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Climate Change and Flood Operations in the Sacramento Basin, California

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ABSTRACT

Climate warming is likely to challenge many current conceptions and regulatory policies, particularly for water management. A warmer climate is likely to hinder flood operations in California's Sacramento Valley by decreasing snowpack storage and increasing the rain fraction of major storms. This work examines how a warmer climate would change flood peaks and volumes for nine major historical floods entering Shasta, Oroville, and New Bullards Bar reservoirs, using current flood flow forecast models and current flood operating rules. Shasta and Oroville have dynamic flood operation curves that accommodate many climate-warming scenarios. New Bullards Bar's more static operating rule performs poorly for these conditions. Revisiting flood operating rules is an important adaptation for climate warming.

KEY WORDS

Climate change, flood control, rule curves, reservoir management

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INTRODUCTION

It is often desirable to change regulatory policies with changing conditions. A changing climate, along with other changes in floodplain land use and flood warning and forecasting, will pose problems and opportunities for existing flood management (IPCC 2007). This paper focuses on the implications of not adapting reservoir operating policies for flood management in California's Sacramento Valley for various forms of climate warming. This complements the existing literature on adapting water management to changes in climate in California (Carpenter and others 2001, 2003; Tanaka and others 2006; Zhu and others 2007; Anderson and others 2008; Hanak and Lund 2008; Medellin–Azuara and others 2008).

When dams are built for flood management, a flood operations curve is developed to guide (or restrict) flood operations throughout the year. These flood-control rule curves define the maximum allowable reservoir pool elevation for each day of the year, and represent the balance between flood control and water supply objectives. Maximum allowed pool elevations have been established using the historical hydrologic record; physical constraints, such as downstream channel capacity, outlet capacities, and reservoir volume; and other operating objectives, such as water supply, hydropower, and recreation.

Because most of California's dams were built in the mid-1900s, the historical record used to create

rule curves includes only the first half of the 20th century. While hydrologic trends and other conditions have changed since then (Collins and Whitin 2004; Saunders and others 2008), the rule curves have not typically been updated. Climate changes pose additional challenges for reservoir operations planning. In much of the western U.S.—particularly watersheds in the northern Sierra Nevada—snowpack provides sizable seasonal water storage, making the West's water storage vulnerable to climatic warming that influences snow fractions in winter precipitation, spring snowpack volumes, and runoff timing (Cayan and Riddle 1993; Mote and others 2005; Regonda and others 2005; Knowles and others 2006; Barnett and others 2008; Medellin–Azuara and others 2008; Saunders and others 2008). Because California receives little precipitation between June and October, adapting to changes in peak flow timing and snowmelt runoff is crucial to reserve water supply for the summer and fall, and to ensure adequate flood storage. The combination of a greater flood risk and reduced seasonal snowpack storage will exacerbate the tension between flood control and water supply storage (Knowles and others 2006).

Several studies have examined climate change effects on reservoir operations. Lee and others (2006, 2009) examined the effect of a 2 °C air temperature increase on flood-control operations in the Columbia River basin and developed optimized rule curves based on monthly time step simulations for a single climate change condition. The results showed that storage deficits decreased when current curves were updated to reflect climate change, without increasing monthly flood risks; however, a daily or sub-daily analysis of flood-control operations would better reflect real-time conditions during a flood. Also, the conclusions relied on a single climate change scenario, and did not examine the range of potential risks, given multiple climate change scenarios. Georgakakos and others (2005) developed the Integrated Forecast and Reservoir Management (INFORM) Project to manage flood-control operations in the Sacramento Basin. This study examined the use of short- and long-term forecasts in real-time operations, and concluded that static rule curves would perform poorly, given climate changes, and could increase the risk of costly failures. New Bullards Bar Dam was not considered in the analysis, though, and its operations are related to those at Oroville Dam. An analysis of Oroville Dam that includes New Bullards Bar adds another dimension to the study that more closely reflects real-time operations of the two dams during floods.

This study explores the effects of climate warming on floods and flood-control operations for three basins in California's Sacramento Valley: the Upper Sacramento River above Shasta Dam, the Feather River above Oroville Dam, and the North Yuba River above New Bullards Bar Dam. Existing rule curves for these dams are tested against a range of climate-warming scenarios. This work builds on previous work by simulating sub-daily run-off conditions and flood-control operation decisions, which provide a more representative examination of flood-control management with changed climate conditions than daily or monthly time steps. It also examines a range of climate scenarios, which allow water managers to consider the "best-case" and "worst-case" scenarios of managing flood flows, given climate change. Finally, this study examines combined flood-control operations of Oroville Dam and New Bullards Bar Dam, which are more reflective of real-time operating constraints.

BACKGROUND

Basin Hydrology

The Upper Sacramento River above Shasta Dam, the Feather River above Oroville Dam, and the North Yuba River above New Bullards Bar Dam are in California's Sacramento Valley (Figure 1). While the size and elevation range varies for each basin, they share some hydrologic characteristics. Winters are wet, with 90% of annual precipitation occurring in 2 to 3 months between November and April. While the snow–rain boundary generally occurs at elevations of around 1,524 m during the wet months, if warm temperatures accompany a storm, rain can occur at the highest elevations. Likewise, if temperatures are cold, snow can fall on the valley floor (USACE 1977, 2004, 2005). The areas above Shasta, Oroville, and New Bullards Bar dams were studied because each basin's

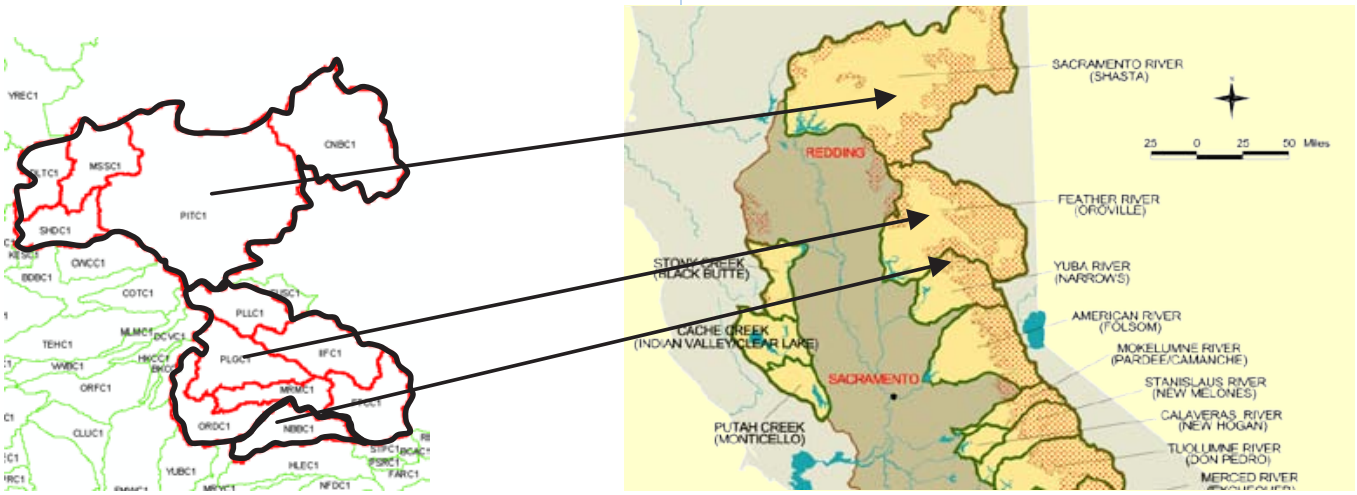

Figure 1 Major watersheds of the Sacramento Valley (and their subbasins) for the three study areas, as represented in the National Weather Service River Forecast System. Dotted areas indicate elevations above 1,524 m, an approximation of the rain–snow boundary elevation (Figure from Collins and Whitin 2004).

relatively low elevation distribution (mean elevation is approximately 1,524 m) and hydrologic regime makes it sensitive to small climate shifts. The amount and timing of runoff are influenced by climatic variables, such as precipitation and temperature, as well as non-climatic factors, such as lithology, soil, and vegetative conditions (Aguado and others 1992). In this study, we examine only temperature and precipitation changes. We do not include other changes, such as land use.

Flood-control Rule Curves

Flood-control rule curves (rule curves) define the maximum allowed reservoir pool elevation for each day of the year, reflecting seasonal runoff patterns and basin conditions. These curves imply a balance between flood-control and water supply objectives for each dam. The most recent versions of rule curves for the three dams in this study are all pen-and-ink drawings, reflecting their now-distant past graphical and methodological origins. Figure 2 shows the rule curve for Oroville Dam. The negatively sloped segments show the early flood season, when water managers draw down the reservoir to prepare for large inflows by increasing the flood-control space in the reservoir. The horizontal segments indicate the season of major storms. The positively sloped segments define the refill period, when water managers begin to store water for use in the dry season.

The rule curves were developed as each dam was constructed, based on the basin's existing hydrologic record; physical constraints, such as downstream channel and outlet works capacity; and functional constraints, such as the water supply, hydropower and other objectives. After the U.S Army Corps of Engineers (the Corps) gained some experience creating rule curves, they published a master manual providing an overview of reservoir regulation (USACE 1959). After they developed this master manual, some rule curves were updated. Rule curves were scheduled to be reviewed and updated if necessary on a 3- to 5-year cycle. In the 1990s, a lawsuit prevented the Corps from updating the Oroville rule curve unless they also developed an Environmental Impact Statement to support the revision. This ruling applied to all reservoirs that reserve federal flood space. NEPA documentation proved to be costly, and beyond the funding established for updating the manuals. So, rule curves for Corps-operated California dams operated have not been updated for at least 15 years (J. Countryman, MBK Engineers, pers. comm., 2008).

Flexibility can be built into rule curves by using parameters that describe how the basin's antecedent conditions alter maximum flood pool draw-down and

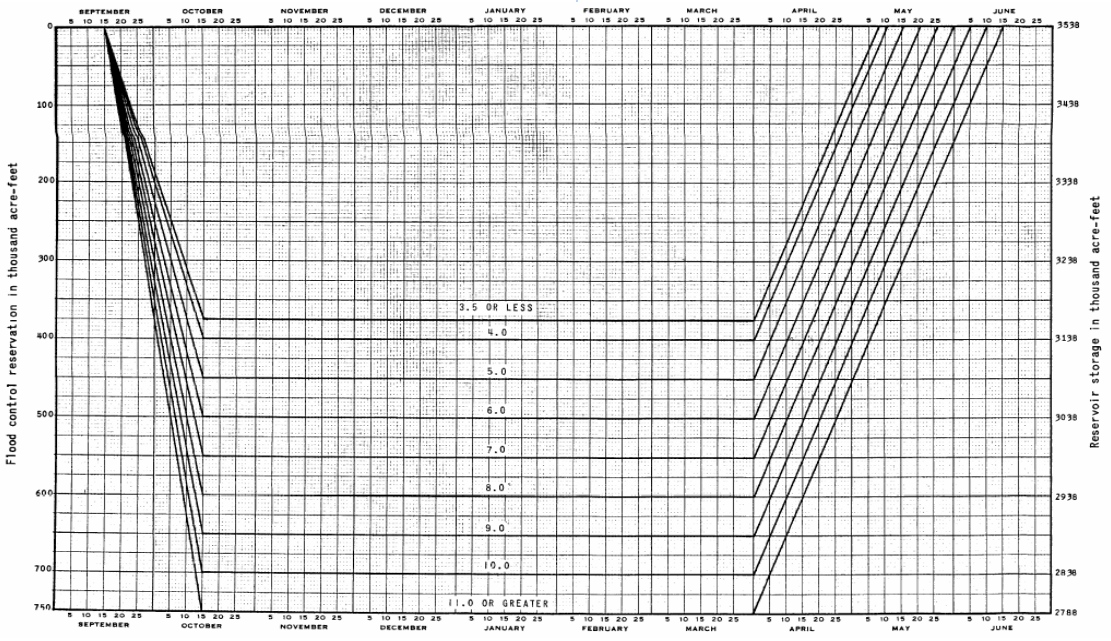

Figure 2 Flood control diagram for Oroville Dam. This pen-and-ink drawing is the most recent version available. Each line represents allowable storage, based on cumulative precipitation (USACE 2005). Oroville Dam's rule curve has flexible draw-down options, but rigid refill options.

refill rates. Such parameters allow water managers to store more water in the reservoir during dry years and increase or prolong flood storage during wetter years. Oroville and Shasta dams' rule curves each use a state variable that quantifies observed precipitation and inflow volumes, respectively. Oroville's rule curve requires less drawdown during dry years (Figure 2). The refill period begins at the end of the flood season and does not take advantage of the rainfall runoff characteristics of the basin. Shasta's rule curve requires the same reservoir pool drawdown volume at the beginning of the flood season, but refill can begin as early as December 25 (Figure 3). The refill rate depends on observed inflows to the reservoir, and better reflects the rain–flood hydrology of the basin. The New Bullards Bar static rule curve has no state parameter, and provides no flexibility for the initial reservoir pool draw-down volume or refill timing (Figure 4).

An unusual feature of flood operations in the New Bullards Bar water control manual is that they are linked to the operation of Marysville Dam. (Flood operations in that basin were developed for a system of dams that included Oroville, New Bullards Bar, and a planned Marysville Dam). For example, the downstream channel capacity constraints include how the Marysville Dam would also affect channel flow volumes. But Marysville Dam was never built, so the flood operations of New Bullards Bar Dam are partially defined by another major flood-control project that does not exist. The original curve for New Bullards Bar Dam, which includes Marysville Dam, was approved in 1978, and remains in effect (USACE 2004).

Climate Change

A shift has occurred in overall hydrologic conditions since the mid-20th century with significant effects for flood management (IPCC 2007). Many studies have evaluated past and projected climate change effects on hydrologic patterns in the western United States and the northern Sierra Nevada (Kim and others 1998; Miller and others 2003; Mote 2003; Collins and Whitin 2004; McCabe and Clark 2005; Mote and others 2005; Regonda and others 2005; Bonfils and others 2006; Knowles and others 2006; Zhu and oth-

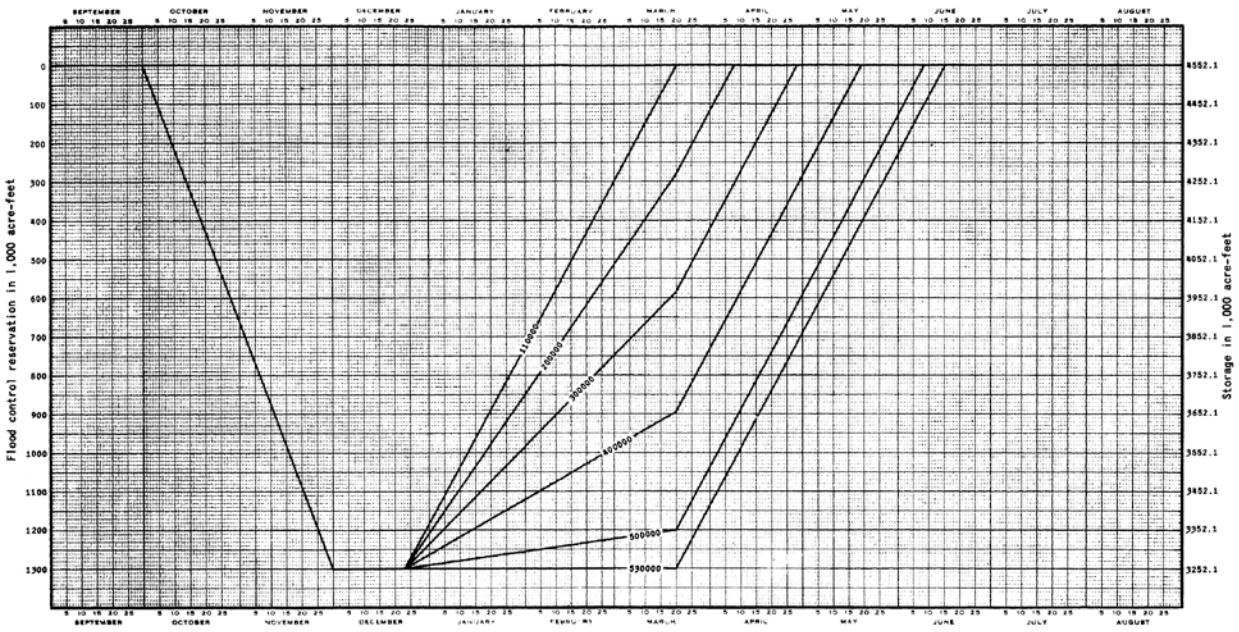

Figure 3 Flood-control diagram for Shasta Dam. This pen-and-ink drawing is the most recent version available. Each line represents allowable storage based on cumulative precipitation (USACE 1977). Shasta Dam's rule curve has a several refill options, but a rigid drawdown option.

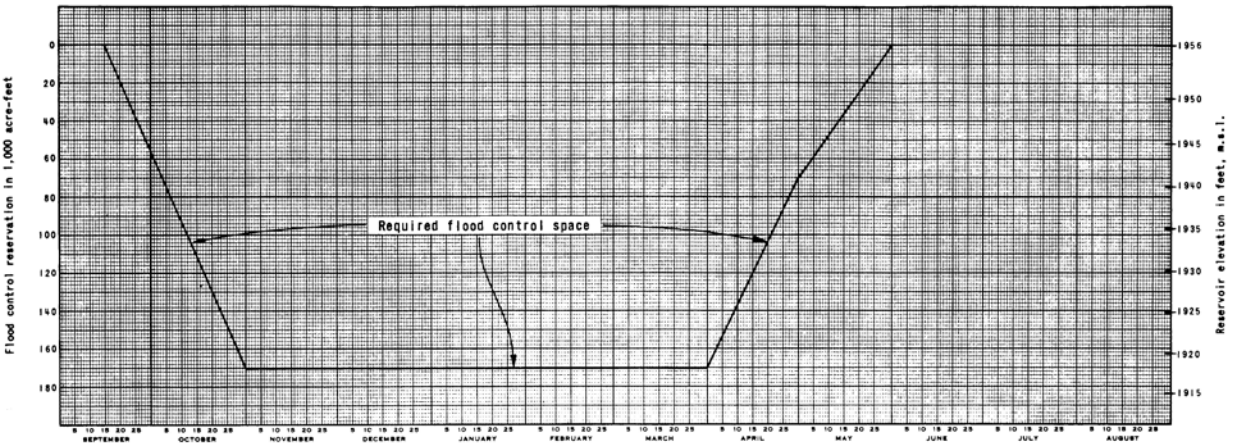

Figure 4 Flood-control diagram for New Bullards Bar Dam (USACE 2004). This pen-and-ink drawing is the most recent version available. The single line illustrates no flexibility for basin wetness parameters, and only one option for drawdown and refill schedules and volumes.

ers 2007; Barnett and others 2008; Saunders and others 2008). These studies focus primarily on temperature and precipitation changes.

Temperature trends that exceed natural variability are frequently used as evidence of climate change. Floods in California are sensitive to temperature changes because they affect fractions of rain versus snow in precipitation, and the timing of snowmelt runoff. Given the sensitivity of flooding to temperature, the mid- to low-elevation basins in the West are the most sensitive to initial increases in temperatures (Lettenmaier and Gan 1990; Mote 2003; McCabe and Clark 2005; Knowles and others 2006;

Hamlet and Lettenmaier 2007). Over the past century, temperatures have increased (Mote and others 2005; Saunders and others 2006). The largest temperature increases are during the winter in the northern Sierra Nevada and Pacific Northwest (Knowles and Cayan 2004; Regonda and others 2005; Knowles and others 2006; Maurer 2007; Saunders and others 2008). Increasing temperatures have increased the fraction of rain in winter precipitation and decreased snow–water equivalents (Kim and others 1998; Droz and Wunderle 2002; Mote and others 2005). Higher fractions of rain have led to higher volumes of winter rainfall runoff. Warmer temperatures also have accelerated spring snowmelt by 10 to 20 days (Regonda and others 2005).

Some efforts exist to make flood operations more responsive to watershed conditions, often by employing short- and long-term forecasts, integrating various objectives into an optimization approach based on water supply goals at the end of the flood season (Carpenter and Georgakakos 2001; Yao and Georgakakos 2001; Georgakakos and others 2005; Lee and others 2006). Each of these efforts identifies different ways to improve reservoir operations in California and the Pacific Northwest.

DATA AND METHODS

We estimate regional climate changes for the three study basins based on downscaled and bias-corrected global climate projections. Ranges of likely temperature and precipitation changes for a 30-year period centered on the year 2025 were estimated from results of 22 GCM runs. The climate changes are applied to 40-year records of observed temperature and precipitation for the study basins. The perturbed historical temperature and precipitation records were then used in the National Weather Service River Forecast System (NWS–RFS) to estimate reservoir inflows over the 40-year period for different climate scenarios. We used these climate-perturbed inflows to test each reservoir's flood-control performance, given climate-perturbed hydrology and static rule curves using the Corps' Hydrologic Engineering Center Reservoir Simulation (ResSim) model. Details about the models and data used are discussed below and in Fissekis (2008).

Climate Change Data

We estimated a likely range of temperature and precipitation changes in each study basin using 11 GCMs identified in the IPCC Fourth Assessment Report (2007). Using these 11 GCMs, we calculated climate projections for two emissions scenarios described by the IPCC (2007): the higher emission scenario, A2, and lower emission scenario, B1. Though A2 does not represent the worst-case scenario for future emissions, it is often used as a high estimate for climate-change studies; B1 generally represents the best-case future emissions scenario. Running GCMs using different emissions scenarios allows comparisons across potential futures (Maurer 2007). Eleven GCMs run for each emission scenario yields 22 climate scenario results.

These GCMs provide global projections that are down-scaled and bias-corrected from 2° resolution to 1/8° resolution. Wood and others (2002) developed the downscaling and bias-correcting techniques for using global model forecast output for long-range streamflow forecasting (Maurer 2007). Downscaling provides regional data for each sub-basin in the three study areas (Figure 1), corresponding to those in the NWS–RFS model used to simulate flood flows for the study basins. The NWS–RFS is discussed in more detail later in this paper.

We used 6-hour time-series temperature and precipitation data from October 1960 through September 1990, from the California–Nevada River Forecast Center (CN–RFC), as a baseline for comparison with the data from the GCM projections for the period 2010 through 2040. We estimated projected changes for the year 2025 relative to the year 1975 using the monthly average value of temperature and precipitation from 1960 to 1990 (30 years centered on 1975) and from 2010 to 2040 (30 years centered on 2025). The ratio-minus-one value of the 2025 average over the 1975 average determines the percent average increase from 1975 to 2025 (Equation 1).

$$\frac{AVG_{2025}}{AVG_{1975}} - 1 = \%\ \text{average change from 1975 to 2025} \quad (1)$$

Finally, we calculated the 10th, median, and 90th percentile values of the 22-model range, which yields a range of temperature and precipitation changes for the year 2025. The 10th, median, and 90th percentile values are used to include 80% of future climate projections, neglecting the least likely extremes. Values for the increases to the temperature record, and percentage change for precipitation, appear in Table 1. Larger numbers of GCM runs and different run statistics could be used for this exercise, but the runs and methods chosen suffice to illustrate the variability and range of estimates available.

Table 1 Temperature and precipitation projection statistics used to perturb the observed record for the three study basins

	Percentile		
	10th	50th (Median)	90th
Δ Temperature	+0.4 °C	+1.0 °C	+1.4 °C
Δ Precipitation	–6.6%	+4.5%	+16.8%

Climate scenarios are identified by the temperature and precipitation perturbations they represent. For example, T+1.0, P–6.6% refers to the climate scenario in which the historical temperature record is increased by 1.0 °C and the historical precipitation record is decreased by 6.6%.

Although temperature and precipitation projections are available for each sub-basin within the three main watersheds, the same change ranges are used for all basins. Projected temperature increases for each sub-basin vary within 0.1 °C. Precipitation changes vary widely: projected precipitation changes vary within 3% for each sub-basin except for the 90th percentile values, which vary more than 7%. A single, average percentile value is applied across all three study basins to test the sensitivity of the basin to temperature and precipitation changes, but not to quantify changes resulting from temperature and precipitation changes. These step changes are used to perturb observed temperature and precipitation data for the three study basins. The observed, 6-hour time step record ranges from October 1, 1960 to September 30, 1999, and includes nine major floods.

National Weather Service River Forecast System

The NWS–RFS is a precipitation-runoff model used for flood and river forecasting. River Forecast Centers around the country, including the California–Nevada office, use the NWS–RFS to make short-term (a day to a week in advance) and long-term (a week to months in advance) forecasts. This model also is used for operations planning, policy, and research.

The NWS–RFS includes snowmelt and rainfall runoff, temporal distributions of runoff, channel losses or gains, channel routing, base flow, reservoir regulation, stage–discharge conversions, time-series manipulations, statistical functions, and water balances. The system uses observed and forecast point data for meteorological components such as temperature and precipitation, and generates information about predicted river stage and discharge at selected forecast points. The RFS also stores information on hydrologic conditions such as snow cover, soil moisture, and channel storage (NOAA 2002).

Infiltration in NWS–RFS is represented using soil "tanks" that fill at a rate determined by transpiration, horizontal drainage, and vertical percolation processes. Soil processes are represented by upper and lower tanks. The upper tank models vertical percolation, horizontal drainage, transpiration, and soil absorption. The lower tank models groundwater processes such as water-table storage and subsurface and base flows. These are described in NOAA (2002).

Hydrology Data

Hydrology data are generated using the perturbed historical temperature and precipitation files to calculate the resultant runoff using the National Weather Service River Forecast System (NWS–RFS). Six-hour time step temperature and precipitation data from October 1, 1960 to September 30, 1999 are used for each sub-basin in the three basins. Shasta has five sub-basins; Oroville, six sub-basins; and New Bullards Bar, one sub-basin. Each temperature scenario, including the observed record, is combined with each precipitation scenario. Including the observed record, 16 unique climate scenarios are explored for each basin. These temperature and pre-

cipitation records are input to the NWS–RFS model to produce 6-hour time step inflows to Shasta, Oroville and New Bullards Bar.

HEC–ResSim Model

The HEC–ResSim model is used to model reservoir releases based on inflow, watershed and dam characteristics, and reservoir operating policies (USACE 2007). This model is used by the Corps to assess release objectives during flood events; it can also be used for planning, policy, and research.

Inputs to this model are the 6-hour time-series runoff hydrology results from the NWS–RFS for the 40-year period. In this project, only reservoir releases are accounted for in the basin model. Local flows downstream of the reservoirs are not included because downstream inflow data are unavailable. One limitation of this model is that it can only apply one rule curve per simulation. Without further programming of the ResSim software, the model cannot incorporate dynamic rule curves such as those used at Oroville and Shasta dams. To overcome this limitation, simulations are repeated for Shasta and Oroville basins, using alternate curves defined in their flood-control manuals.

Flood events are sampled to reflect a range of storm timings, intensities, and rain-to-snow ratios (Table 2). Cold storms illustrate how increasing temperatures affect snow events and large seasonal snowpacks. Cold storms include January 1969, January 1980, December 1982, March 1983, and March 1995. Average temperatures during some of the cold storms are above freezing in some of the study basins but below freezing in others; however, snowpacks for cold years are some of the largest on record (DWR 1969, 1980, 1982, 1983, 1995, 1997). Therefore, while the isolated events may not show a strong response to temperature increases, the effect of increasing temperatures over the season is significant. Events with temperatures above freezing in the upper basin elevations, and storms that mainly consist of rain are called warm events. Warm storms are January 1960, December 1964, February 1986, and January 1997. Some storms occur within days of smaller precipitation events; storms that follow an antecedent event are indicated in the table.

Some climate change scenarios are excluded from the analysis because of processing errors. For the Oroville watershed, hydrologic data describing the T+0.4 °C, P–6.6% are unavailable. For the Shasta watershed, data for T+1.4 °C, P–6.6% scenario watershed also are unavailable. However, because this study looks at

Table 2 Characteristics of major floods used in this study, illustrating the effect of temperature and precipitation

Name	Event type	Antecedent event?	Duration (hrs)	Runoff volumes (TAF) (% of mean annual flow)		
				Shasta	Oroville	NBB [a]
January 1963	Warm	No	144	756 (13)	710 (16)	267 (21)
December 1964	Warm	No	312	1900 (33)	1840 (40)	847 (67)
February 1986	Warm	Yes	402	1770 (31)	2466 (54)	598 (48)
January 1997	Warm	Yes	408	2064 (36)	1768 (39)	569 (45)
January 1969	Cold	Yes	498	1170 (20)	1057 (23)	434 (34)
January 1980	Cold	Yes	330	809 (14)	1109 (24)	430 (34)
December 1982	Cold	No	144	436 (8)	324 (7)	119 (9)
March 1983	Cold	Yes	570	2295 (40)	2071 (46)	418 (33)
March 1995	Cold	No	522	2018 (35)	1959 (43)	428 (34)

[a] New Bullards Bar

basin sensitivity and does not quantify the hydrologic response because of climate change, we examine the general trends of the hydrologic response to temperature and precipitation changes for consistency with the other two study basins.

EFFECTS OF CLIMATE CHANGE ON STORMS

Across the three study basins, storm responses to changes in temperature and precipitation regimes are broadly similar. Discharge rates during warm storms respond strongly to changes in precipitation intensities, but weakly to temperature changes because warm storms contain little snowfall that would be affected by increased temperatures. For cold storms, discharge volumes respond strongly to both temperature and precipitation changes. For cold storms near freezing, small temperature increases can raise temperatures above freezing, yielding higher fractions of rain and wetter basin conditions (i.e., increased soil moisture content).

To illustrate the broad trends across all three study basins, results from New Bullards Bar basin are presented. Temperature trends during each storm event are provided to help define it as warm or cold. Mean area temperatures are given for elevations above and below 1,524 m, the general elevation of the snow–rain boundary is defined by the NWS–RFS model. Hydrographs show inflows for climate scenarios that perturb temperature, to illustrate how warm and cold events respond differently to temperature increases.

Increasing temperatures have little effect on warm storms, as illustrated by the January 1997 rain event. In the upper and lower basins, average temperatures are 1.7 °C and 7.4 °C, respectively. The hydrograph for the January 1997 storm illustrates the runoff for the observed and perturbed temperature scenarios (precipitation intensities were not changed) (Figure 5). The hydrographs for each scenario generally overlap; the magnitude and timing of warm storm inflows are not affected by increasing temperatures. The precipitation composition of warm storms does not change when temperatures increase because temperatures during the observed event are already above freezing.

Cold storms respond more to increasing temperatures. Temperatures during the March 1983 snow event are near freezing. Average temperatures in the upper and lower basins are 0.8 °C and 5.9 °C. Because temperatures in the upper basin are close to freezing, small shifts in temperature can affect overall discharge. Such strong effects are illustrated in the March 1983 hydrograph for New Bullards Bar (Figure 6).

Runoff trends respond to the smallest temperature increase, +0.4 °C, with no increase in precipitation. Temperature increases of +0.4 °C, +1.0 °C, and +1.4 °C increase discharge volumes by 9.7%, 22.2%, and 30.8%, respectively, and discharge peaks by 13%, 30%, and 41%, respectively. Near-freezing storms that contain more snowfall are more sensitive to warming.

Cold storms, during which temperatures are significantly below freezing, also respond to small tem-

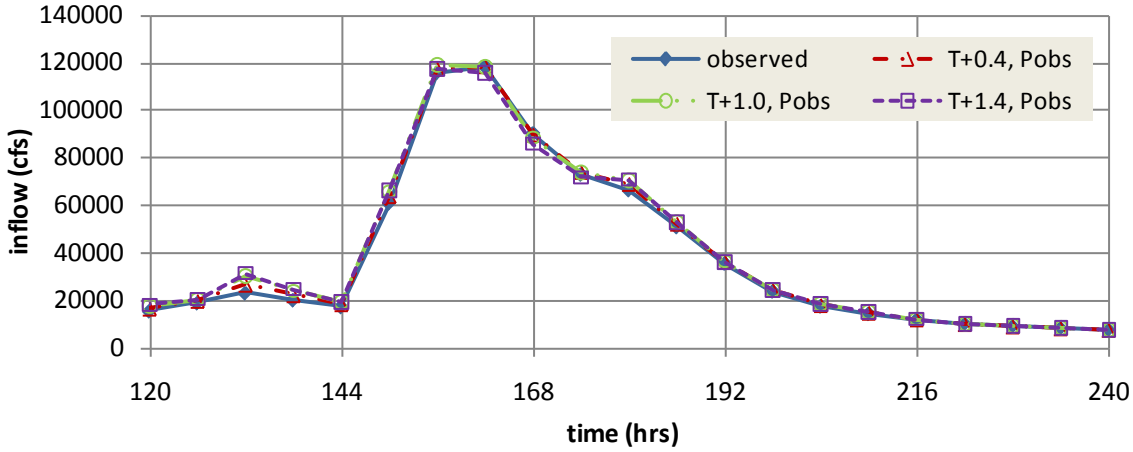

Figure 5 Runoff trends for the January 1997 rain event in the New Bullards Bar basin for four temperature scenarios

perature increases, though less than for storms near-freezing. For the January 1969 snow event, average temperatures in the upper and lower basins were −1.8 °C and 3.8 °C, respectively.

Despite observed temperatures significantly below freezing, small temperature increases raise discharge rates and volumes for the January 1969 event (Figure 7). Discharge volumes for the total storm (which include smaller runoff events before and after the main storm) increase for the +0.4 °C, +1.0 °C, and +1.4 °C climate scenarios by 9.4%, 20.6% and 29.1%, respectively. However, when the main storm event (hours 264 to 360) is examined independently from antecedent runoff events, discharge volume for the +0.4 °C, +1.0 °C, and +1.4 °C climate scenarios increase 8.2%, 21.8% and 31.4%, respectively. Thus for low elevation basins, cold events with temperatures below freezing can still be sensitive to small temperature increases. However, cold storms several degrees below freezing are less sensitive to temperature increases than storms near freezing.

The January 1969 main storm was preceded, and followed, by smaller storms. The three peaks during the January 1969 event also illustrate how warmer temperatures can increase runoff volumes even when precipitation intensities are reduced (observed precip-

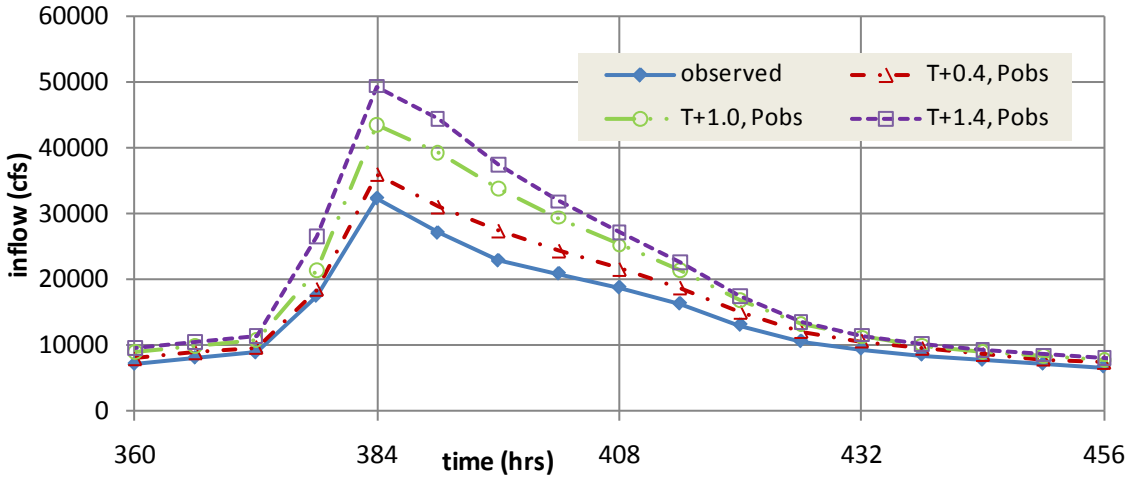

Figure 6 Hydrographs for the observed and perturbed temperatures for the March 1983 storm in the New Bullards Bar basin

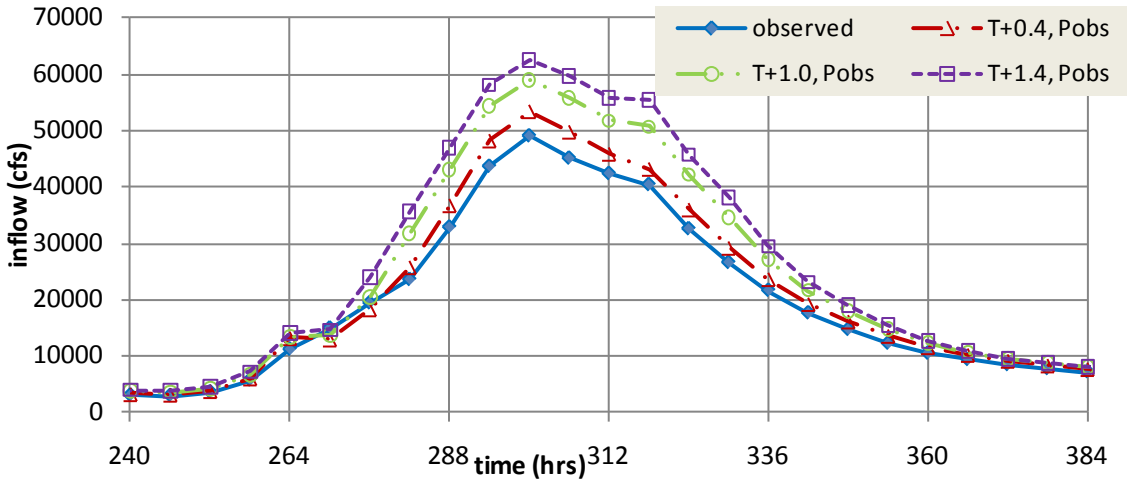

Figure 7 Runoff for the observed and perturbed temperature climate scenarios in the New Bullards Bar basin for the January 1969 event

itation is decreased by 6.6%). This trend was observed in all three basins and is explained by the antecedent basin conditions to each event.

During the antecedent event to the January 1969 storm, each climate scenario that simulates increased temperatures and decreased precipitation generates lower discharge rates and volumes than the observed storm (Figure 8A).

Three days after the antecedent event, discharge from the main storm begins. As the main storm begins, runoff rates from the +1.4 °C and +1.0 °C surpass the runoff rates from the observed storm, because of the increased fraction of precipitation that falls as rain (Figure 8B). Increased discharge results from both temperature changes and antecedent basin conditions. The prior event increases basin wetness, which accelerates the time to infiltration saturation, and increases the volume of surface runoff. The main storm peak also emphasizes the role of temperature and how it affects discharge. Now, the increased discharge from increased temperatures and decreased storm intensity is more pronounced. The total discharge volume exceeds that from the observed storm; the discharge peaks from the perturbed warmer, drier scenarios also surpass the observed peak.

After the main storm, another small storm occurs within a few days (Figure 8C). By now, even the smallest temperature shift generates discharge volumes greater than the observed storm, despite the reduced precipitation for this scenario. The only climate scenario that yields less discharge than the observed storm is the simulation of the observed temperature record with less precipitation.

Though each climate change scenario represents the same decreased precipitation, runoff rates for each scenario have different patterns. The observed temperature record combined with 6.6% less precipitation leads to 11.5% less runoff than the observed storm. The smallest temperature increase (T+0.4 °C) and 6.6% less precipitation (P–6.6%) did not increase runoff from the observed storm, but did increase runoff from that with the observed temperatures and decreased precipitation. These differences may result from changed soil moisture conditions, and merit further investigation.

EFFECTS OF CLIMATE CHANGE ON RESERVOIR OPERATIONS

Although each study basin had similar trends in hydrologic response to temperature and precipitation perturbations, each basin reservoir is unique in its ability to manage floods and provide a full water-supply pool at the end of the flood season. Flood results for each reservoir are presented below, though only figures for Shasta Dam's results are included. Additional results for Oroville and New Bullards Bar dams appear in Fissekis (2008).

Of the three reservoirs, Shasta Dam performed the best for flood control with warmer climates. For every sampled flood and every climate change scenario, Shasta Dam's storage never exceeds the flood

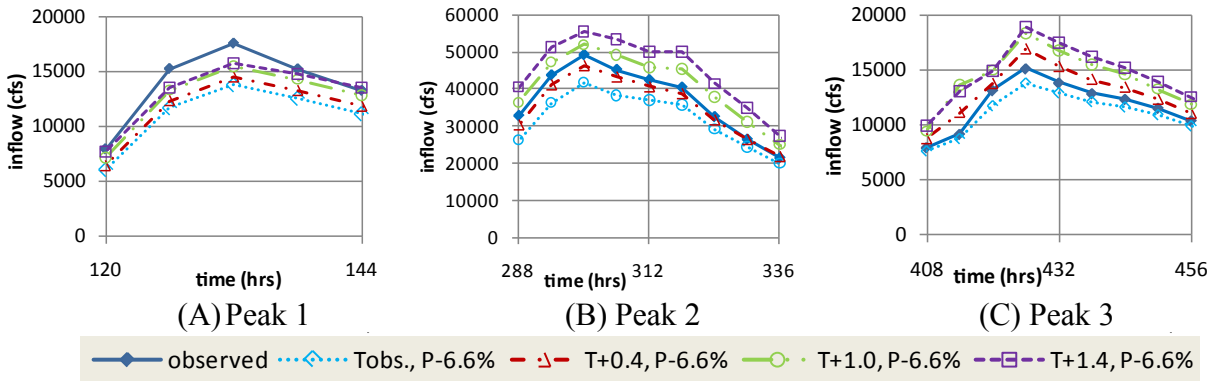

Figure 8 January 1969 storm with decreased precipitation and various temperature increases at New Bullards Bar

pool. Also, reservoir pool elevations are more sensitive to precipitation changes than temperature changes (Figure 9). The storage exceedence curves are sensitive to changes with temperature and precipitation. More precipitation, shifts exceedence curves to the right, indicating that the reservoir is more likely to contain larger volumes. However, warmer temperatures shift the exceedence curves left, reducing the likelihood of high storage volumes.

For all climates examined, Shasta Dam fills its conservation pool infrequently when the refill period begins in March (Figure 9). When the start of the refill period is delayed until March, the water supply pool is filled in less than 15% of years the 40-year study period. When the rule curve is changed to allow refilling to begin in January with the same climate scenarios and study period, Shasta Dam fills the conservation pool in about 45% of the years in the same period.

Flood-control curves at Oroville Dam balance flood operations with water supply goals at the end of the flood period better than the curves at Shasta Dam

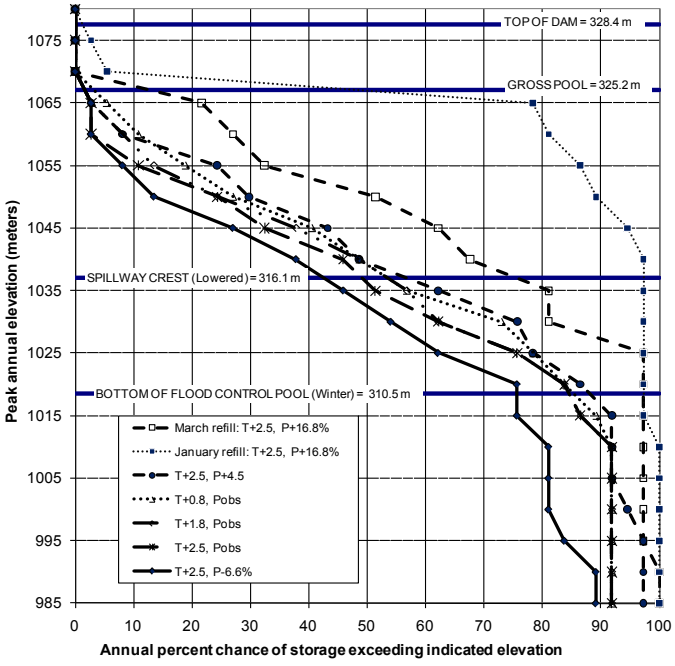

Figure 9 Exceedence curves for Shasta Dam with illustrating increased temperatures, increased and decreased precipitation, and altered refill schedules. Increased temperatures and observed and perturbed precipitation with post-March refill.

and New Bullards Bar Dam. Similarly to Shasta Dam, the reservoir rule curve for Oroville Dam requires a drawdown to 258.6 m (the deepest drawdown elevation on the flood-control diagram) and begins to refill in April. Given that the reservoir is consistently drawn down for flood control, some storms still cause the reservoir to rise into the surcharge pool, a zone above the flood pool used to pass spillway flows.

For Oroville Dam, all temperature scenarios that increase precipitation by 16.8% result in at least one flood causing the reservoir to exceed the flood-control zone. In the climate change that raises temperatures by 1.4 °C and increases precipitation intensity by 16.8%, two of the flood events raise the reservoir pool elevation into the surcharge zone (Table 3). During all other flood events, as modeled here, the reservoir never exceeds the flood-control zone. Also, despite requiring the deepest reservoir drawdown, Oroville fills its conservation pool at the end of every flood season (although conservation storage operations are modeled in less detail here).

Exceedence curve changes for Oroville follow similar patterns as Shasta. As precipitation increases, the exceedence curve shifts to the right, indicating that the reservoir stores larger volumes of water more often. However, as temperatures increase, exceedence curves shift left, storing less water.

New Bullards Bar Dam performs the worst for flood protection under several climate change scenarios. For the observed record, one modeled flood causes the reservoir to fill the surcharge zone. Both temperature and precipitation increases cause several floods to fill the surcharge zone, reach the top of the dam and, in seven storms, overtop the dam (Table 4). These critical zone encroachments all occur during the rising limb of the main peak of the flood wave and last only a few hours. This illustrates one drawback of ResSim—the model, unlike a reservoir operator, does not consider forecasted flows. Instead, the model only takes observed flows into account, releasing only enough water to keep the reservoir under the rule curve reservoir pool elevation rather than releasing extra water in anticipation of future, larger flows. However, unlike the Shasta and Oroville simulations, no alternative curves are defined for New

Table 3 Peak reservoir pool elevations for floods with climate changes in the Oroville reservoir basin

Oroville Dam: zone of peak pool elevation for sampled floods						
	Climate change					
Temperature (°C)	**Obs**	**Obs**	**+0.4**	**+1.0**	**+1.4**	**+1.4**
Precipitation (%)		**+16.8**	**+16.8**	**+16.8**	**+4.5**	**+16.8**
Jan–63	F	F	F	F	F	F
Dec–64	F	F	F	F	F	F
Jan–69	F	F	F	F	F	F
Jan–80	F	F	F	F	F	F
Dec–82	F	F	F	F	F	F
Mar–83	F	F	F	F	F	F
Feb–86	F	TS	TS	TS	TS	TS
Mar–95	F	F	F	F	F	TS [a]
Jan–97	F	F	F	F	F	F

[a] spillway used.

Obs = Observed; F = flood; TS = top of surcharge.

Table 4 Peak reservoir pool elevations for floods with climate changes in the New Bullards Bar basin

New Bullards Bar Dam: zone of peak pool elevation for sampled floods [a]												
	Climate change											
Temp (°C)	**Obs**	**Obs**	**Obs**	**+0.4**	**+0.4**	**+0.4**	**+1.0**	**+1.0**	**+1.0**	**+1.4**	**+1.4**	**+1.4**
Prec (%)		**+4.5**	**+16.8**	**Obs**	**+4.5**	**+16.8**	**Obs**	**+4.5**	**+16.8**	**Obs**	**+4.5**	**+16.8**
Jan–63	F	F	F	F	F	F	F	F	F	F	F	F
Dec–64	TS	TD	O	TD	O	O	TD	O	O	TS	O	O
Jan–69	F	F	F	F	F	F	F	F	F	F	F	F
Jan–80	F	F	F	F	F	F	F	F	F	F	F	F
Dec–82	F	F	F	F	F	F	F	F	F	F	F	F
Mar–83	F	F	F	F	F	F	F	F	F	F	F	F
Feb–86	F	F	F	F	F	F	F	F	TD	F	F	O
Mar–95	F	F	F	F	F	F	F	F	F	F	F	F
Jan–97	F	F	O	F	TS	TD	F	TS	O	F	TS	TD

[a] For all data in the table, the spillway was used.

Obs = Observed; F = flood; TS = top of surcharge; TD = top of dam; O = overtops dam.

Bullards Bar to allow additional flood-control space for wetter conditions. While flood-control operations for New Bullards Bar Dam performed poorly, refill goals are met at the end of every flood season for all climate scenarios.

Exceedence curves for New Bullards Bar follow the same patterns as the curves for Shasta and Oroville dams. When temperatures increase, curves shift to the left, with water storage volumes decreasing as temperatures increase. More precipitation increases water storage volumes, and exceedence curves shift to the right.

DISCUSSION

Though each basin has unique hydrologic characteristics, broad trends appear in our results that are consistent with previous studies. These results include the effect of increasing temperature on mid- and low-elevation basins, the different responses of warm and cold storms to temperature increases, and the apparently poor performance of static flood rule curves. Each set of results indicates how existing flood operations would be challenged by various forms of climate warming.

For mid- to low-elevation basins, the hydrologic regime is sensitive to small shifts in temperature. Small temperature increases affect both warm and cold storms. For all three study basins, the smallest temperature increase (0.4 °C) causes more of the storm to fall as rain, and less as snow. Even storms occurring with observed temperatures below freezing are affected. The coldest storms are not cold enough to escape the effects of temperature increases. The basin-wide response to increasing temperatures is larger storm runoff volumes. Reservoirs receive larger inflow volumes over shorter periods. The increased fraction of rain in precipitation may affect how quickly the basin achieves infiltration saturation; if the basin saturates earlier, ensuing storms generate more surface runoff.

Warm storms are affected indirectly by increasing temperatures. Warm storms do not change precipitation composition with higher temperature; they are already predominately rain. However, higher temperatures increase evaporation and transpiration rates, creating dryer basin conditions. Drier antecedent conditions allow larger volumes of water to percolate into the soil (NOAA 2002). The increased infiltration capacity reduces surface runoff. Two of the warmest storms—December 1964 and January 1997—generate less runoff in the warmest temperatures scenarios. But increased basin wetness combined with smaller, antecedent cold events can affect warm storms similarly to cold storms; the warm temperatures cause earlier, cold events to precipitate more rain than snow, which causes the basin to reach saturation sooner. Even though the composition of warm storms is unaffected, runoff volumes increase because of the reduced infiltration capacity resulting from the wetness caused by the earlier storms. Again, reservoirs receive larger runoff volumes.

Warmer temperatures also can affect storm runoff more than changes in precipitation intensity. In some cases, storm discharge volumes increased with warmer temperatures, despite decreases in precipitation. Though the storm durations are not changed, the basin is affected by wetter antecedent conditions from earlier, colder events that are affected by the small temperature increase. The wetter soil conditions yield more rainfall runoff than even warm storms. These effects are magnified as temperatures increase until all storms become principally rain storms.

The flood-control rule curve results also support previous findings about the problems of static rule curves with a changed climate. The rule curve for New Bullards Bar, which does not respond to the basin's antecedent snowpack or wetness, performs poorly for most climate changes examined. Reservoir pool elevations exceed the flood pool zone during 19 of the 144 sampled storms, and overtop the dam for eight sampled storms. Maximum release limits prevented New Bullards Bar from releasing water quickly enough to avoid overtopping. Release volumes are often restricted due to common downstream control points with Oroville Dam that prevent more water from being released from New Bullards Bar until its pool reaches critical zones. Shasta simulation results show how adding flexibility to flood-control rule curves can improve both flood protection and water supply operations.

CONCLUSIONS

Both the hydrologic regime and flood-control operation in the Sacramento basin are affected by increasing temperatures. We list four important effects here:

1. Flood flows in the Sacramento Basin will change given even small temperature increases. Most important, small temperature increases affect the precipitation composition of storms, causing more rainfall runoff in previously cold storms.
2. Greater precipitation intensities of a given storm increase the volume of rainfall runoff; however, decreased precipitation intensities do not always decrease storm flow volumes. Temperature effects are sometimes strong enough to overcome the effects of reduced precipitation intensities, resulting in increased runoff volumes. In all cases, greater runoff volumes increase flood risk.
3. Static rule curves, such as the curve for New Bullards Bar Dam, appear to perform poorly for a range of climate scenarios. At times, reservoir pool levels exceed the dam's crest to overtop the structure. Changes that may improve the performance of New Bullards Bar's flood operations include reviewing the prescribed draw-down rates of the flood pool, incorporating a state parameter (i.e., cumulative precipitation) to allow more flexible release decisions, incorporating forecast information into release decisions to allow larger releases earlier in the flood event, or revising the existing operations manual to remove guidelines that depend on Marysville Dam. Though reservoir pool elevations in Oroville Dam did not overtop the dam, the surcharge pool and spillway were required to manage flood flows that exceeded the flood pool's capacity. However, because the results of the Oroville Dam and Shasta Dam flood operation simulations showed better performance than New Bullards Bar Dam, the poor performance may be specific to New Bullards Bar. Simulating dynamic options in real-time (i.e., incorporating multiple curves into a single simulation rather than simulating each curve independently) would improve understanding of their potential benefits.
4. Dynamic flood rule curves, such as the curves for Oroville and Shasta dams, provide more flexible drawdown and refill requirements, with better refill performance. While reservoir pool elevations did not exceed the flood pool in Shasta Dam, refilling the conservation pool was challenging; refill was significantly improved by simulating the more flexible options defined by Shasta Dam's rule curve. Though the simulations applied each possible curve defined for Shasta Dam independently, the option to adjust the refill timing was required to improve refill performance. This suggests that even if a single curve is applied to reservoir operations, the option to choose from multiple curves—depending on basin conditions—improves refill performance. However, the specific benefits of using dynamic curves remain to be sufficiently quantified.

FUTURE STUDIES

This study provides a preliminary evaluation of how flood-control operations for projects in the Sacramento Basin respond to climate change. All temperatures were increased by a fixed amount. However, temperature increases are likely to vary on both diurnal and seasonal cycles; the largest increases occur from January to March (P. B. Duffy, Climate Central, pers. comm., 2008). Knowles and others (2006) found that declines in the fraction of snow versus rain occurred the most in January in the northern Sierra Nevada and Pacific Northwest, indicating that intra-annual patterns of warming are worth examining as they occur during peak precipitation periods in the Sacramento Basin. Also, minimum temperatures increase more than maximum temperatures in the diurnal cycle (Walther and others 2002). Refining this study by refining the temperature increase pattern could yield significant results.

Improving HEC–ResSim to include dynamic rule curves for operation simulations will improve the ability to test the performance of existing curves. While alternative curves can be applied using programming, including dynamic curves into upcoming versions of HEC–ResSim would be advantageous (J. D. Klipsch, U.S. Army Corps of Engineers Hydrologic

Engineering Center, pers. comm., 2008). Though other models can apply dynamic curves, the Corps has not approved of their use during flood operations, and thus could not demonstrate the limitations of current management tools.

Another refinement to this study would be to repeat the reservoir operations with changes to flood operating rules, making Oroville and Shasta flood operating rules less responsive (more static) to basin moisture conditions, and making New Bullards Bar flood operations more responsive to basin moisture conditions.

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