---|---|---|---|---|---|---|---|
|  |  | Initial | minimum |  |  |  |  |
| 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 March 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 April 2005 - 16 April 2005 | 05-Bidwell | -- | -- | -- | -- | -- | ** |
|  | 05-Franz | 160 | 35 | 125 | 78 | 30 | 6700 |
|  | 15-Franz | 395 | 320 | 75 | 19 | 36 | 14,000 |



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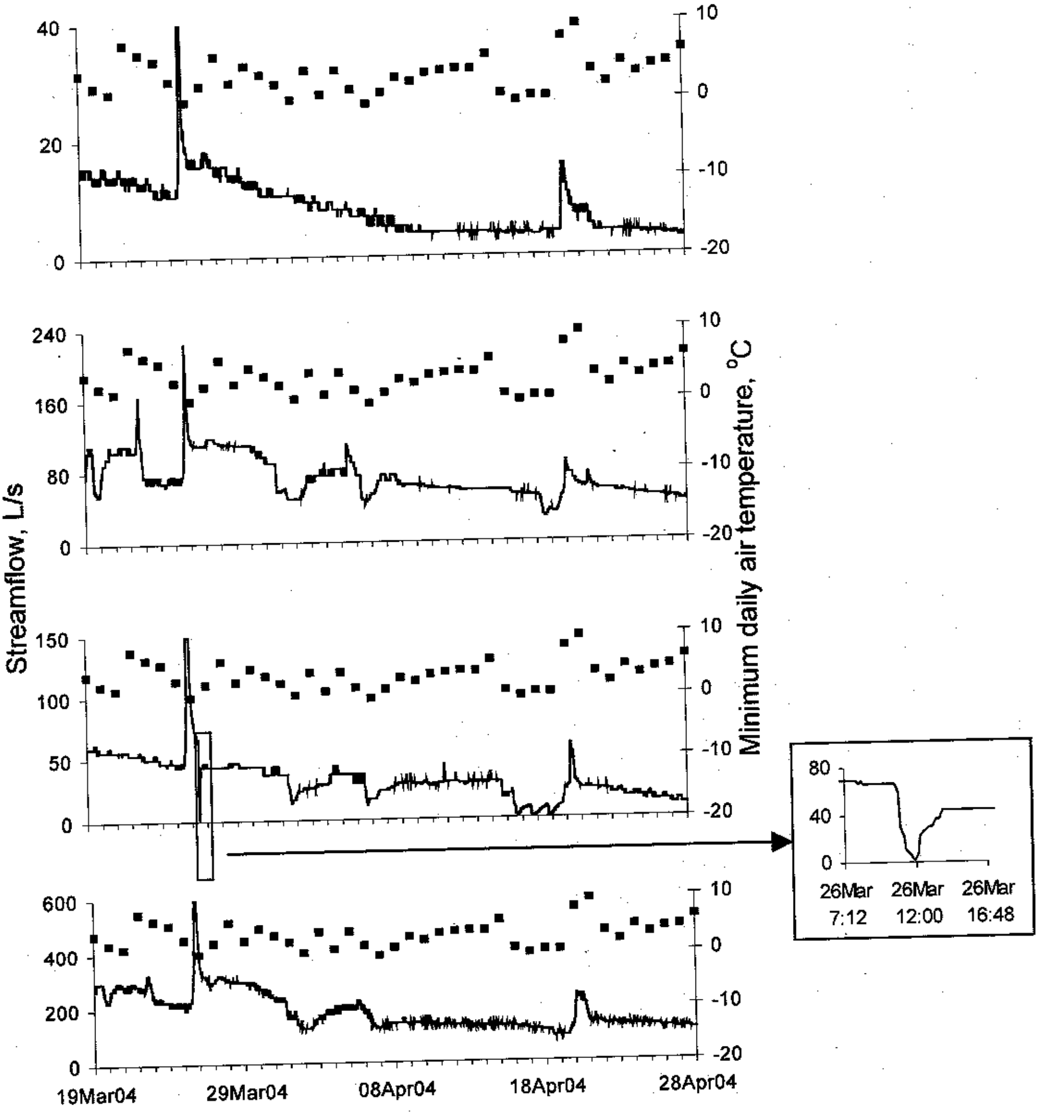

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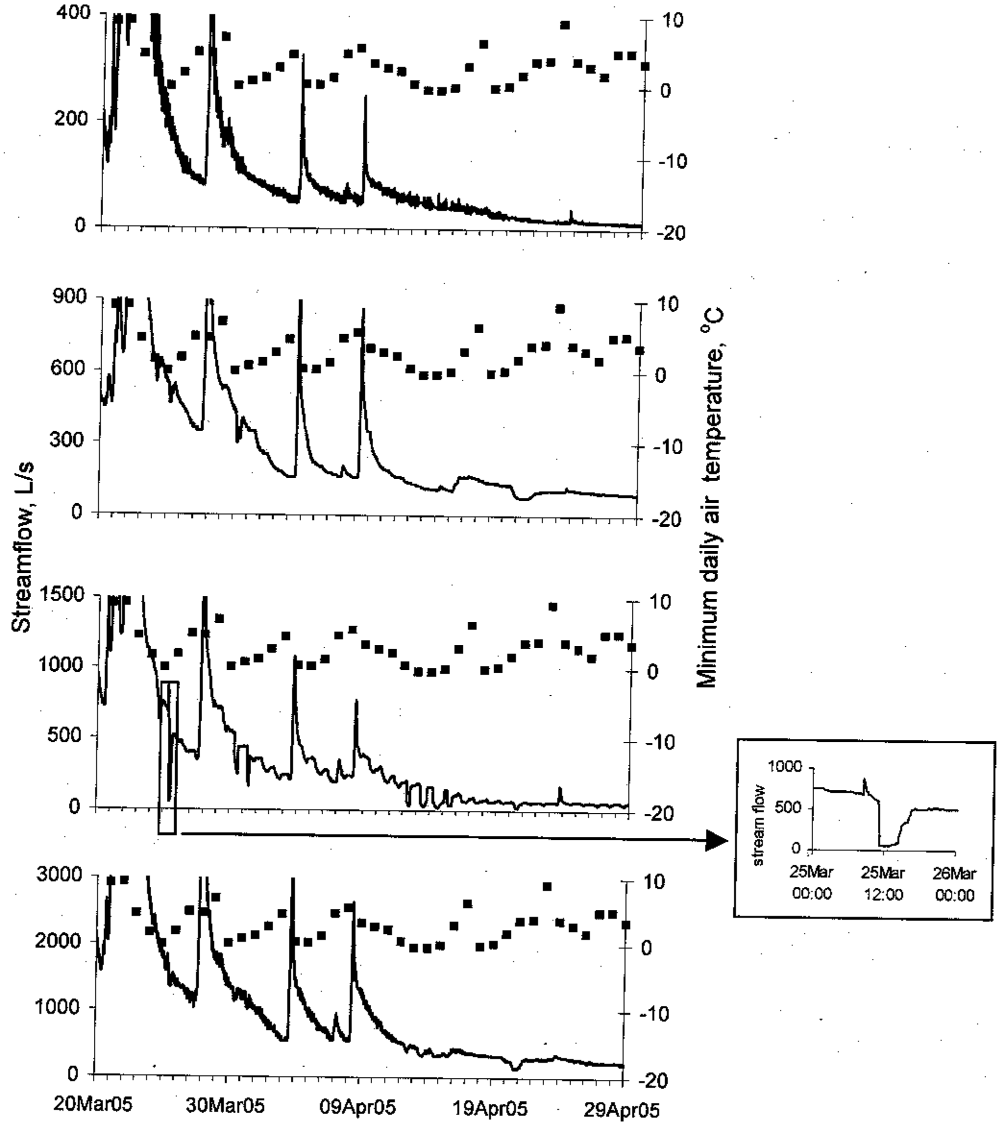

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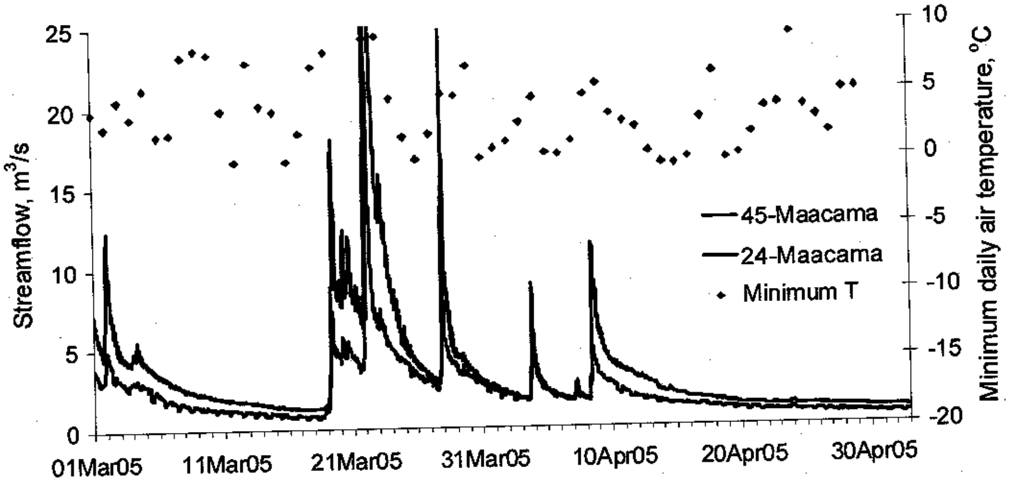

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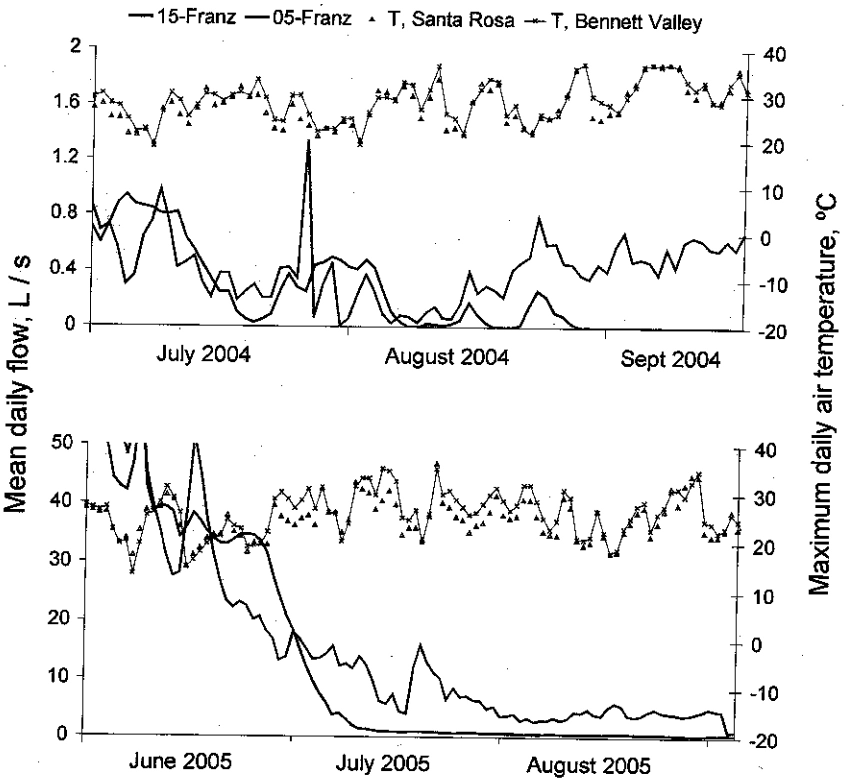

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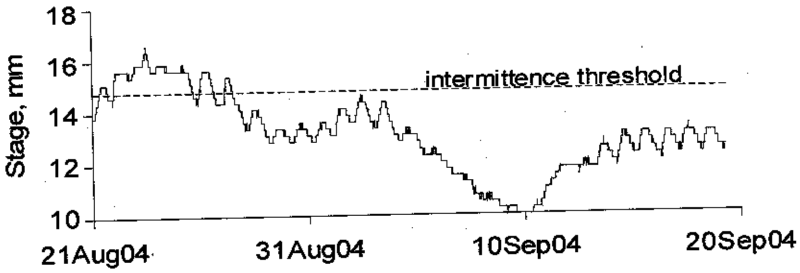

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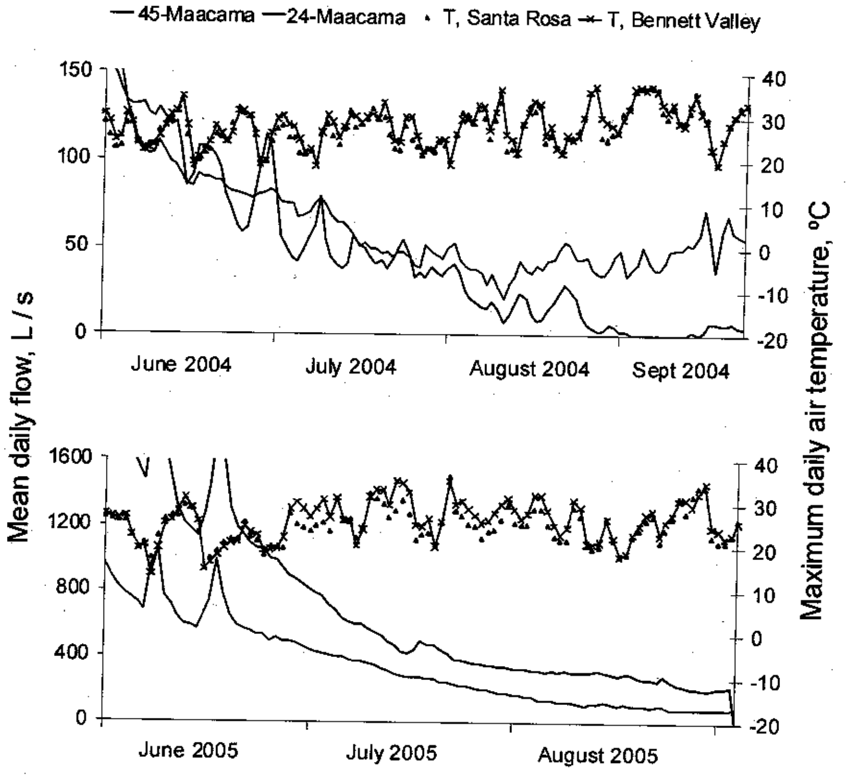

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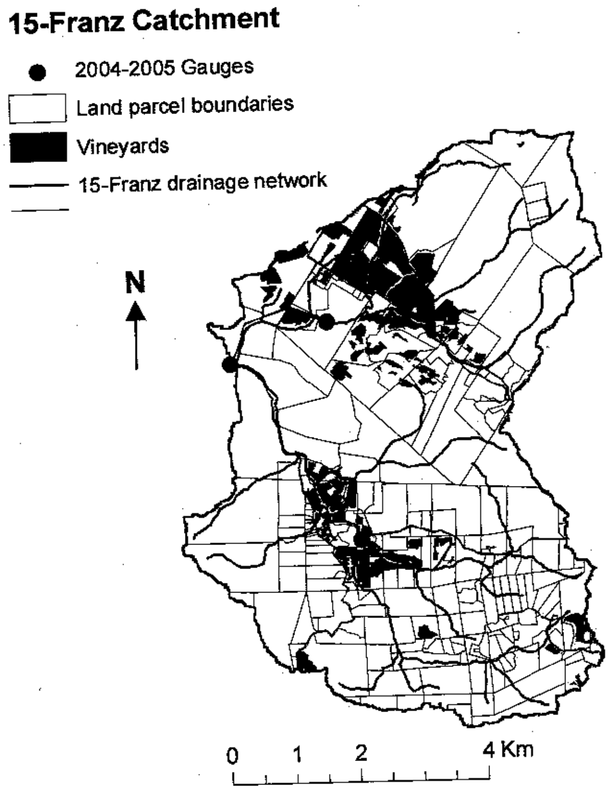

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