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A spatially explicit framework for assessing the effects of weather and water rights on streamflow

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A B S T R A C T

Policies that establish availability of water for human uses are key tools for ecologically sustainable water management. In places where water management is decentralized and dispersed across a catchment, spatially explicit tools are essential for evaluating the cumulative effects of many instream diversions on discharge and water availability through the drainage network. We developed a spatially explicit model to evaluate the cumulative impacts of surface water rights under a decentralized management regime, and apply this framework to the Navarro River catchment, in northern California, and evaluate impacts relative to formal policies to determine whether water is available for further appropriation given environmental needs. Model results show that upstream water rights comprise a small fraction of normal-type winter discharge; but they comprise a much larger portion in dry years and all of discharge during the summer dry season. In a normal-type rainy winter season, water rights comprise less than 5 percent of the average discharge during the through almost all of the drainage network: by policy standards, water is widely available for further appropriation during this winter period. Most stream reaches where upstream water rights comprise more than 10 percent of discharge are small headwater streams (zero- and first-order). During other periods such as November and April (the beginning and end of the rainy season, respectively), impairment by water rights remains low under average conditions; but under dry conditions, most streams order 0–2 with upstream water rights are impaired more than 10 percent (with some more than 50 percent). During average summer conditions, 45 percent of the drainage network with upstream water rights is impaired by more than 20 percent; and 25 percent of these streams are impaired by more than 50 percent. These results indicate that water is available for further appropriation in winter; but water rights can cumulatively impair discharge by more than ten percent in small and large streams under dry-type conditions, and by more than 50 percent basinwide during the dry season.

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1. Introduction

Managing water to meet human and environmental needs is an increasingly common water resources paradigm in the 21st Century. The benefits of protecting streamflow and groundwater for environmental purposes are well-documented: they maintain habitat and processes necessary for sustaining aquatic and riparian organisms, and they sustain ecosystem services that benefit human well-being through the flow of goods and services from nature to people (Costanza et al. 1997; De Groot, Wilson, & Boumans, 2002; Wu, 2013). Requirements to maintain streamflow dynamics such as environmental flows (described by Arthington and Pusey (2003) as those streamflow dynamics that maintain geomorphic and ecological processes) are increasingly seen as necessary to protect the processes that sustain aquatic biota and public trust resources (Poff et al. 2010; Richter, 2010).

In places where water is regulated by large reservoirs, managing streamflow to protect environmental needs is relatively straightforward. The flows necessary to sustain environmental needs can be determined through modeled outcomes or measured empirically (Tharme 2003), and once the dynamics of reaching and sustaining those flows have been agreed upon, streamflow can be released from dams according to prescribed flow release schedules (Postel & Richter, 2003; Richter & Thomas, 2007; Richter, Warner,

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Meyer, & Lutz, 2006). Models have been developed to identify the dynamics of flows necessary to provide the natural variability that would occur in the absence of a large reservoir capable of regulating all streamflow dynamics (Poff et al. 2010; Richter, Baumgartner, Powell, & Braun, 1996, 2012; Richter, Davis, Apse, & Konrad, 2012).

If water is not managed from a central location, protecting flows for environmental needs is more complex. Agricultural producers, rural residents, recreational operations, and other types of land managers outside of the areas served by large water providers often obtain water from streams, springs, and groundwater through individual methods (Antonino et al. 2005; Deitch, Kondolf, & Merenlender, 2009a; Habets, Philippe, Martin, David, & Leseur, 2014; Liebe, van de Giesen, & Andreini, 2005; Malveira, de Arujo, & Guntner, 2011; The Economist, 2007). The resulting water management regime is decentralized, managed by individual water users rather than a central water supplier; it results in small dispersed impacts spatially distributed through a drainage network, rather than focused on one particular location (Deitch, Merenlender, & Feirer, 2013). Surface water diversions under a decentralized management regime are smaller than those that occur at large water supply reservoirs because they only provide water to meet the needs of one or a few water users, but depending on where and when they occur, such small diversions can have substantial effects on streamflow locally where they operate (Deitch, Kondolf, & Merenlender, 2009b).

The majority of the area in northern Coastal California is under a decentralized water management regime. Outside of a few large municipalities and small agricultural areas with water providers, people who live and work along streams obtain water through individual methods. Because of low abundance and poor quality of groundwater, and seasonal precipitation trends that result in virtually no rainfall during summer months, water is commonly diverted from streams and adjacent shallow aquifers to meet water needs through the dry season (Deitch & Kondolf, 2015). This means of obtaining water results in a direct ecological conflict: juvenile steelhead and coho salmon (*Oncorhynchus mykiss and O. kisutch,* respectively) also rely on water through the summer months to rear before migrating to the ocean. The common need for water through summer can result in adverse impacts to the streamflow that provides oversummering habitat for these juvenile fishes in the summer dry season (Deitch et al. 2009b; Grantham, Newburn, McCarthy, & Merenlender, 2012).

Changes in environmental laws in the 1990s (in particular, the listing of steelhead and coho salmon under the federal Endangered Species Act and a state court-ordered directive to protect public trust resources) prompted the California State Water Resources Control Board (State Water Board) to develop a Policy for Maintaining Instream Flows in Northern California Coastal Streams (Policy) to address this seasonal conflict between human and ecosystem water needs (SWRCB, 2010). To provide adequate ecosystem protections, the Policy prohibits granting water appropriations during summer, instead only allowing new water appropriations over a defined winter period. Land managers seeking a new water appropriation thus need to store water onsite in tanks or small reservoirs in winter for use in summer. Additional restrictions were placed on new water appropriations to ensure adequate protections for winter flows (discussed in more detail below), but overall, the Policy assumes that new instream diversions in winter can be accommodated while still offering adequate ecological protections that diversions during other times of year cannot.

The application of this new Policy in coastal California has led to many concerns and questions about the limitations it imposes. Water users and agricultural interest groups have voiced concern that the concentration of diversion to winter-only may, in some cases, affect senior water right holders; and in others, prevent new water right applicants from obtaining water they need for agricultural production. Environmental advocates have expressed concern that the cumulative effects of many small diversions could impair flow in winter beyond what could be predicted and cause widespread impacts throughout the drainage network. Because of the decentralized nature of water management in this region, these questions are not easily answered: the effects of diversions on streamflow will vary through the drainage network, as well as through the year from rainy winter to dry summer.

Spatially explicit GIS tools that can integrate cumulative effects of spatially distributed impacts and variations in discharge over space and time are critical for answering these important questions. In the research that follows, we use a spatially explicit basin-scale model to calculate the cumulative impacts of existing water rights on discharge through the Navarro River drainage network, as well as, according to the Policy, whether and where additional water is available for further appropriation. Because of the importance of climate variability in understanding human–ecosystem interactions, we also evaluate effects of water rights on discharge during other times of year and under dry-year types to compare impacts under different climatic conditions.

2. Methods

2.1. Study area

The Navarro River catchment in Mendocino County, California, drains a mostly forested 800 square km catchment (with some chaparral and grassland used for pasture) and reaches the Pacific Ocean 190 km northwest of the San Francisco Bay (Fig. 1). Over the past century, the predominant uses of land have been for timber harvesting in the conifer forest and pasture in the chaparral and grassland; in recent decades, some of the pasture has been converted to wine grape vineyards and apple orchards (covering approximately 1010 ha).

The climate of the Navarro is typical of coastal California: it is characterized as Mediterranean, with most precipitation occurring as rainfall during wet winters and very little occurring during the dry summer. PRISM precipitation models estimate that rainfall in the Navarro catchment ranges from 1000 mm to 1500 mm in an average year; approximately 90 percent of the rainfall occurs during the wet half of the year (November through April). Less than 3 percent occurs during July, August, and September. Streamflow in the Navarro River and its major tributaries mirrors this pattern, alternating between an abundance of flow and frequent flooding through winter to approaching or reaching intermittence in summer (Fig. 2).

The long summer dry season necessitates irrigation for agricultural production (Smith, Klonsky, Livingston, & DeMoura, 2004; McGourty, Lewis, Harper, Elkins, & MetzNoseraPapperSanford, 2013). Vineyards, which represent the most common form of row crop agriculture in the catchment, require much less water than other types of crop in California—to a depth of as little as 6 cm per area (reported by McGourty et al. [2013] as 0.2 acre-feet of water per acre, which corresponds to 610 cubic meters per hectare)—but the characteristically poor aquifer characteristics of the regional Franciscan bedrock means that water managers often turn to ambient surface water sources to meet needs.

2.2. Analytical framework

To evaluate cumulative impacts of existing water rights and determine whether and where water can be further appropriated within the Navarro River drainage network, we created a GIS-based

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