AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS

Aquatic Conserv: Mar. Freshw. Ecosyst. **19**: 274–284 (2009)

Published online 15 January 2009 in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/aqc.1012

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

MATTHEW J. DEITCH[a,*], G. MATHIAS KONDOLF[b] and ADINA M. MERENLENDER[a]

[a]*Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA*

[b]*Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, CA, USA*

ABSTRACT

1. Small streams are increasingly under pressure to meet water needs associated with expanding human development, but the 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 stream flow at ecologically relevant time scales.
3. The classic water balance model was adapted to evaluate how small instream diversions can affect catchment stream-flow; the adapted model maintains the basic mass balance concept, but limits the parameters and considers surface water data at an appropriate timescale.
4. This surface water balance was applied to 20 Russian River tributaries in north-central California to evaluate how recognized diversions can affect stream flow throughout the region.
5. The model indicates that existing diversions have little capacity to influence peak or base flows during the rainy winter season, but may reduce stream flow during spring by 20% in one-third of all the study streams; and have the potential to accelerate summer intermittence in 80% of the streams included in this study.
6. The surface water balance model may be especially useful for guiding river restoration from a hydrologic perspective: it can distinguish among streams with high diversion regimes that may require more than just physical channel restoration to provide ecological benefits, and can illustrate the extent to which changing the diversion parameters of particular water users can affect the persistence of a natural flow regime.
7. As applied to Russian River tributaries, the surface water balances suggest that reducing demand for stream flow in summer may be as important as physical channel restoration to restoring anadromous salmonids in this region.

Received 25 July 2007; Revised 29 July 2008; Accepted 27 August 2008

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; Marston *et al.*, 2005; Page *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; Bunn and Arthington, 2002; Whiting, 2002; Lytle and 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; Wohl *et al.*, 2005; Suen and Eheart, 2006). Where stream-flow data are available to illustrate pre- or post-dam stream-flow conditions, managers can use tools such as indicators of hydrologic alteration or IHA, Richter *et al.*, 1996; Dundee Hydrologic Regime Assessment Method or DHRAM, Black *et al.*, 2005)

*Correspondence to: Matthew J. Deitch, Center for Ecosystem Management and Restoration, Oakland, CA, USA. E-mail: dietch@cemar.org

to explore how these projects affect discharge and direct management operations to match a natural flow regime more closely.

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 stream flow 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 the literature to evaluate or predict the effects of small projects on stream flow.

Tools designed to make ecologically meaningful evaluations of small-scale water projects on stream flow 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 stream-flow 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 streams of small projects on stream flow. This paper describes a tool for ecologists and water resource managers based on the classic water balance (Thornthwaite and Mather, 1955; Dunne and Leopold, 1978) that can be used to predict the impacts of small decentralized water diversions on catchment discharge. The tool is then applied to evaluate the impacts of small instream diversions on stream flow in the major tributaries to the Russian River catchment, a sixth-order stream in the centre of the northern California wine country. Evaluations are then used to predict the potential effects that these projects may have on anadromous salmonids (namely, steelhead trout *Oncorhynchus mykiss* and coho salmon *Oncorhynchus kisutch*, whose listings on the federal Endangered Species Act provide the primary impetus for aquatic ecosystem conservation in the region) which use these tributaries for a large part of their life cycle.

STUDY AREA AND METHODS

Water users have employed 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), resulting in more than 2600 points of diversion in the 3800 km^2 catchment. The need for water in this region is partly a result of its Mediterranean climate: virtually all of the annual precipitation occurs as rainfall between November and April, precluding reliance 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: stream flow 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 may thus be greatest on stream hydrology and aquatic ecosystems during the spring and summer: 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 raised concerns over the increasing number of small-scale water projects in headwater tributaries of the Russian River catchment because of the potential impacts to environmental flows necessary for aquatic and riparian biota. As a result, the agency charged with appropriating surface water in California has granted a small fraction of new water rights since 1990, citing a need for methods to examine the impacts of existing abstractions on water resources at scales relevant to ecological processes (SWRCB, 1997).

Much of the discussion of impacts of small surface water abstractions on aquatic ecosystems in this region has focused on native anadromous salmonids, which are the focus of regional environmental policy in the Pacific coastal watersheds of the USA (Viers, 2008; e.g. SWRCB, 1997; USEPA, 1999; USEPA, 2000; CDFG, 2002; RWQCB, 2007; SWRCB, 2007). In addition to their cultural appeal and economic benefits, the usefulness of native anadromous salmonids as a keystone species stems from the spatial and temporal breadth of their life cycle (Viers, 2008) and the well-adjusted nature of their life cycle to regional flow regime patterns (Moyle, 2002). Adults migrate inland and spawn in freshwater streams ranging from headwater tributaries to lower reaches 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). Stream flow that recedes through spring must maintain adequate conditions to complete incubation and supply energy to juvenile salmonids via downstream drift. Juveniles must remain in streams through summer until the rainy season begins again in late autumn; many juvenile salmonids remain in freshwater streams for more than one year before migrating back to the ocean (Moyle, 2002).

Increasing small abstractions in coastal California drainages in the late 20th century occurred simultaneously with a steady decline in anadromous salmonid numbers (NMFS, 1996; SWRCB, 1997; Leidy *et al*., 2005), resulting in the listing of seven distinct populations of anadromous salmonids in coastal California as threatened or endangered under the federal Endangered Species Act (CDFG, 2006). Though the life cycle of these fish is well-adjusted to regional stream-flow patterns, alterations to stream flow at particularly sensitive times may disrupt important ecological processes. Stream-flow alterations during this dry season may be a primary consideration to the conservation of salmonid populations in this region, as well as to aquatic biota in general: 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), and unexpected

DOI: 10.1002/aqc

changes in stream-flow dynamics (e.g. magnitudes and rates of change) may change the suitability of a stream reach as habitat for any organism that depends on those flow conditions for survival.

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

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

where P is precipitation, Q is stream discharge, ET is evapotranspiration (a combination of plant transpiration and surface evaporation), ΔG is change in groundwater storage, $\Delta\theta$ 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 modelling techniques to predict how land management decisions that alter catchment processes affect discharge (Fohrer *et al*., 2001; de Roo *et al*., 2001; Wegehenkel, 2003; Ott and Uhlenbrook, 2004; Vaze *et al*., 2004). Other recent applications include informing water budgeting and water management on a regional or national scale (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 (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 timescale over which it typically operates is not congruent with stream flow. 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. Although data at monthly and annual scales are useful for illustrating broad-scale changes in discharge over time for many common management objectives, such timescales are insufficient for characterizing stream flow, which ultimately dictates the timing and duration of ecological processes. Stream flow 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 stream flow may be short term, as brief as hours (Deitch *et al*., 2008).

To evaluate the potential impacts of small water projects on catchment discharge at ecologically meaningful time scales, the classic water balance was modified by retaining the mass-balance concept but considering only the interactions between stream flow already in the drainage network and the diversions from that drainage. Input (I) is defined as the sum of surface water contributed to the stream from the upstream drainage network, described by stream flow measured at a defined point in the catchment. 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, the surface water balance can be described as:

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

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

Application

Publicly available data were used 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). Stream-flow data provided the temporal resolution necessary to match rates of instream diversion (i.e. volume per second); all streams were unimpaired by large dams or hydroelectric projects at the time of collection and depicted stream flow under low development, thus representing a more natural flow regime than present discharge measurements would express. For six streams gauged in the 1960s, stream flow measured in water year 1966 was chosen 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 stream flow characteristics, so the water balances depicted here illustrate potential changes in flow through an annual cycle in a typical year. For Pena Creek, which operated in the 1980s, streamflow from median annual discharge year 1981 was used for input.

Change in storage (i.e. maximum allowable water removal) in each study drainage was determined from surface water rights applications available to the public through the California State Water Resources Control Board (SWRCB) Water Right Information Management System; these applications describe 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. Approved pumping rates listed in water rights data for each study stream were gathered and summed 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

DOI: 10.1002/aqc

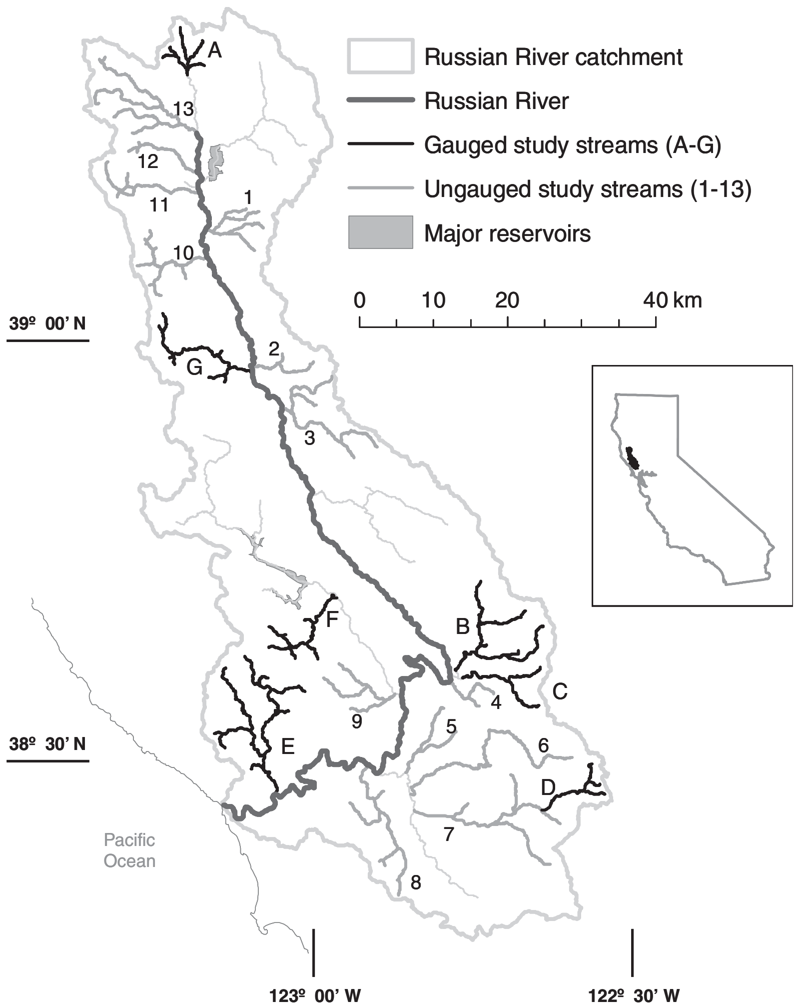

Figure 1. Study streams, tributaries to the Russian River, gauged (A–F) and ungauged (1–13). Identifiers correspond to letters and numbers in Tables 1 and 3.

Table 1. Gauged Russian River tributaries used in the surface water balance application: stream flow gauge and catchment properties

Stream	USGS gauge number	Total area, km^2 (letter, Figure 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)

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, all catchment diversions were included and daily stream flow at each gauge was adjusted as a ratio of total- to gauged-catchment areas to estimate total catchment flow (e.g. daily stream flow 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).

To depict surface water balances input and change in storage were plotted for each stream on the same graph. Stream flow hydrographs illustrated input (I) as described above. Instantaneous water demand (ΔS) was graphically depicted as the daily maximum rate of diversion on each day as derived from water rights records, which can be termed a 'demand hydrograph'. The demand hydrograph expresses the maximum impact that diversions can have on total catchment discharge at any time. Projected output (O) for each day can be calculated or conceptualized as the difference between I and ΔS.

DOI: 10.1002/aqc

Water balance expansion to ungauged catchments

For the second analysis, surface water balances were created for all other Russian River tributaries fourth-order and greater to explore more thoroughly the potential impacts of diversions on stream flow in the Russian River drainage network (1–13, Figure 1). As above, records of all registered diversions were gathered and summed for 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. Input (I) was estimated by converting flow from each of the seven gauged streams in Part 1 to flow-per-area ($\mathrm{L\,s^{-1}\,km^{-2}}$); flow values for each day were then ranked, and the high, middle, and low values for each day were selected to create a high, median, and low-flow estimate for a Russian River tributary through 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 the initial low-flow estimate did not depict important flow regime features (illustrating no peak flow events, atypical even among dry-type streams in a normal year), median-year flow data from Pena Creek were instead used to depict dry-type conditions because those data had lowest per-area annual discharge and dried the earliest among gauged streams. Water balances for ungauged streams were depicted through similar methods to the seven gauged streams above: wet-type, median-type, and dry-type stream-flow estimates serve as three scenarios for input into the model, and demand hydrographs illustrate how diversions could impair stream flow.

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 the winter, rises during spring and the early summer, and recedes in late summer and fall. Peak flows during winter exceed basin demand by more than 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; Figure 2). By

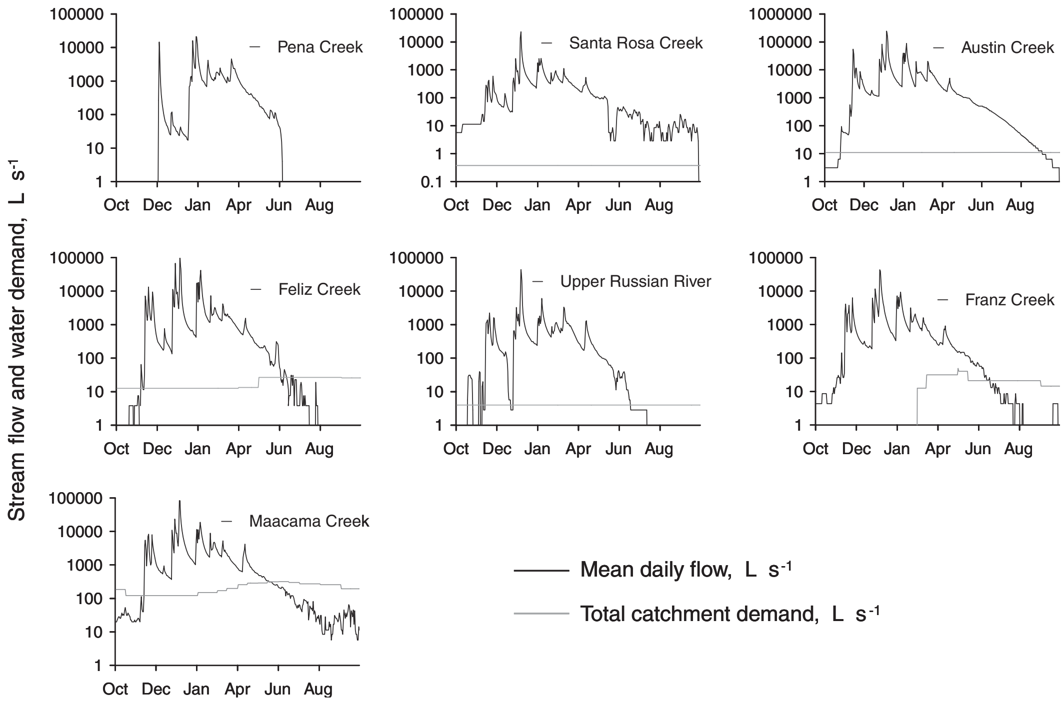

Figure 2. Log-scale plots of surface water balances through a typical water year (based on historical stream-flow data) for seven gauged Russian River tributaries, Mendocino and Sonoma Counties, California, USA.

DOI: 10.1002/aqc

Table 2. Comparison of catchment stream flow 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, $L s^{-1}$	Demand, $L s^{-1}$	Flow, $L s^{-1}$	Demand, $L s^{-1}$	Flow, $L s^{-1}$	Demand, $L s^{-1}$	Flow, $L s^{-1}$	Demand, $L s^{-1}$
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

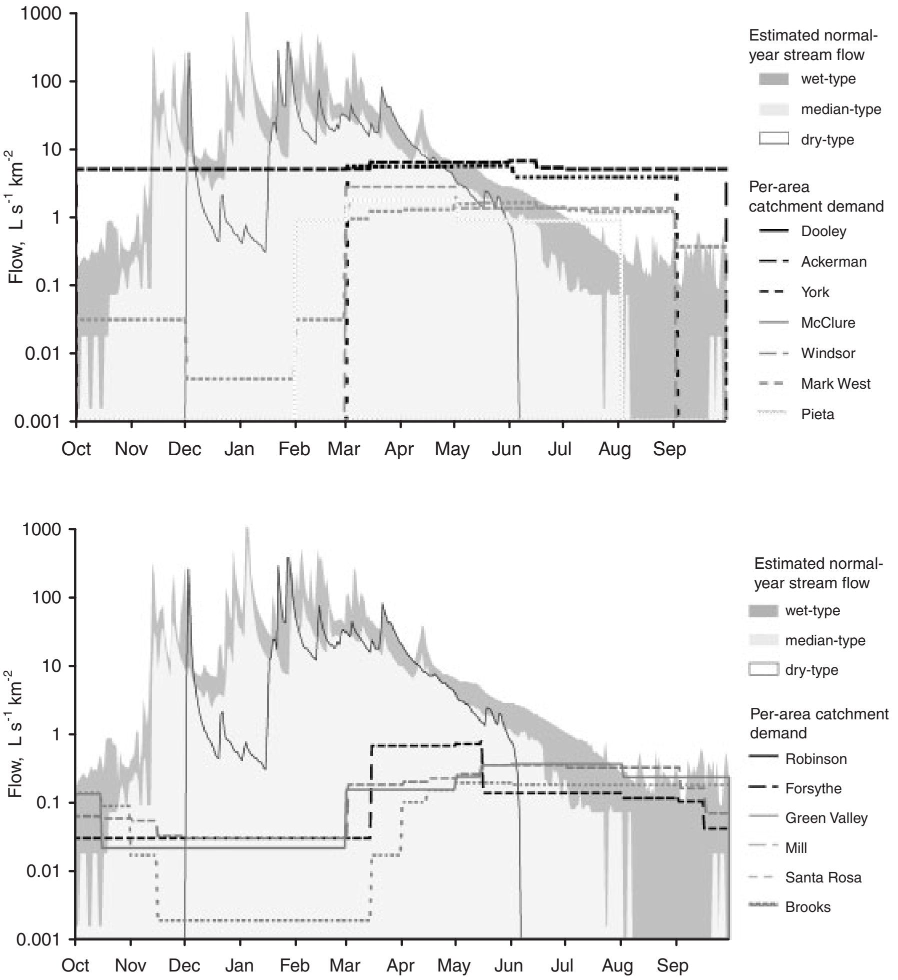

Figure 3. Surface water balances through a water year for the 13 ungauged Russian River tributaries used in this study: estimates of normal-year flow under a wet-type, middle-type, and dry-type flow regime, and surface water demand from each catchment, both as $L s^{-1} km^{-2}$ (plotted on a logarithmic 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 $0.001 L s^{-1} km^{-2}$ throughout the year).

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 ($8000 L s^{-1} km^{-2}$ in the wet-type and $2400 L s^{-1} km^{-2}$ in the dry-type streams) and base flow magnitudes (Figure 3). They also differ with respect to the

DOI: 10.1002/aqc

Table 3. Ungauged Russian River study tributaries used in the surface water balance application: catchment properties, and catchment demand as a percentage of stream flow 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 $0\,L\,s^{-1}$)

Stream	Area, km^2 (No., Figure 2)	Number diversions	Demand as percentage of flow, 26 Jan.		Demand as percentage of flow, 01 April		Demand as percentage of flow, 15 May		Demand as percentage 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	**

point at which they become intermittent in summer: the wet-type stream flow 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 stream flow 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 stream flow 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. Flushing flows, which maintain channel form and gravel size distribution for salmonid spawning (Kondolf and Wilcock, 1996; Wilcock *et al*., 1996), are probably unimpaired by small instream diversions in this region because peak flows are much higher than cumulative demand in all streams studied. Beyond the implications for salmonids, the preservation of flushing flows suggests that these small instream diversions will not affect high-flow processes necessary for maintaining the structure of riparian plant communities such as removal of encroaching vegetation and floodplain inundation (Elderd, 2003). In addition, instantaneous catchment demand comprises less than 10% of base flow over most of the winter in all streams. Though this suggests that winter base flows are mostly unimpaired by approved instream diversions for most of the winter in a normal year, diversions may have local impacts on spawning and upstream passage at certain times or in particularly dry years; and influence other processes such as organic matter breakdown and nutrient transport/retention that occur predominantly under base flows (Doyle *et al*., 2005; Doyle and Stanley, 2006).

Instream diversions from Russian River tributaries have greater potential to impair ecological processes through spring and summer because stream flow recedes steadily at the same time as water demand increases 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 diversions could cause intermittence to 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 probably 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). In extreme cases, stream reaches

DOI: 10.1002/aqc

that become intermittent early in the year could continue to lose water volume through the dry season, reducing habitat for juveniles and making pools more susceptible to temperature and dissolved oxygen mortality thresholds. Observations and empirical evidence suggest that late summer diversions may continue to deplete pools even where surface flow has ceased (Fawcett *et al*., 2003; Deitch, 2006).

Sudden changes in stream flow in spring, acceleration of seasonal flow recession, and persistent depression of flow in summer will all influence the structure of aquatic ecosystems beyond the direct effects to anadromous salmonids. Sudden changes in stream flow in spring can dry parts of riffles; if of sufficient duration, these changes may cause mortality among those macroinvertebrates with low mortality that cannot move to submerged portions of the riffle. The loss of macroinvertebrates earlier in the year may change food web dynamics both in the short term and through the remainder of the dry season as well, having cascading effects on aquatic and riparian fauna that depend on macroinvertebrates as food (Lake, 2003). Accelerated flow recession may also cause normal-type years to resemble dry-type years more closely; the macroinvertebrate communities that occur in streams in this region during dry-type years tend to be more dominated by lentic-type fauna than lotic-type (Beche and Resh, 2007a), and the persistent occurrence of dry-type communities can have long-term effects beyond the occurrence of dry years as well (Beche and Resh, 2007b). In addition, prolonged isolation of pools may disrupt natural biochemical regimes (e.g. dissolved oxygen, nitrogen), potentially threatening survivorship of salmonids (Carter, 2005) as well as any other fish that depend on particular water quality standards. The imbalance between stream flow and demand in nearly all study streams presented above suggests that summer water demand may be a primary limitation to the persistence of anadromous salmonids and healthy aquatic ecosystems in general throughout this region.

Model assumptions, strengths, and utility

Like any model, the surface water balance described here makes assumptions that may cause inaccurate depictions of interactions among components of interest (here, stream flow 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 probably 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 stream flow 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 stream flow recedes quickly when water is needed for frost or heat protection at magnitudes approximately equal to the demand hydrographs presented here (Deitch *et al*., 2008).

The simplification of catchment processes may also constrain the ability of the surface water balance to depict actual diversion impacts. The 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 the 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. Instead it 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 stream flow can be supplemented by shallow aquifers.

Despite these drawbacks, the surface water balance incorporates some important strengths. The most important feature of this 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 abstraction 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.

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. The capacity to incorporate different types of hydrologic conditions (e.g. normal-type or dry-type years) can allow managers to explore scenarios describing impacts of water management practices on stream flow, a utility that has been useful for water resources management and development relative to aquatic ecosystem conservation (Lake and Bond, 2007). From the perspective of human water needs, this model can illustrate the effects of additional diversions at different times of year; or shifting existing approved diversions from periods of low availability to periods of relative water surplus. Such practices would result in a 're-shaping' of the demand hydrograph to resemble more closely the stream-flow hydrograph. From an ecosystem perspective, the model can illustrate the effects of abstraction on ecosystem flow thresholds that are linked to particular magnitudes; the daily-scale time step can also illustrate the change in threshold frequency that may occur as a result of diversion practices. Combining human and ecosystem considerations, managers can identify those water users whose permitted rates of diversion may threaten ecosystem thresholds and can

DOI: 10.1002/aqc

explore the ecosystem benefits of changing those diversions that have the greatest impacts relative to ecosystem thresholds.

The surface water balance model may also be useful for prioritizing stream ecosystem restoration projects. River restoration tends to emphasize physical channel rehabilitation, but geomorphic reconstruction can benefit biota only if stream flow is sufficient to support the necessary ecological processes (Palmer *et al*., 2005; Kondolf *et al*., 2006; Stromberg *et al*., 2007). If the study streams presented above were under consideration for a limited amount of restoration funds to create over-summering habitat for juvenile salmonids, the water balances could be used to indicate those streams that are more likely to become intermittent as a result of water management practices, and thus less likely to provide intended over-summering benefits. Those streams with fewer diversions, relative to discharge, could be prioritized more highly for physical restoration because the relationship between supply and demand suggests that catchment water management practices are less likely to affect stream flow.

CONCLUSIONS

The surface water balance presented above provides a useful framework for evaluating the effects of decentralized water projects on catchment stream flow over an ecologically relevant timescale. Direct instream diversions may pose a threat to aquatic ecosystem sustainability in most Russian River tributaries studied here: pumping in spring and summer can cause acceleration of the annual summer drought, and cause streams to become intermittent when they may not under natural conditions. Though managers and restoration ecologists frequently emphasize physical channel rehabilitation, the data presented here indicate that naturally low stream flow in summer months coupled with catchment water abstraction practices may 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.

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 if planned and operated in accordance with winter instream flow needs. The surface water balance can illustrate 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 require careful planning and may entail additional expense. Without acknowledging the effects of small-scale instream diversions over fine temporal scales, ecologically sustainable water management cannot be achieved.

ACKNOWLEDGEMENTS

This research was funded through National Science Foundation Biocomplexity Award 0119992, United States Environmental Protection Agency STAR Cumulative Effects Award R829803, and United States Environmental Protection Agency STAR Ecological Thresholds Award 83243901; and through the Beatrix Farrand Fund in the Department of Landscape Architecture and Environmental Planning at the University of California, Berkeley. The authors are also grateful to V. Resh for additional support and helpful feedback through the planning and research process; and to P. Boon and an anonymous reviewer for helpful comments regarding an earlier manuscript draft.

REFERENCES

Arthington AH, Bunn SE, Poff NL, Naiman RJ. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**: 1311–1318.

Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter BD, Steinman AL. 2002. Meeting ecological and societal needs for freshwater. *Ecological Applications* **12**: 1247–1260.

Beche LA, Resh VH. 2007a. Short-term climatic trends affect the temporal variability of macroinvertebrates in California 'Mediterranean' streams. *Freshwater Biology* **52**: 2317–2339.

Beche LA, Resh VH. 2007b. Biological traits of benthic macroinvertebrates in California mediterranean-climate streams: long-term annual variability and trait diversity patterns. *Fundamental and Applied Limnology*: *Archiv für Hydrobiologie* **169**: 1–23.

Black AR, Rowan JS, Duck RW, Bragg OM, Clelland BE. 2005. DHRAM: a method for classifying river flow regime alterations for the EC Water Framework Directive. *Aquatic Conservation*: *Marine and Freshwater Ecosystems* **15**: 427–446.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapo-transpiration. *Journal of Hydrology* **55**: 3–23.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61.

Bunn SE, Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30**: 492–507.

California Department of Fish and Game (CDFG) and the National Marine Fisheries Service. 2002. Guidelines for Maintaining Instream Flows to Protect Fisheries Resources Downstream of Water Diversions in Mid-California Coastal Streams (Draft). CDFG and NOAA, Santa Rosa, CA.

California Department of Fish and Game (CDFG). 2006. Federal and State Endangered Species Act Status for California Anadromous Fish as of April 20, 2006. CDFG, Sacramento, CA.

Carter K. 2005. The effects of dissolved oxygen on steelhead trout, coho salmon, and chinook salmon biology and function by life stage. California Regional Water Quality Control Board, North Coast Region, Santa Rosa, California, USA.

Cowell CM, Stroudt RT. 2002. Dam-induced modifications to upper Allegheny River streamflow patterns and their

biodiversity implications. *Journal of the American Water Resources Association* **38**: 187–196.
de Roo A, Okijk M, Schmuck G, Koster E, Lucieer A. 2001. Assessing the effects of land use changes on floods in the Meuse and Oder Catchment. *Physics and Chemistry of the Earth* (*B*) **26**: 593–599.
Deitch MJ. 2006. Scientific and institutional complexities of managing surface water for beneficial human and ecosystem uses under a seasonally variable flow regime in Mediterranean-climate Northern California. Ph.D. dissertation, University of California, Berkeley, CA.
Deitch MJ, Kondolf GM, Merenlender AM. 2008. Hydrologic impacts of small-scale instream diversions for frost protection and heat protection in the California wine country. *River Research and Applications,* DOI: 10.1002/rra.1100.
Doyle MW, Stanley EH. 2006. Exploring potential spatial-temporal links between fluvial geomorphology and nutrient-periphyton dynamics in streams using simulation models. *Annals of the Association of American Geographers* **96**: 687–698.
Doyle MW, Stanley EH, Strayer DL, Jacobson RB, Schmidt JC. 2005. Effective discharge analysis of ecological processes in streams. *Water Resources Research* **41**: W11411.
Dunne T, Leopold LB. 1978. *Water in Environmental Planning*. W.H. Freeman and Company: New York.
Elderd BD. 2003. The impact of changing flow regimes on riparian vegetation and the riparian species *Mimulus guttatus*. *Ecological Applications* **13**: 1610–1625.
Fawcett MH, Roth JC, Smith DW. 2003. Salmonid juvenile density monitoring in Sonoma County streams, synthesis of a ten-year study (1993–2002). Merritt-Smith Consultants; for the City of Santa Rosa, California, USA.
Fitzhugh TW, Richter BD. 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. *BioScience* **54**: 741–754.
Fohrer N, Haverkamp S, Eckhardt K, Frede H-G. 2001. Hydrologic response to land use changes on the catchment scale. *Physics and Chemistry of the Earth* (*B*) **26**: 577–582.
Gasith A, Resh VH. 1999. Streams in mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. *Annual Review of Ecology and Systematics* **30**: 51–81.
Habets F, Etchevers P, Golaz C, Leblois E, Ledoux E, Martin E, Noilhan J, Ottle C. 1999. Simulation of the water budget and the river flows of the Rhone basin. *Journal of Geographical Research* **104**: 31145–31172.
Hatton TJ, Pierce LL, Walker J. 1993. Ecohydrological changes in the Murray-Darling basin 2. Development and tests of a water balance model. *Journal of Applied Ecology* **30**: 274–282.
Kondolf GM, Boulton AJ, O'Daniel S, Poole GC, Rachel FJ, Stanley EH, Wohl E, Bang A, Carlstrom J, Cristoni C, *et al.* 2006. Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and Society* **11**: 5.
Kondolf GM, Wilcock PR. 1996. The flushing flow problem: defining and evaluating objectives. *Water Resources Research* **32**: 2589–2599.
Lake PS. 2003. Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology* **48**: 1161–1172.
Lake PS, Bond NR. 2007. Australian futures: freshwater ecosystems and human water usage. *Futures* **39**: 288–305.
Leidy R, Becker G, Harvey B. 2005. Report on the status and distribution of salmonids in the San Francisco Bay. Center for Ecosystem Management and Restoration, California Coastal Conservancy, Oakland, California, USA.
Liebe J, van de Giesen N, Andreini M. 2005. Estimation of small reservoir storage capacities in a semi-arid environment: a case study in the Upper East Region of Ghana. *Physics and Chemistry of the Earth* **30**: 448–454.
Lytle DA, Poff NL. 2004. Adaptation to natural flow regimes. *Trends in Ecology and Evolution* **19**: 94–100.
Magilligan FJ, Nislow KH. 2005. Changes in hydrologic regime by dams. *Geomorphology* **71**: 61–78.
Malmqvist B, Rundle S. 2002. Threats to the running water ecosystems of the world. *Environmental Conservation* **29**: 134–153.
Marchetti MP, Moyle PB. 2001. Effects of flow regime on fish assemblages in a regulated California stream. *Ecological Applications* **11**: 530–539.
Marston RA, Mills JD, Wrazien DR, Bassett B, Splinter DK. 2005. Effects of Jackson Lake Dam on the Snake River and its floodplain, Grand Teton National Park, Wyoming, USA. *Geomorphology* **71**: 79–98.
Mathooko JM. 2001. Disturbance of a Kenya Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* **458**: 131–139.
McIntosh MD, Benbow ME, Burky AJ. 2002. Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawaii, stream. *River Research and Applications* **18**: 569–581.
McKay SF, King AJ. 2006. Potential ecological effects of water extraction in small, unregulated streams. *River Research and Applications* **22**: 1023–1037.
Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk JCJ, Lang H, Parmet BWAH, Schadler B, Schulla J, Wilke K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. *Climatic Change* **49**: 105–128.
Moyle PB. 2002. *Inland Fishes of California*. University of California Press: Berkeley, CA.
National Marine Fisheries Service (NMFS). 1996. Factors for decline: a supplement to the notice of determination for west coast steelhead under the Endangered Species Act. NMFS Protected Species Branch, Portland, Oregon, USA.
Nislow KH, Magilligan FJ, Fassnacht H, Bechtel D, Ruesink A. 2002. Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut River. *Journal of the American Water Resources Association* **3**: 1533–1548.
Ott B, Uhlenbrook S. 2004. Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model. *Hydrology and Earth System Sciences* **8**: 62–78.
Page K, Read A, Frazier P, Mount N. 2005. The effect of altered flow regime on the frequency and duration of bankfull discharge: Murrumbidgee River, Australia. *River Research and Applications* **21**: 567–578.
Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, *et al.* 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**: 208–217.
Poff NL. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* **36**: 101–121.
Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* **47**: 769–784.
Postel SA, Richter BD. 2003. *Rivers For Life*: *Managing Water for People and Nature*. Island Press: Washington, DC.

Potter KW. 2006. Small-scale, spatially distributed water management practices: implications for research in the hydrologic sciences. *Water Resources Research* **42**: W03S08.
Pringle CM. 2000. Threats to U.S. public lands from cumulative hydrologic alterations outside their boundaries. *Ecological Applications* **10**: 971–989.
Rader RB, Belish TA. 1999. Influence of mild to severe flow alterations on invertebrates in three mountain streams. *Regulated Rivers*: *Research and Management* **15**: 353–363.
Regional Water Quality Control Board (RWQCB). 2007. Napa River watershed sediment TMDL and habitat enhancement plan. California RWQCB, San Francisco Bay Region, Oakland, California, USA.
Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**: 1163–1174.
Richter BD, Thomas GA. 2007. Restoring environmental flows by modifying dam operations. *Ecology and Society* **12**: 12.
Shankar D, Kotamraju V, Rhetye SR. 2004. A quantitative framework for estimating water resources in India. *Current Science* **86**: 543–552.
Singer MB. 2007. The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. *River Research and Applications* **23**: 55–72.
Spina AP, McGoogan MR, Gaffney TS. 2006. Influence of surface-water withdrawal on juvenile steelhead and their habitat in a south-central California nursery stream. *California Fish and Game Journal* **92**: 81–90.
Stednick JD. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* **176**: 79–95.
Stromberg JC, Beauchamp VB, Dixon MD, Lite SJ, Paradzick C. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology* **52**: 651–679.
Strzepek KM, Yates DN. 1997. Climate change impacts on the hydrologic resources of Europe: a simplified continental scale analysis. *Climatic Change* **36**: 79–92.
Suen J-P, Eheart JW. 2006. Reservoir management to balance ecosystem and human needs: incorporating the paradigm of the ecological flow regime. *Water Resources Research* **42**: W03417.
Suttle KB, Power ME, Levine JM, McNeely C. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. *Ecological Applications* **14**: 969–974.
State Water Resources Control Board (SWRCB). 1997. Staff Report on the Russian River Watershed. SWRCB Division of Water Rights, Sacramento, CA.
State Water Resources Control Board (SWRCB). 2004. The Water Right Process. SWRCB Division of Water Rights, Sacramento, CA.
State Water Resources Control Board (SWRCB). 2007. Policy for maintaining instream flows in northern California coastal streams. SWRCB Division of Water Rights, Sacramento, CA.
Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441.
The Economist. 2007. Australia's water shortage: The big dry. *The Economist* 383 (8526): 81–84.
Thornthwaite CW, Mather JR. 1955. The Water Balance. Laboratory of Climatology, Publication number 8, Centerton, New Jersey, USA.
United States Environmental Protection Agency (USEPA). 1999. South Fork Eel River Total Maximum Daily Loads for Sediment and Temperature. US EPA Region IX, San Francisco, California, USA.
United States Environmental Protection Agency (USEPA). 2000. Ten Mile River Total Maximum Daily Load for Sediment. US EPA Region IX, San Francisco, California, USA.
Vaze J, Barnett P, Beale G, Dawes W, Evans R, Tuteja NK, Murphy B, Geeves G, Miller M. 2004. Modeling the effects of land use change on water and salt delivery from a catchment affected by dryland salinity in south-east Australia. *Hydrological Processes* **18**: 1613–1637.
Viers JH. 2008. Objective classification of Navarro River salmon habitat: a watershed-based critical habitat case study. *Aquatic Conservation*: *Marine and Freshwater Ecosystems* **18**: 147–162.
Walter MT, Wilkes DS, Parlange J-Y, Schneider RL. 2004. Increasing evapotranspiration from the conterminous United States. *Journal of Hydrometeorology* **5**: 405–408.
Ward AD, Trimble SW. 2004. *Environmental Hydrology*, 2nd edn. CRC Press: Boca Raton, FL.
Wegehenkel M. 2003. Long-term evaluation of land use changes on catchment water balance — a case study from north-east Germany. *Physics and Chemistry of the Earth* **28**: 1281–1290.
Whiting PJ. 2002. Streamflow necessary for environmental maintenance. *Annual Review of Earth and Planetary Science* **30**: 181–206.
Wilcock PR, Kondolf GM, Matthews WVG, Barta AF. 1996. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* **32**: 2911–2921.
Willis TC, Baker EA, Nuhfer AJ, Zorn TG. 2006. Response of the benthic macroinvertebrate community in a northern Michigan stream to reduced summer streamflows. *River Research and Applications* **22**: 819–836.
Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palimer MA, Poff NL, Tarboton D. 2005. River restoration. *Water Resources Research* **41**: W10301.
Yin XG, Nicholson SE. 1998. The water balance of Lake Victoria. *Hydrological Sciences Journal — Journal des Sciences Hydrologiques* **43**: 789–811.