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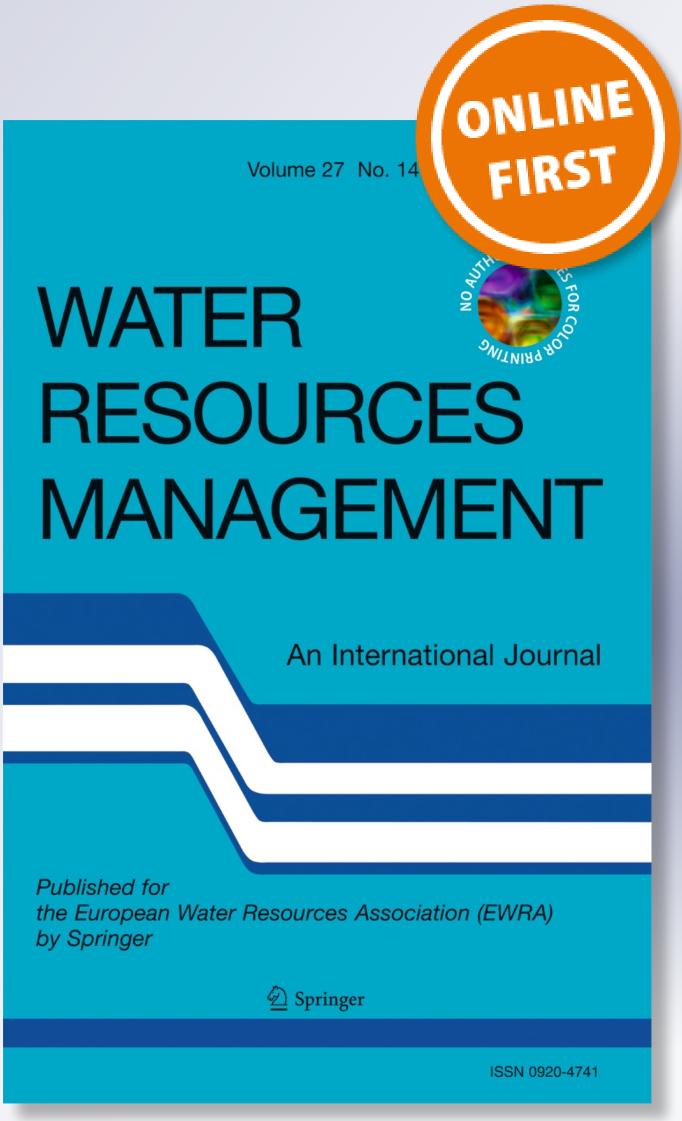

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Cumulative Effects of Small Reservoirs on Streamflow in Northern Coastal California Catchments

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Abstract With small reservoirs increasingly employed to meet human water needs, tools that consider cumulative effects of multiple small reservoirs through space and time are essential for understanding impacts of these spatially distributed stresses on catchment hydrology and related ecological processes. We used a GIS-based hydrologic model to predict streamflow impairment caused by 438 small reservoirs in a 743 km^2 study area in Sonoma County, California, USA. The GIS model was designed to consider the varying effects that these reservoirs have through the project area drainage network, as well as the varying effects they have over time (as reservoirs fill and no longer impair flow downstream). Results indicate that, at the onset of the water year (when reservoirs are assumed to be empty), more than 25 % of the drainage network below reservoirs is impaired by over 50 %. Nine weeks into a normal-type water year, approximately 25 % of the drainage network below reservoirs is impaired by at least 25 %; and at 15 weeks, five percent of the drainage below reservoirs is impaired at least 25 %. Impairment is more persistent in a dry-type year. Nine weeks into a dry year, almost 40 % of the drainage network below reservoirs is impaired by at least 25 %; and at 15 weeks, 25 % of the drainage is impaired by at least 25 %. Results illustrate that impairment caused by reservoirs varies appreciably over space, but as reservoirs fill over time, impairment is lower through most of the drainage network.

Keywords Cumulative effects · Hydrologic impairment · Spatial and temporal scales · Water resource management · Scenario planning · Drought conditions

1 Introduction

Water management is emerging as a principal challenge to humankind in the 21st Century. Long-term water availability forecasts indicate challenges to resource managers throughout the foreseeable future: drier and more variable climate projections point to reduced or more variable water supply (Gleick 1989; Barnett et al. 2004; Kundzewicz et al. 2008; Elsner et al. 2010;

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Bekele and Knapp 2010). As water resource managers and planners consider the benefits and costs of potential management actions on human water needs and ecosystem sustainability (e.g., Aldous et al. 2011; Markoff and Cullen 2008; Payne et al. 2004), increasing population and water-intensive activities suggest that water needs will increase in many regions (Vorosmarty et al. 2000). Further complicating these matters, large dams are decreasingly regarded as a viable means to meet these growing water needs: the sociopolitical, economic, and environmental consequences frequently outweigh the benefits they provide (Naiman and Dudgeon 2011; Scudder 2005; Postel and Richter 2003) and the variability of water supply across long periods of time has made large reservoirs uncertain as a steady water supply (Barnett and Pierce 2008; Christensen et al. 2004).

As an alternative, individuals in locations with growing water needs and no large-scale water providers frequently employ small-scale projects to meet various water needs (Liebe et al. 2005; Antonino et al. 2005; Downing et al. 2006; Deitch et al. 2009a; The Economist 2007; Mushtaq et al. 2007; Malveira et al. 2011). Small-scale water projects, such as small reservoirs and low-magnitude diversions, may be viewed as a more sustainable means of meeting water needs: they entail smaller abstraction volumes because they serve fewer users than large projects, and they are spatially distributed, thus dispersing the pressures from one central location to several ones of smaller magnitude across the drainage network (Potter 2006). Small reservoirs have been shown to have additional ecological benefits when managed for nutrient loading and groundwater recharge (Camargo et al. 2005; Tiessen et al. 2011).

Despite these advantages, an abundance of small water projects may place stresses on aquatic ecosystems beyond which the normal processes that organize those ecosystems can no longer recover (Pringle 2000). Small-scale water projects can cause measurable changes in streamflow (Deitch et al. 2009b); such small changes in streamflow can alter the composition and function of aquatic macroinvertebrate communities (Lawrence et al. 2012; McKay and King 2006; Wills et al. 2006; Dewson et al. 2007), reduce habitat connectivity across a longitudinal gradient (Mantel et al. 2011), and alter higher trophic levels (Pringle 2003; Anderson et al. 2006; Grantham et al. 2012). However, because watershed processes and associated ecological functions vary over space and over time (e.g., Augustijn et al. 2011; Deitch and Kondolf 2012), the hydrologic and ecological impacts of small reservoirs are likely to be different depending on their size, hydrologic regime, and location in the drainage network.

The effects of small reservoirs and low-head dams have received considerable attention in the biological literature, but their cumulative impacts and influence on streamflow has only recently appeared in scientific literature. This may be due to the complexity of quantifying cumulative impacts in a catchment-wide context. Small reservoirs may occur anywhere in the catchment where need and appropriate physical conditions exist; as a result, they can exert varying pressures at many locations in the drainage network (Dunne et al. 2001). Also, the cumulative effect of several projects will vary temporally and spatially: the impact of small reservoirs will attenuate over time (if a reservoir fills, it may no longer impede surface flow until it is drawn down again) and impacts downstream are influenced by tributary confluences as well as the size and locations of other reservoirs on those tributaries.

To date, most studies of the hydrologic impacts of reservoirs have focused on large impoundments on big rivers, where flow-routing and other large watershed rainfall/runoff models can be used to make assessments of change, such as the Colorado River (e.g., Christensen et al. 2004; Christensen and Lettenmaier 2007) and the Murray-Darling basin (Schreider et al. 2002); or statistical tools comparing measured pre- and post-impairment streamflow data are used to illustrate how reservoirs affect a less-impaired flow regime (e.g., Richter et al. 2003; Ouyang et al. 2011; Moran-Tejeda et al. 2012). Impacts of small reservoirs and other distributed pressures (such as land use change) on stream hydrology have focused on catchment-scale effects, as modeled at a particular location downstream of several impacts in a catchment, rather than variations through the drainage network (e.g., Callow and Smittern 2009; Malveira et al. 2011; Mamede et al. 2012; Krysanova et al. 1998; Stehr et al. 2010). The absence of studies examining combined spatial and temporal impacts of small reservoirs on streamflow may be due to the complexities of space and time described above; as well as unknown information describing the size of reservoirs and how they are operated (as records describing their construction may not exist).

A thorough understanding of how impacts vary across space is important for water resource management where managers, planners, and regulators are interested in impacts and tradeoffs of various practices on streamflow and associated ecological processes (Nikolic et al. 2013). For example, in coastal California, small headwater reservoirs are frequently employed to meet agricultural water needs. While their impacts immediately downstream are clear (until the reservoir is filled, no water passes the earthen dams typically constructed to form these impoundments), the cumulative downstream effects of hundreds spread across the headwaters of a catchment is impossible to discern without tools that consider spatial relationships and the entire drainage network. Such tools are especially important when considering the tradeoffs between impacts of small reservoirs and other methods to meet agricultural needs such as direct diversions.

The principal ecological concern about small reservoirs in the study area is that the cumulative effect of several in headwater streams could cause substantial impairment in downstream reaches that support federally protected coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) during the rainy season, when reservoirs fill and these adult salmonids migrate upstream and spawn (CDFG 2004; SWRCB 2010; NMFS 2012). In this study, we apply a GIS-based cumulative impact evaluation model to consider the effects of small reservoirs across space and over time in a region with hundreds of small reservoirs in coastal Sonoma County, California, focusing on the rainy season as reservoir fill from discharge upstream. We incorporate a time-series analysis to illustrate the impairment caused by reservoirs individually and cumulatively through the basin, and the change in impairment caused by these reservoirs as they fill during the rainy season for two different hydrologic scenarios, one for a normal-type year and another for a dry-type year, to characterize the differences in those impacts through the drainage network.

2 Site Description and Methods

2.1 Study Area

Small reservoirs have provided a means to meet agricultural water needs in rural coastal California USA throughout the past century. The climate of this region is characterized as Mediterranean (Conacher and Conacher 1998): depending on location, it receives from 700 to over 1,300 mm of precipitation in an average year, but virtually all occurs as rainfall between October and April with less than 5 % on average from May through September. In the absence of large-scale water providers, wine grape growers in this region commonly rely on small-scale water projects such as small reservoirs and instream diversions to supply water for frost protection, irrigation, and heat protection through the growing season. Surface water is often preferred over groundwater because the underlying Franciscan-type bedrock produces very low groundwater yield (surface water is especially useful for frost and heat protection uses, when growers spray relatively large volumes of water over the grape plants during brief periods; Deitch et al. 2009b). Small reservoirs are a popular means of meeting agricultural water needs: more than 1,500 small reservoirs exist within the 3,800 km^2 Russian River basin in coastal California (SWRCB 1997).

Vineyard development and requests to divert surface water have both increased in northern Coastal California over the past 30 years, especially in small headwater catchments (Merenlender 2000; SWRCB 1997). The resulting increase in water use has coincided with legal protections offered to aquatic resources: the listing of coho salmon and steelhead trout under the federal Endangered Species Act requires that agencies with regulatory jurisdiction of water diversions ensure that new water appropriations do not interfere with needs of these salmonids. Streamflow at the onset of the rainy season (typically in November and December, toward the beginning of the water year) is of special concern because it acts as a signal for upstream migration of adult salmonids in lower stream reaches and maintains migration corridors (CDFG 2004; SWRCB 2010; NMFS 2012). Streamflow during this period is likely most-impaired as early-season discharge refills reservoirs depleted through the summer growing season and absence of rainfall causes streams to approach intermittence naturally. Small reservoirs are commonly empty at the beginning of the water year, a result of water storage having been fully employed for agricultural uses as well as the terms of invasive species plans (namely, to control bullfrogs) as regulated by the California Department of Fish and Wildlife.

2.2 Analytical Framework

We created a GIS-based watershed model and used a mass-balance framework to evaluate the cumulative effects of small reservoirs on streamflow through our study area drainage network. To model discharge (*input*) from upstream into each reservoir (and throughout the drainage network), we modeled streamflow using a simple drainage basin area-ratio transfer based on historical streamflow records measured within the study area. We scaled daily discharge from a historical USGS streamflow gauge centrally located in the project area (Maacama Creek near Kellogg, gauge number 11463900, which operated from 1961 through 1980) for every grid cell along the digitized drainage network according to a ratio of catchment area (i.e., the area-scaled discharge at a point with 1 % of the upstream area of the Maacama gauge was 1 % of the discharge at the Maacama Creek gauge) and by precipitation, where area-scaled streamflow at a point in the drainage network was multiplied by a ratio of average annual rainfall above that point to average annual rainfall above the USGS Maacama Creek streamflow gauge. Long-term average rainfall data from the PRISM data group (www.prism.oregonstate.edu/) were used as rainfall inputs for scaling streamflow. This method for modeling streamflow was chosen because of its clarity and simplicity to incorporate into GIS, as well as for its regulatory application: California's SWRCB, which regulates surface water rights, advises water right applicants in this region to scale streamflow by catchment area and precipitation in the process of determining whether there is additional water to allow a new water right (SWRCB 2010). An evaluation by the US Geological Survey (Mann et al. 2004) found that the basin area ratio transfer method generally performed better than rain-based methods of estimating streamflow in this region.

The model incorporates small reservoirs into a flow accumulation grid-based drainage network derived from a 10-m digital elevation model; impairment caused by each reservoir on flow downstream (*change in storage*, ΔS) is a function of reservoir volume and discharge from upstream. To model reservoir volume, we began by identifying, digitizing, and quantifying the surface area of reservoirs using orthorectified aerial photos and GIS tools; reservoir volume was estimated by fitting a linear relationship of surface area to reservoir volume (R^2=0.86) using a subset of 100 reservoirs in the region with known volume (where volume was listed in water rights records, available online through the California State Water Resources Control Board (SWRCB)'s Water Rights Information Management database at www.waterrights.ca.gov). While not an ideal method for deriving reservoir volume, most reservoirs in the study region have no quantitative information describing capacity on file with regulatory agencies (almost all are formed by earthen dams or berms and many are not permitted for a water right by the SWRCB). We then placed the reservoirs into our model by identifying the downstream-most point of each reservoir on the drainage network (termed the *impact point*) as the point at which each reservoir effectively separates the area upstream from the drainage network below, with the catchment above defined as the area contributing discharge into the reservoir.

The reservoir-impaired flow at a given downstream location (*output*) on a given day was calculated by subtracting the daily modeled flow at the reservoir's impact point from the daily modeled flow at the downstream location. The impact of a given reservoir may not be year-round; rather, the duration of its impairment is related to its volume capacity and annual discharge from upstream. Small reservoirs in coastal California typically operate through a technique described as "fill-and-spill": reservoirs store all discharge from upstream beginning at the onset of the rainy season, cutting off that portion of the catchment from the rest of the drainage network, until the scaled cumulative discharge for the year at the impact point (beginning on October 1, which marks the end of the growing season and, potentially, the beginning of the rainy season) exceeds the reservoir's storage volume. When a given reservoir has filled, the catchment upstream from the reservoir is reconnected and contributes flow below. The GIS framework provides a means to calculate cumulative reservoir effects throughout the drainage network by subtracting flow at all reservoir impact points upstream from flow at each point in the drainage and for tracking the time when each reservoir fills under a given streamflow scenario. Reservoirs were assumed to be empty at the onset of the analysis.

We applied this analytical framework to a 743 km^2 area in eastern Sonoma County, California. This area includes 438 reservoirs in the catchments of nine tributaries to the Russian River identified as critical habitat for steelhead trout under the Federal Endangered Species Act, with catchments ranging in size from 20 to 110 km^2 (Fig. 1). Reservoir capacity among the 438 reservoirs in the study area varies from 140 m3 to 435,000 m3; upper quartile, median, and lower quartile are 24,000 m3, 11,300 m3, and 5,500 m3 (19.5, 9.2, and 4.5 acre-ft), respectively. The upstream catchments of reservoirs in this region vary from 0.1 ha to 1,060 ha; upper quartile, median, and lower quartile are 1.6 ha, 7.0 ha, and 23 ha, respectively.

Agricultural (predominantly vineyard) development in these catchments ranged between 2 and 12 % of the total catchment area, spread among hillslopes and valleys throughout the region. Because of the importance of considering multiannual variability in water resource management (e.g., Assani et al. 2011), we compared these impacts in the dry-type and normal-type streamflow years. We ran analyses of streamflow to model cumulative impacts in a median-type flow year (1966, with median annual discharge of the 21-year period of gauge operation) and a dry-type flow year (1972, marking the lower quartile of annual discharge) to show how reservoirs could impair flow under two different hydrologic scenarios (Fig. 2). We chose median- and dry-type years for analysis because they offer insights into the pressures placed by humans on aquatic systems in a normal year, and then in a year when water resources are more limited. This latter condition may be especially important for understanding ecosystem resilience relative to added pressures placed by human water demands (we chose not to analyze a wet-type year because we were less interested in characterizing pressures placed during times of resource abundance).

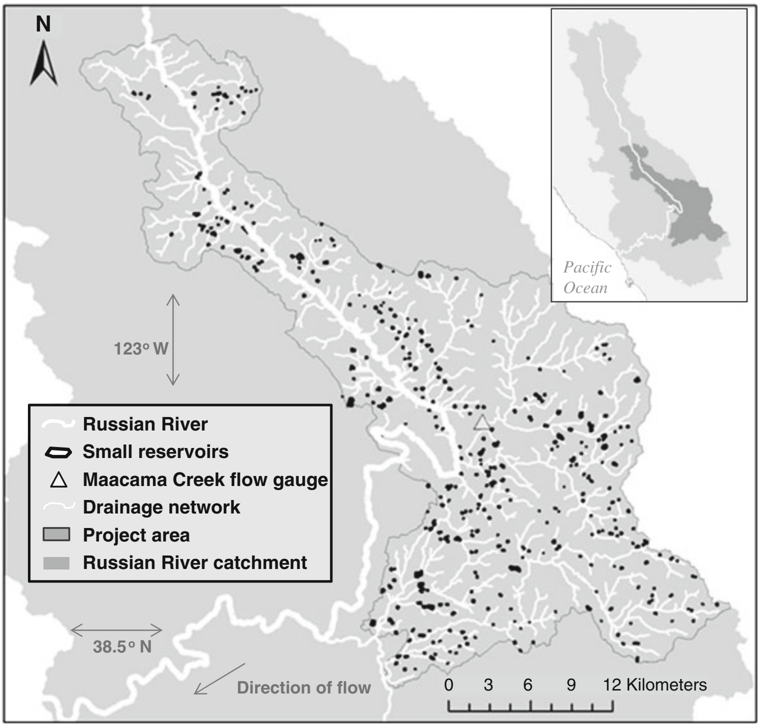

Fig. 1 Reservoirs in the study area portion of the Russian River catchment, along with historical streamflow gauge location (Maacama Creek near Kellogg, USGS 11463900)

We examined the spatial extent of impacts by identifying the drainage network impaired by reservoirs in the study area according to four classifications of impairment: channel network impaired less than 10 %; impaired between 10 and 25 %; impaired 25–50 %; and impaired more than 50 %. Impacts were evaluated at weekly intervals to identify changes in reservoir storage and cumulative impairment through the drainage network through the year.

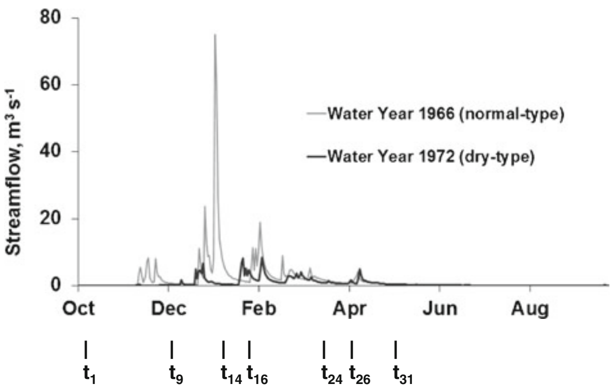

Fig. 2 Streamflow hydrographs for Maacama Creek in a median-type water year (1966) and dry-type water year (1972), with weekly intervals t1-t31 identified

We then summed the length of stream impacted under each classification of impairment described above at five time intervals and plotted these impacts according to stream order and upstream catchment area. Using the same framework, we also considered impacts only on those streams capable of supporting spawning for salmonids: a catchment area of 50 ha was chosen as a threshold for analysis as a simplified spatially definable estimate for a stream that might be capable of supporting spawning steelhead trout. This distinction of upstream catchment size allows for comparison of cumulative impacts relative to unimpaired streams, which helps to understand the extent of impairment over the entire drainage network.

3 Results

3.1 Reservoir Volumes, Location, and Duration of Local Impacts

Reaches immediately below reservoirs are subjected to the greatest impacts (based on model assumptions, no water will flow below reservoirs until the reservoir has filled and begins to spill over its dam. Under a normal-type flow regime, reservoirs remain unfilled until Week 7 (mid-November; Fig. 3). By Week 9, (early December), sufficient streamflow has occurred to begin filling reservoirs; 350 of the 438 reservoirs remain unfilled, meaning that there are 350 stream reaches in the study area where dams are impeding all discharge downstream at this stage in the water year. Most reservoirs have filled by Week 14 (early January), although the model predicts that 118 reservoirs remain unfilled from upstream flow throughout the year.

In a dry year, the impacts of reservoirs occur over a longer duration into the year. All reservoirs remain unfilled until Week 9, and 75 % of all reservoirs remain unfilled at Week 17 (late January; Fig. 3). By the end of the year, just over half of reservoirs have filled.

3.2 Cumulative Impacts to the Drainage Network

Reservoirs in the study area impair more than just the immediate stream reach below. The extent of impairment at any location in the drainage network varies with proximity to

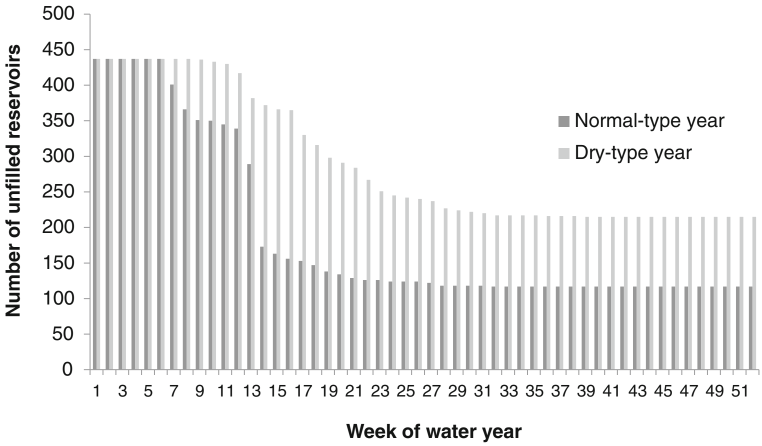

Fig. 3 Temporal distribution of reservoirs remaining unfilled, by week, during a normal-type and dry-type water year (based on Maacama Creek streamflow input; see Fig. 1)

reservoirs and time through the water year. In the project area, approximately 25 % of the entire drainage network below small reservoirs has its discharge reduced by more than half at the beginning of the water year; and approximately two-thirds of the drainage network is impaired by at least 10 % (Fig. 4a–b).

As the water year continues, the extent of impairment varies between normal-type an dry-type years. In a normal-type year, by Week 9, approximately 25 % of the drainage below dams is impaired by more than 25 %; and by Week 15, just over five percent of this drainage network is impaired by 25 % (Fig. 4a). By Week 24 in a normal year, the fraction of drainage network impaired by more than 10 % is small (Fig. 4a). In a dry year, impairment persists later into the rainy season. In Week 9 of a dry-type year, almost 40 % of the drainage below dams is still impaired by at least 25 %; and by Week 15, 25 % of this drainage is still impaired by that same fraction (Fig. 4b). More than ten percent of this drainage remains impaired by more than 25 % through Week 31 of a dry-type year.

The spatial distribution of reaches affected by reservoirs also varies through the year, and is different over time in normal- compared to dry-type years. At the beginning of a normal-type year, reservoir impairment affects most of the drainage network, in headwaters as well as lower reaches (Fig. 5a). By Week 9, the distribution of impairment shifts from the entire drainage to mostly headwater streams and downstream portions of a few particular tributaries (Fig. 5b). Impairment becomes more limited to headwater tributaries as the year progresses, and is almost entirely concentrated to regions immediately below reservoirs by Week 24 (Fig. 5c–d).

In a dry-type year, impairment caused by reservoirs is the same as in a normal-type year because no water has begun to accumulate in any reservoir (Fig. 6a). In Week 9, impairment

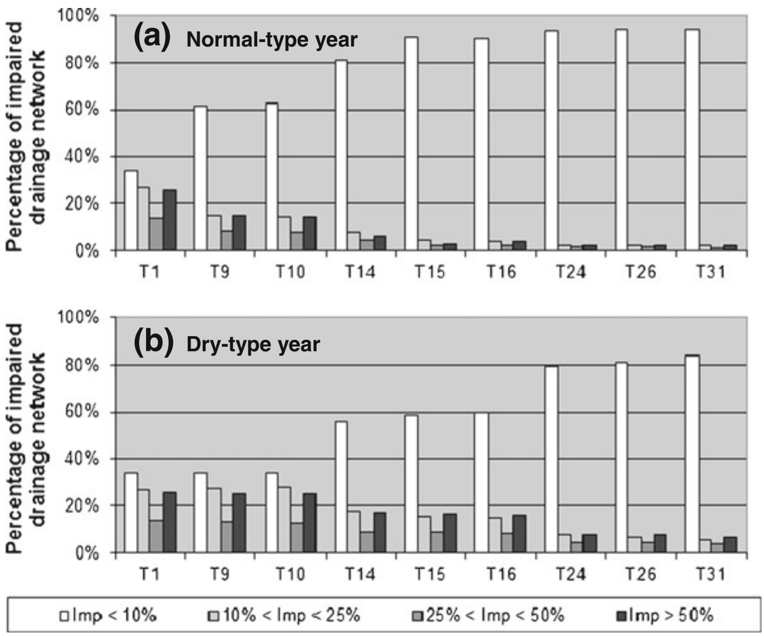

Fig. 4 a–b Change in impairment (Imp), by percentage of impaired drainage network, caused by small reservoirs through the course of (**a**) a normal-type and (**b**) a dry-type year (e.g., in Week 1, 32 % of the impaired drainage is impaired by less than 10 % and 24 % of the impaired drainage network is impaired by more than 50 %)

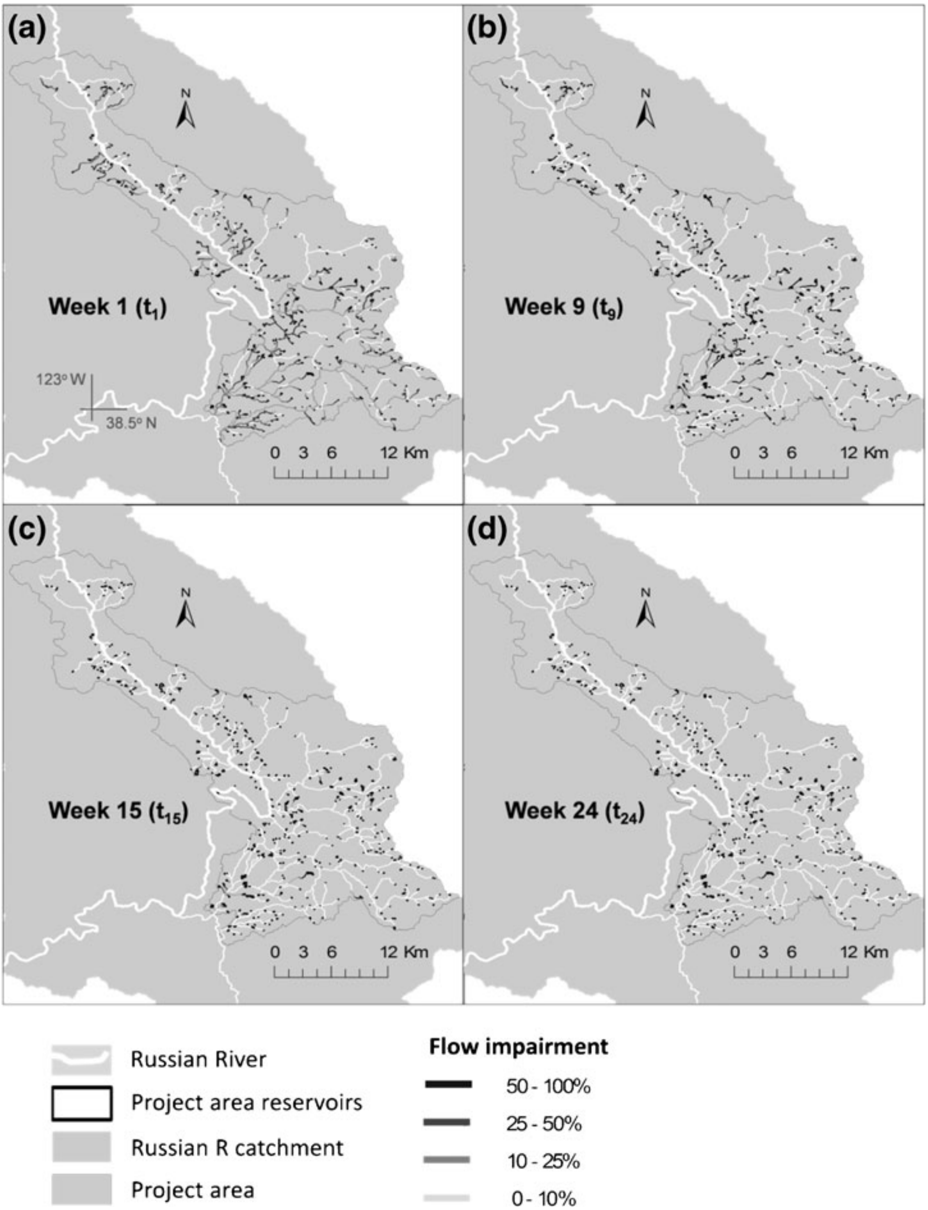

Fig. 5 a–d Impacts of small reservoirs over the impaired portion of drainage network, at onset of water year (Week 1), Week 9, Week 15, and Week 25 of a normal-type water year (see Fig. 1), as percentage of flow not reaching a given location due to upstream storage

caused by reservoirs still persists through much of the drainage network, in upper and lower reaches alike (Fig. 6b); and by Week 15, impairment is less pervasive but still affects some lower reaches (Fig. 6c). By Week 31, impairment is concentrated to upper reaches (Fig. 6d).

Though the impacts of small reservoirs vary according to location in the drainage network and arrangement of reservoirs upstream, data from the GIS model can illustrate how flow

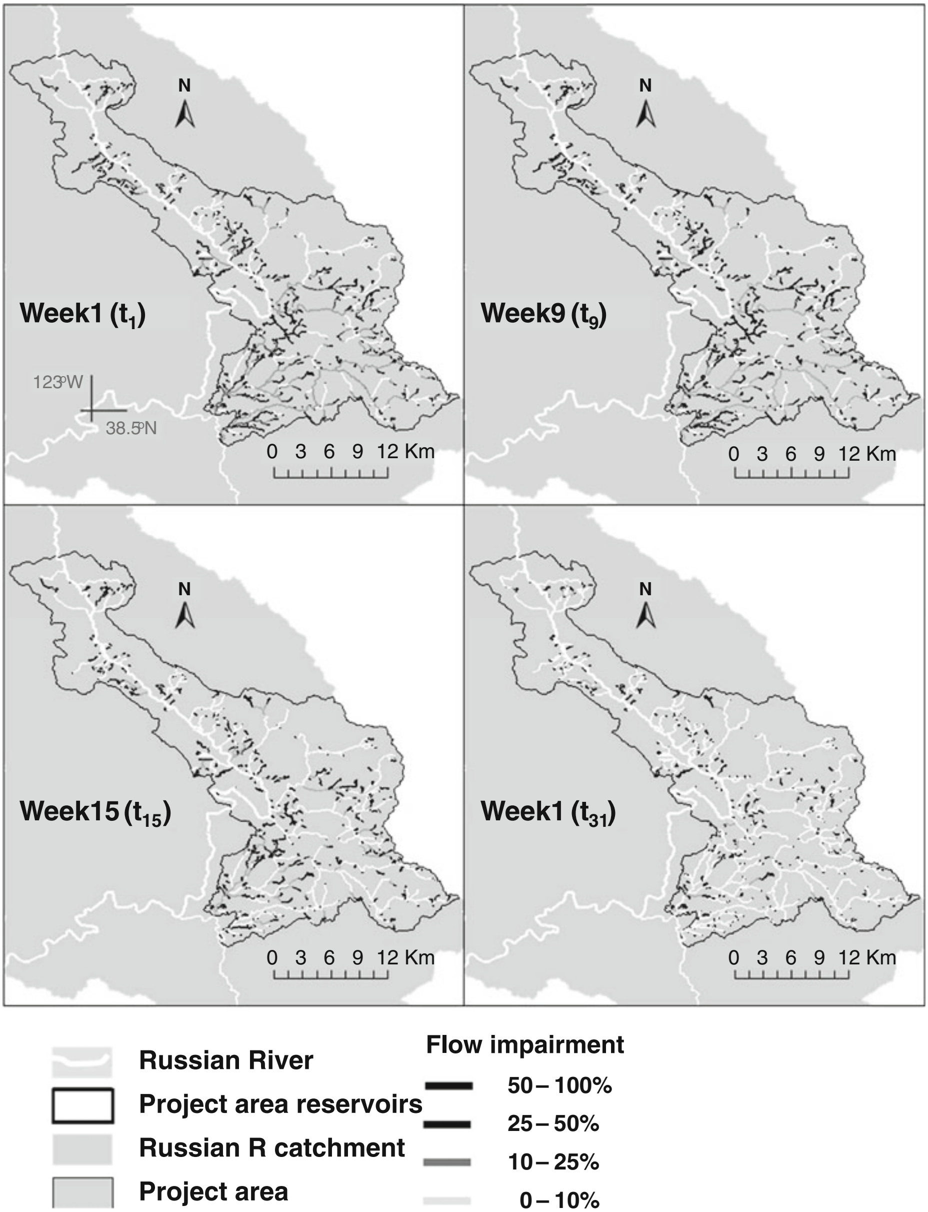

Fig. 6 **a**–**d** Impacts of small reservoirs over the impaired portion of drainage network, at onset of water year (Week 1), Week 9, Week 15, and Week 31 of a dry-type water year (see Fig. 1), as percentage of flow not reaching a given location due to upstream storage

can vary over time at two locations. For example, a downstream reach draining 110 km2 has 90 % of its unimpaired normal-year flow over the first 9 weeks (through November) and 99 % by week 15 (January). A reach farther upstream, draining 2.6 km2, has 59 % of its unimpaired flow through Week 9 and 100 % (indicating completely filled reservoirs) by week 15 (Fig. 7). This comparison also indicates that model output data shows the same flow regime characteristics as unimpaired flow (Fig. 2) under low impairment.

3.3 Regional-Scale Cumulative Impact to Salmonid-Bearing Streams

Within the project area, approximately 53 % of the drainage network with upstream catchment area greater than 50 ha is impaired to some extent by one or more small reservoirs (as described above, this threshold was chosen as the upstream limit for capability to support salmonid spawning). Of the drainage network below reservoirs with an upstream catchment area more than 50 ha (shaded gray streams, Fig. 8), approximately 30 % of the drainage network is impaired by at least 25 % at the beginning of the water year (Fig. 9a). This equates to 15 % of the *entire* drainage network with upstream catchment greater than 50 ha, given that 47 % of the drainage network classified as such has no small reservoirs upstream. Discharge by Week 10 reduces the drainage network impaired by 25 % to less than 10 % in a normal-type year but still comprises more than 27 % of the impaired drainage in a dry year (Fig. 9a, b).

By early January, after high-flow events in both the normal- and dry-type year (Week 15), the total amount of drainage network with upstream catchment greater than 50 ha impaired by at least 25 % has fallen to 1.5 % in the normal-type year and to 13 % in the dry-type year (Fig. 9a, b). The proportion of drainage impaired by at least 10 % has fallen to 5 % in the normal-type year, but remains 30 % in the dry-type year. By mid-February, marking more than half-way through the rainy season (Week 24), the total drainage impaired by reservoirs more than 25 % has fallen to less than 0.5 % in a normal year and 3 % in a dry year.

4 Discussion

The results above demonstrate the usefulness of spatially explicit models in understanding how distributed impacts affect conditions locally as well as cumulatively through a drainage network; understanding catchment processes is a key component to sustainable water resource management (Deitch and Kondolf 2012). Through most of winter, impacts are greatest in headwaters and are attenuated farther downstream, as additional drainage network contributes unimpaired streamflow. Empirically based models, such as this small reservoirs example, are increasingly recognized as useful to examine cumulative watershed impacts as

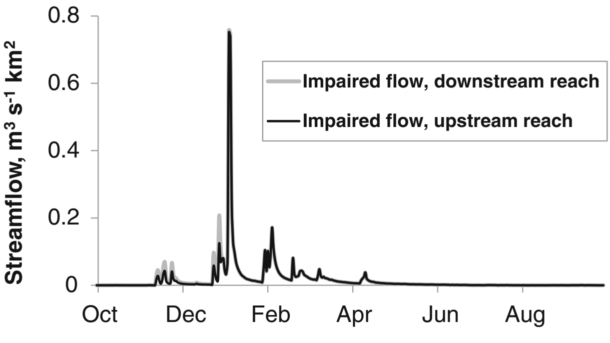

Fig. 7 Impaired streamflow (per area), normal year, at a downstream reach (110 km^2) and an upstream reach (2.5 km^2)

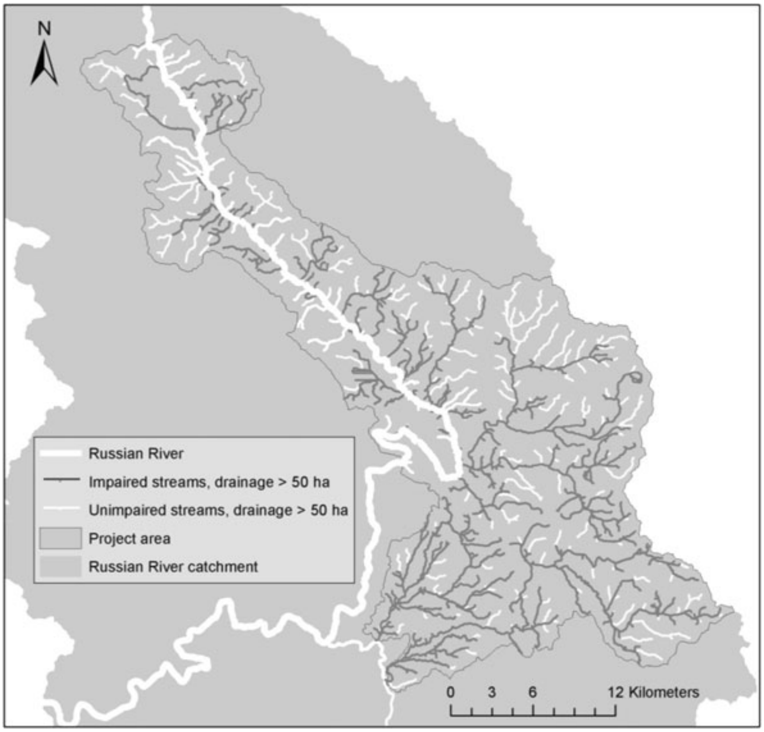

Fig. 8 Drainage network of streams with upstream catchment area greater than 50 ha, with (impaired) and without (unimpaired) small reservoirs upstream within the project area

compared to paired-catchment studies (Dunne et al. 2001; Zegre et al. 2010). This small reservoirs study also demonstrates how impacts vary across time; temporal considerations are important for evaluating disturbances in management and policy applications (MacDonald 2000), which many paired catchment and statistical cumulative impacts evaluations do not sufficiently address (Loftis et al. 2001).

The results above illustrate how small reservoirs impair flow immediately downstream until they fill (and many, according to model estimates, do not fill). Their cumulative effects are substantial at the beginning of the year, impairing more than 25 % of the drainage network with catchment areas greater than 50 ha by 50 % or more. However, the spatial distribution of impacts is not evenly distributed: it is instead focused on headwater streams, and reaches farther downstream (early-season migration corridors for salmonids) are less impaired even early in the water year. Additionally, overall impairment is reduced by early-season rainfall events: after this early rainfall, less than five percent of the drainage network is impaired by more than 10 %, as reservoirs become full early in the year.

Results of models like the one presented here can provide a foundation for discussion of ecological tradeoffs among regional water management practices, which is an important component of resource planning (Dole and Niemi 2004; Harma et al. 2012; Spyce et al. 2012; Weber et al. 2012). In this study area, reservoir storage may cause less ecological harm than other methods employed to meet agricultural water needs. For example, water uses like frost protection and heat protection require high volumes of water over short periods; growers frequently rely on water stored in reservoirs or on direct diversion from streams

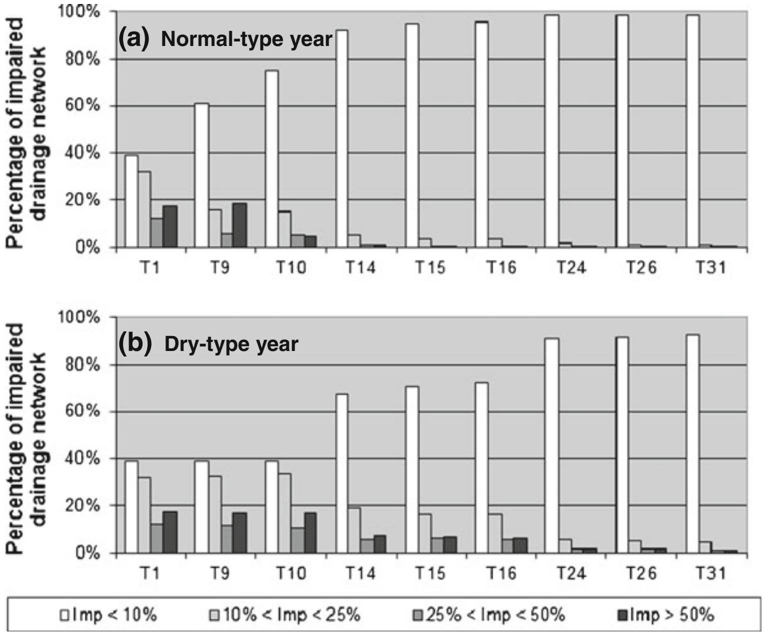

Fig. 9 **a**–**b** Change in impairment (Imp), by percentage of impaired drainage network with upstream catchment area greater than 50 ha, caused by small reservoirs through the course of (**a**) a normal-type and (**b**) a dry-type year (e.g., in Week 1, 32 % of the impaired drainage is impaired by less than 10 % and 24 % of the impaired drainage network is impaired by more than 50 %)

to meet water needs. Direct diversion for frost protection in March and April (often the end of the rainy season) can cause intermittence over the brief duration when pumping occurs, during peak juvenile salmonid outmigration (Deitch et al. 2009b). In contrast, existing small reservoirs filled via upstream have large impacts upstream from reaches capable of supporting salmonids early in the year; but locations farther downstream, which are likely to be corridors for adult salmonid migration to suitable spawning grounds in early few rainfall events. The concentration of impairment in a few locations suggests that small reservoirs may operate without having adverse impacts to streamflow through most of a normal-type year winter, are almost uniformly unimpaired by existing small reservoirs following the first. A reduction of headwater streamflow by 10 to 20 % through reaches that support anadromous salmonids early in winter may be a preferred outcome compared to reducing streamflow by 100 % in spring and summer.

Conflicts between human and ecological water needs are greater when conditions are drier than normal (Postel and Richter 2003). Dry-year impacts are more extensive temporally than normal-year impacts because the discharge required to fill reservoirs takes longer to occur. Nearly 30 % of the drainage network with upstream catchments greater than 50 ha is impaired more than 10 % at the conclusion of the first few storms of the dry-type year. While most of this impact is concentrated among headwater streams, it is more pervasive temporally. The existing suite of reservoirs in the study area will place greater pressures on aquatic biota in a dry-type year than under normal conditions; and while this dry-year scenario is by definition likely to occur in 1 year out of every four, predictions of dry-type conditions occurring more frequently through this century (Barnett et al. 2004) means that hydrologic impacts associated with dry-type years will be more pervasive in the future.

Tools that merge water security and ecological considerations will likely be important in the coming century (Norman et al. 2013). In addition to modeling impacts of reservoirs on streamflow, this model also demonstrates the effects of climate variability on agricultural water security: more than a quarter of reservoirs in the project area will not fill from surface flow in a normal-type year, suggesting that other mechanisms or methods (such as slower pumping from aquifers or diversion from larger nearby streams) would be necessary to fill these reservoirs. A greater number, nearly half, are unlikely to fill from upstream surface flow in a dry-type year; those grape growers who are dependent on water in reservoirs filled via inflow are less likely to have their water needs met under such conditions. As in other cases documented worldwide (Faramarzi et al. 2013; Rosa et al. 2012; Jung and Change 2012; Fiebig-Wittmaack et al. 2012), the dry-type conditions expected to become more common this century threaten water security: growers in this study region who are reliant on surface flow into small reservoirs may not have adequate water to meet their needs more frequently in the future.

Spatial models like this one can also be useful for water efficiency optimization and policy formulation (Merenlender et al. 2008; Grantham et al. 2013). Stakeholders can modify model inputs, including size, number, and location of reservoirs to optimize storage and minimize cumulative impacts on flow through the drainage network below. Similarly, policy makers can change inputs of reservoirs and water year scenarios to develop policies that provide adequate protections in winter while reducing pressures of direct instream diversion in summer. The spatial and temporal considerations provided by this reservoir impacts model can help to explore the cause of the differences in the results of this study compared to other small reservoir impacts evaluations that found substantial impacts to streamflow on a catchment scale (Malveira et al. 2011; Mamede et al. 2012). Such models have been used in developing decision support systems in regions of varying climate and extent of development (Coelho et al. 2012).

Though headwater reservoirs may provide a less damaging means of water management relative to streamflow, they may cause additional impacts beyond those that were modeled above. Headwater streams are important sources of fine and coarse sediment, nutrients, organic matter, and large wood, providing the foundation for a wide range of important ecological and hydrological processes locally and over the remainder of the drainage network below (MacDonald and Coe 2007; Freeman et al. 2007; Winter 2007; Alexander et al. 2007). Small reservoirs have potential to disconnect these headwater inputs and processes from the downstream drainage network indefinitely, potentially causing adverse impacts to aquatic ecosystems even in places where the flow regime is fully restored. For example, a reduced sediment load could cause increased channel erosion as the stream attempts to adjust to its natural sediment dynamics (Kondolf 1997) For these headwater inputs and processes, the cumulative impacts of small reservoirs do not become reduced over time, and though their impacts will vary with location and space, their effects may be continuous downstream. Spatial tools such as the framework described here may provide the means to evaluate cumulative impacts to these processes as well, assuming their temporal dynamics can be expressed for model inputs.

5 Conclusions

As humans face increasing challenges to maintaining a consistent water supply in the coming decades, spatially distributed projects like small reservoirs are likely to become increasingly common to meet water needs. Tools that consider cumulative impacts through space and time are essential for understanding the impacts of spatially distributed projects on catchment hydrology and associated ecological processes. In the portion of Sonoma County presented here, results indicate that the cumulative impact of the existing small reservoirs may have strong influence on early-season streamflow, but impacts become less over time. Knowing the size of reservoirs that have persistent impacts and their location in space can help managers develop practices and policies to minimize cumulative effects and still provide for beneficial human uses.

Tools like this reservoir impacts model may be most useful to identify pragmatic solutions to solving the complex issues that spatially distributed reservoirs raise. Small reservoirs that store water in winter provide a more ecologically sustainable alternative to summer diversion: summer diversion may result in drying of ecologically significant stream reaches. However, an excess of reservoir number or size may also have significant effects on stream hydrology. The results of this study also raise questions about the ecological ramifications of small projects and their hydrologic impacts: understanding the impacts of small streams on stream ecosystems depends on knowing the ecological significance of reducing streamflow by 10 % or 20 % or 50 %, and the impact of reducing streamflow over varying duration and at different locations through the year. Tools such as the model presented here are essential first steps for understanding impacts of these projects on stream ecology, but understanding the effects of these projects on stream ecology requires more careful analysis of how reduced flow at certain times of year can affect ecological processes.

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