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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 (ΔS) 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:

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

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 (ΔS), 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 ΔS.

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 (ΔS) 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	**

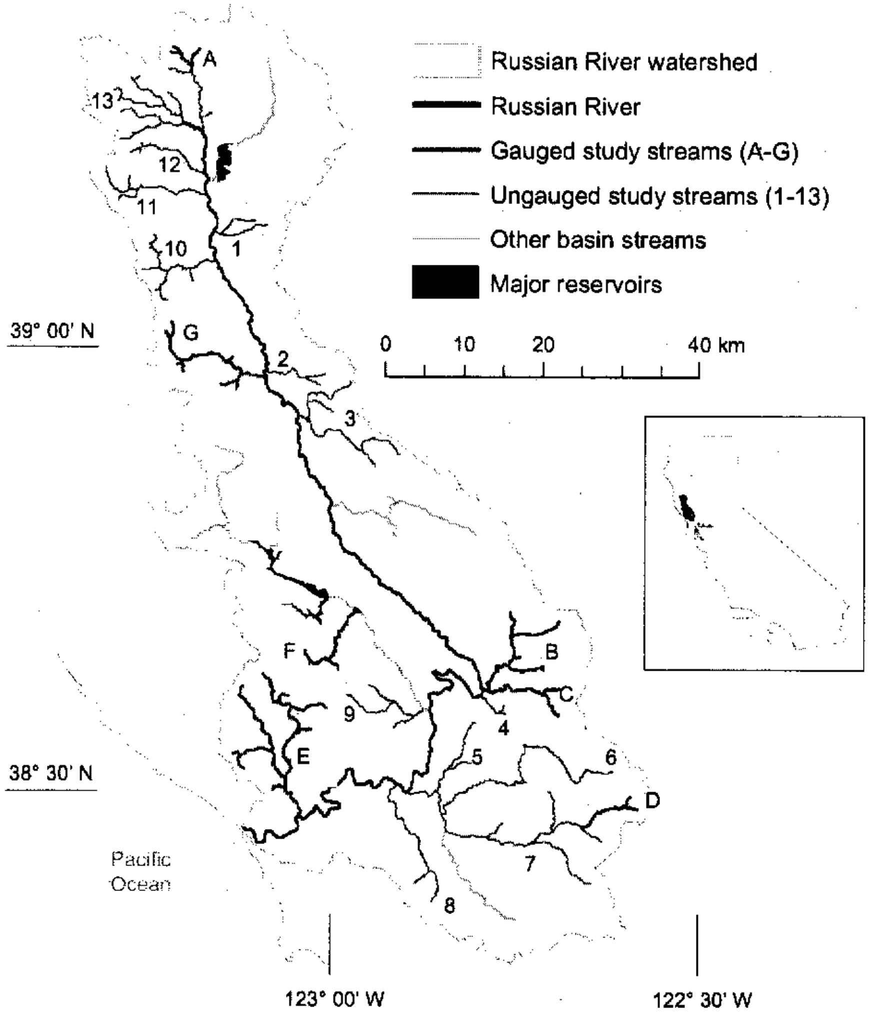

Figure 1. Study streams, tributaries to the Russian River, gauged (A through F) and ungauged (1 through 13). Identifiers correspond to letters and numbers in Tables 1 and 3.

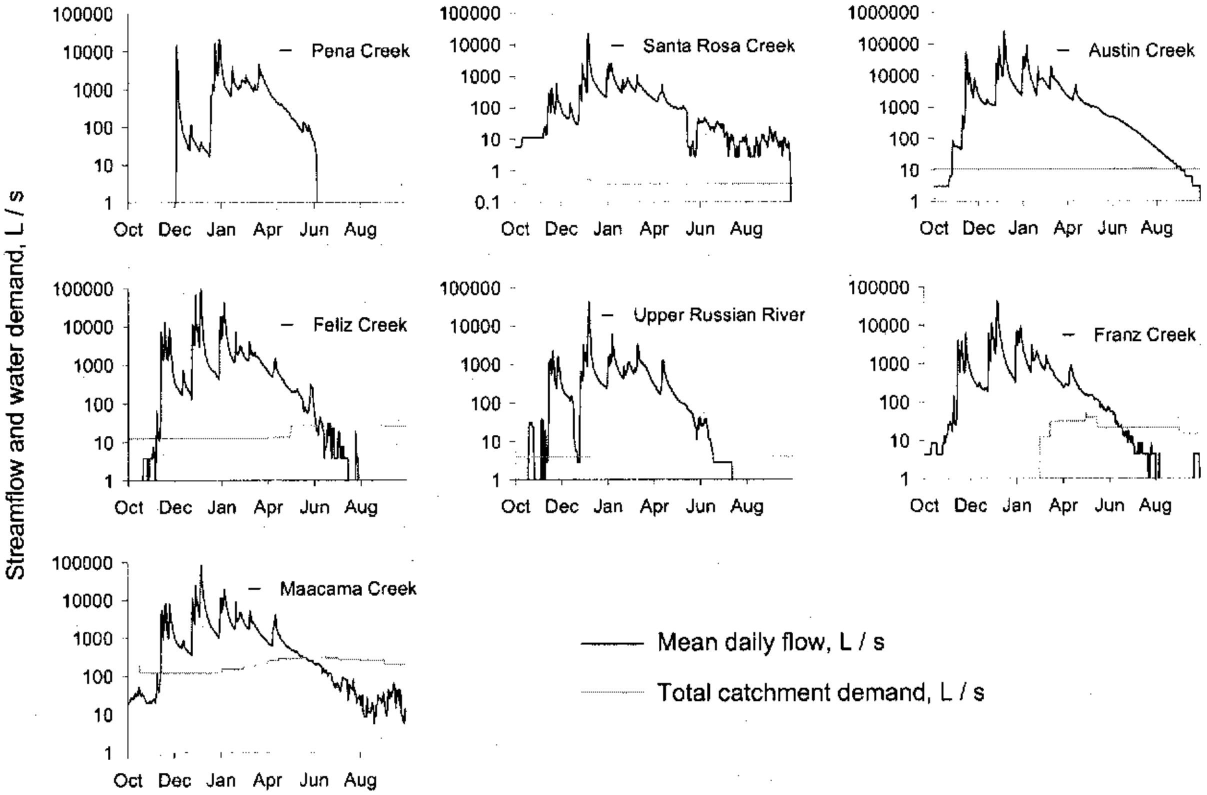

Figure 2. Log-scale plots of surface water balances through a typical water year (based on historical streamflow data) for seven gauged Russian River tributaries, Mendocino and Sonoma Counties, California, USA.

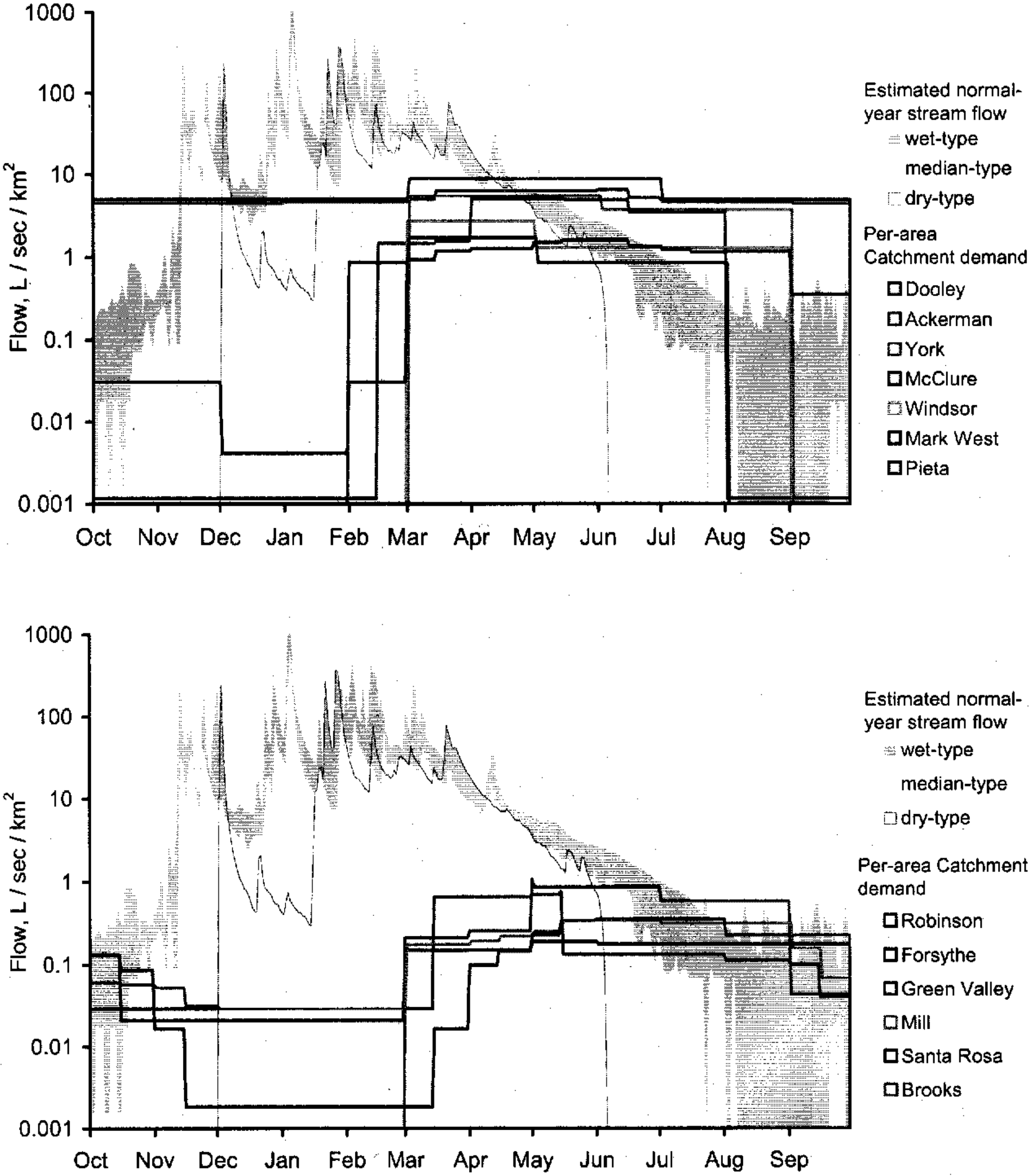

Figure 3. Surface water balances through a water year for the thirteen ungauged Russian River tributaries used in this study: estimates of normal-year flow under a wet-type, middle-type, and dry-type flow regime, and surface water demand from each catchment, both as L/sec/km^2 (plotted on a logarithmic 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).