Case Study

Impact of Artificial Reservoir Size and Land Use/Land Cover Patterns on Probable Maximum Precipitation and Flood: Case of Folsom Dam on American River

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Abstract: The design of the dams usually considers available historical data for analysis of the flood frequency. The limitation of this approach is the potential shift in flood frequency due to physically plausible factors that cannot be foreseen during design. For example, future flood extremes may change, among other factors, due to strong local atmospheric feedbacks from the reservoir and surrounding land use and land cover (LULC). Probable maximum flood (PMF), which is the key design parameter for hydraulic features of a dam, is estimated from probable maximum precipitation (PMP) and the hydrology of the watershed. Given the nonlinearity of the rainfall-runoff process, a key question that needs to be answered is How do reservoir size and/or LULC modify extreme flood patterns, specifically probable maximum flood via climatic modification of PMP? Using the American river watershed (ARW) as a representative example of an impounded watershed with a large artificial reservoir (i.e., Folsom Dam), this study applied the distributed variable infiltration capacity (VIC) model to simulate the PMF from the atmospheric feedbacks simulated for various LULC scenarios (predam, current scenario, nonirrigation, and reservoir-double). The atmospheric feedbacks were simulated numerically as PMP using the regional atmospheric modeling system (RAMS). The RAMS-generated PMP scenarios were propagated through the VIC model to simulate the PMFs. Comparison of PMF results for predam and current scenario conditions showed that PMF peak flow can decrease by about 105 m^3/s, while comparison of current scenario with nonirrigation PMF results showed that irrigation development has increased the PMF by 125 m^3/s. On the other hand, the reservoir size had virtually no detectable impact on PMP and consequently on PMF results. Where downstream levee capacity is already underdesigned to handle a dam's spillway capacity, such as for the case study, such increases indicate a likely impact on downstream flood risk to which any flood management protocol must adapt. The premise that modern dam design and operations should consider an integrated atmospheric-hydrologic modeling approach for estimating proactively potential extreme precipitation variation due to dam-driven LULC change is well-supported by this case study. **DOI: 10.1061/(ASCE)HE.1943-5584.0000722.**

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Introduction

In the United States, dams are a critical component of infrastructure and are responsible for producing around 240 billion kW h of electricity through hydropower [2010 estimates according to USEIA (2011)], storing around 1,000 million acre-feet (MAF) of water (compared to around 1,400 MAF of mean annual runoff) throughout the continental United States (Graf 1999) and protecting urban, rural, and other small community areas from flood damages. Dams are structures built across a river (Oxlade 2006) or any artificial barrier that serves to store or divert water by creating an impoundment called a reservoir. Some of the purposes of these dams (hereafter used alternatively with reservoir) include hydropower generation, water supply, fishing, flood control, recreation, and navigation. According to the International Commission on Large Dams (ICOLD), a dam between 5 and 15 m high is classified as small, 15–30 m is medium, and greater than 30 m or with a reservoir volume of more than 3 million m^3 is large. Other classification includes one that is used by Association of State Dam Safety Officials (ASDSO) based on criteria for storage and height prescribed by each state (http://www.damsafety.org). For example, according to California's Department of Water Resources Division of Safety of Dams (DSOD), dams are classified as jurisdictional and nonjurisdictional dam and reservoir sizes. Dams with height less than 25 feet and storage less than 50 acre-feet are all nonjurisdictional dam, while those dams with greater height and storage are classified as jurisdictional dam.

There are about 75,000 dams in the US with a height greater than 2 m from the ground (Graf 1999). Around the world, about 800,000 dams are estimated to have been built (Center for Strategic and International Studies 2005). Construction of new dams or the continuation of existing ones around the world is expected to persist for reasons of economic growth, population increase, and rising water demand, particularly in the developing world (Biswas and Tortajada 2001; Hossain et al. 2010; Hossain et al. 2011).

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Dam construction is rarely a clear-cut issue in civil engineering development as its precise impacts cannot be identified proactively (Graf 2003). Designing a dam requires broad and multidisciplinary study that ranges from socioeconomic to hydrological and hydraulics aspects. The impact of large dams on hydrology and ecology needs to be understood (Richter et al. 1996). Economic development is one of the broader benefits of dams through hydropower, irrigation, fishery, navigation, and flood control. In the United States, these dams have been the core of economic development during the twentieth century (Graf 2003). For example, the Folsom Dam, the object of the case study herein, provides 10% of local power needs from hydropower and a recreational place with annual visitors of 2 million [U.S. Bureau of Reclamation (USBR) 2007a]. Almost 50% of Californians get their water supply from two projects comprising several dams: the State Water Project and federal Central Valley Project [Central Valley Flood Management Planning Program (CVFMPP) 2012]. However, dams also cause large social interference and demographic resettlement (Gleick 2011), and their failure is catastrophic. There is also an impact on the annual peak flow typically on downstream direction of these dams (Gross and Moglen 2007).

Overtopping of dams has been a cause of their failure all over the world (De Michele et al. 2005). In the United States, around 2,900 dams are deemed by the National Dam Inspection Safety Act (NDISA) to be unsafe due to the capacity of their spillway being unable to discharge flood flow [Federal Emergency Management Agency (FEMA) 2004]. Based on the national inventory of dams (NID) data that is compiled by the Association of Dam Safety Officials (ASDSO), 4,404 dams were found vulnerable to structural and hydraulic failure in 2008, which is an increase of 2,977 from 1999 (ASDSO 2011). In addition to the structural failure hazard, there is a larger sedimentation impact associated with a dam. As velocity of the river flow into the reservoir tends to zero, the transported sediments settle down and reduce the effective storage of the reservoir. On the downstream side, the released flow has higher flow velocity, which leads to a significant erosion of the river bed and bank.

One of the major inputs for dam design is an inflow design flood (IDF). Different considerations are taken while determining an IDF by different agencies (USACE, USBR, and FEMA) and U.S. states (FEMA 2004). According to the U.S. Army Corps of Engineers (USACE 1991), a risk should not be tolerated in cases when people's lives are threatened. This risk is the associated probability of failure of a given structure due to a specific flood magnitude and frequency of the event (Nagy et al. 2002). Decreasing the frequency will decrease the risk. History has already taught us that dam failure can be one of the reasons for major and catastrophic flooding (Baker et al. 1988). The failure of South Fork Dam in Johnstown, Pennsylvania, which took the lives of more than 2,200 people (Frank 1988) and the economic loss of $17,000,000, and that of St. Francis dam in 1928, which caused 450 causalities (Rogers 2006), are examples of sheer catastrophic events due to dam failure.

The conventional methods by which dams are usually designed include a flood of a given probability of occurrence or the probable maximum flood (PMF). PMF is a flow hydrograph that represents the maximum runoff condition resulting from the probable maximum precipitation (PMP) (USBR 1987). FEMA (2004) lays out different possible IDF selection criteria. The IDF can either be the PMF or a flood of a given return period depending on the designers' criteria. When the IDF is not equal to the PMF (or a given percentage of the PMF), long historical measured flow data is used in flood frequency analysis for determining a flood with a specified return period, usually 100 years. However, this approach ignores a possibility that observed storms reflect the expected extreme flow better than measured stream flow (FEMA 2004). Though it is difficult and uncertain to assign a return period for a PMF, a value of return period of 10,000 years is usually provided (Haimes 2009). Standard methods used to estimate PMF include many uncertainties, and there is a possibility that an estimated PMF may be exceeded [National Research Council (NRC) 1999]. These uncertainties can be attributed to the conventional procedures used in estimating PMP (Woldemichael et al. 2012).

The prediction of IDF by applying flood frequency analysis has endured much criticism and uncertainty due to the fact that the main assumption, which is the stationarity of hydrologic events, is not satisfied (Douglas and Fairbank 2011; Milly et al. 2008; Stedinger and Griffis 2008). At the same time, flood frequency analysis has bias (NRC 1999). A different approach to IDF determination described by FEMA (2004) is the incremental damage assessment (IDA) method. In the IDA method, the damage that will occur due to a flood increment is studied step by step. That is, if the damage that would occur as a result of a higher flood is the same as a damage caused by a given flood, then this flood can be taken as the inflow design flood.

There is now a strong argument to incorporate the local, mesoscale, or regional climate impact of reservoirs in dam design and their operation (Degu et al. 2011; Hossain et al. 2011). The National Oceanic and Atmospheric Administration (NOAA) has a location-based approach of calculating PMP for durations of 1 to 72 h and areas of 10 to 10,000 square miles for the United States. These approaches use procedures provided in hydrometeorological reports (HMR) specific to the location (the reader is referred to NOAA for the list of HMR and the corresponding locations). For example, in California, HMR No. 58 is used to estimate the site-specific PMPs. Consideration of future dam impact during the dam design period can potentially minimize flood risk that would otherwise occur due to improper capacity, operations, and lack of emergency provisions (Hossain et al. 2011). Costa et al. (2003) studied the impact of land cover change on a river discharge in the Amazon and found that considerable increase in discharge is observed without significant increase in the precipitation. This effect has been physically explained to be a result of altered evapotranspiration and infiltration patterns. Reservoirs have also altered the temporal discharge distribution around the world (Biemans et al. 2011).

Hossain et al. (2010) found in their study that extreme precipitation in the midwestern and western United States can be potentially affected by the presence of large dams. The 1% probability precipitation of these areas has increased from 1 to 5%. This points to the need to study the terrestrial impact of such changes in extreme precipitation. Given that the transformation of rainfall to runoff is a nonlinear process, it is necessary to investigate how the modification of a PMP pattern is potentially transformed into PMF, since the highest precipitation does not always produce the highest runoff (Ohara et al. 2011). Runoff generation in general can be assumed to be dependent on land use land cover (LULC) and rainfall rate. If LULC interferes with processes like soil moisture condition and base flow component of the rainfall runoff generation transformation, alteration of either rainfall rate and/or LULC will considerably affect runoff rate. For the case of American River Watershed (ARW), the majority of the three-day (72 h) rain-driven catastrophic discharge occurred during the post-dam era, after 1950 (CVFMPP 2012). The NRC (1999) has therefore stated that variation in climate should be considered in revised flood frequency analysis under such cases.

According to the World Meteorological Organization (WMO), PMP is defined as theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geological location at a particular time of the year. Uncertainties and lack of future storm prediction capacities in conventional PMP estimation methods have led to a recent study by Woldemichael et al. (2012) that provides the foundation for the current investigation. Woldemichael et al. (2012) simulated PMP values using the atmospheric model called regional atmospheric modeling system (RAMS) over American ARW and considered the anthropogenic effects of the Folsom Dam and LULC change. There is now a well-established physical link between LULC conditions and mesoclimate and weather patterns (Cotton and Pielke 2007), which is used as a premise for the study by Woldemichael et al. (2012). Their study found that the strongest increase in the 72-h PMP values are due to irrigation development that took place after the construction of the Folsom dam; while the creation of the Folsom lake yielded very modest increases in the 72-h PMP values. The increase in precipitation is due to an increase in evapotranspiration as a result of irrigation development. The wind direction over ARW is to the northeast, which puts Folsom Dam on the downwind direction. The orographic precipitation from the Sierra Nevada range is likely supplemented by the precipitation from upwind irrigation (i.e., downstream of Folsom) producing a higher precipitation over the entire watershed of ARW.

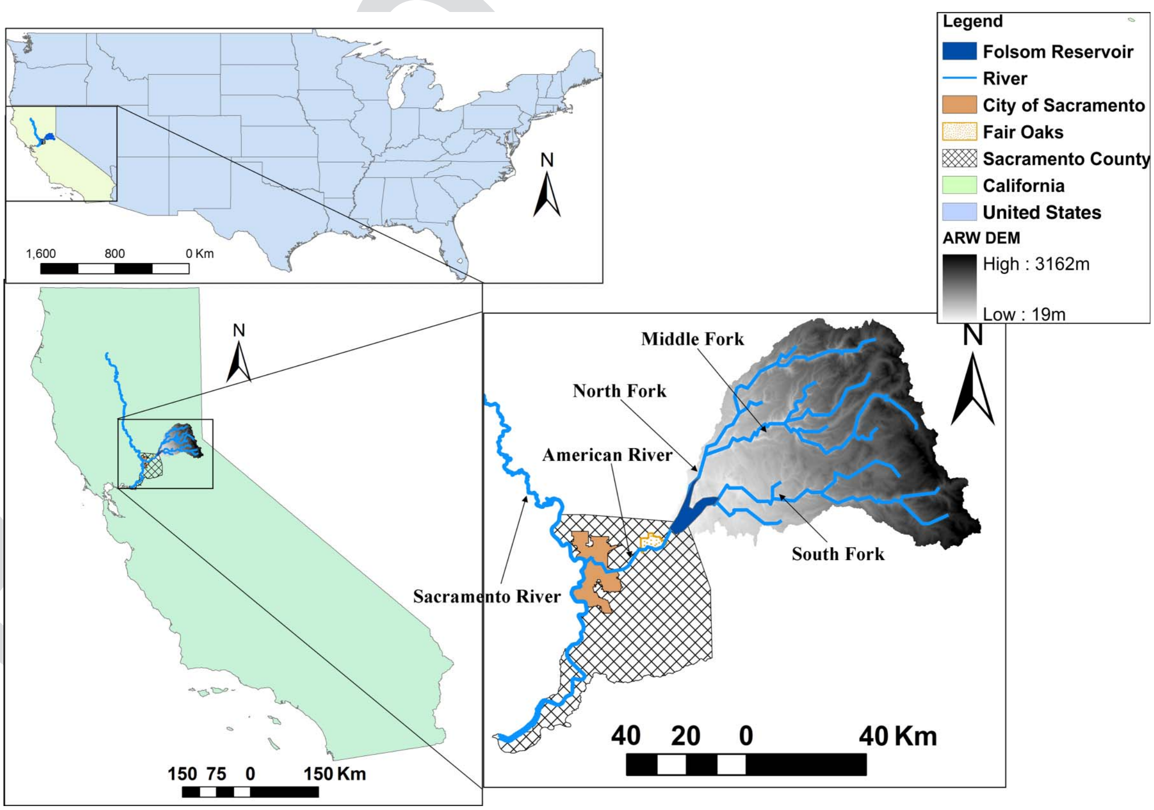
The study of modification of PMF due to dam and LULC patterns can potentially improve the flood resilience of existing dams. This motivation is applied to Folsom Dam to understand the terrestrial role of modified PMP-based PMF for different LULC and reservoir size scenarios explored in Woldemichael et al. (2012). The objective of this case study is to answer the question How do reservoirs and/or LULC modify extreme flood patterns, specifically probable maximum flood through local atmospheric feedback mechanisms? It considered the predam and postdam LULC scenarios that affect the hydrometeorology and hydrological processes. This paper is organized as follows. The authors present the study area and its characteristics, followed by the data and methodology. Results and conclusion are presented last.

Case Study Area

Watershed and Flooding History

This study selected the case of the Folsom Dam (Fig. 1) and the American River Watershed (ARW). The Folsom Dam was built on the American River 32 km northeast (and upstream) of Sacramento, California, in 1956 by USACE (USBR 1999). It has a total watershed area of 4,823 km^2 (USACE 2005) (Fig. 1). The ARW exhibits a wide variation in elevation from 3,160 m at the mountains near the Sierra Nevada range to about 100 m near the Folsom Dam. The major downstream city is Sacramento (where the American River meets the Sacramento River) (Fig. 1), which has a population of 466,488 according to 2010 census data (U.S. Census Bureau 2010). Flooding has always been a major issue for the region downstream of the Folsom Dam. The floods that occurred in 1986 and 1997 have caused a combined loss exceeding 1 billion U.S. dollars (CVFMPP 2011). Structural measures like dams, levees around the Sacramento River, and bypass systems for Sacramento are currently the main protection against such floods (CVFMPP 2011).

The two floods that occurred in 1986 and 1997 have influenced engineers of the USACE to re-evaluate the flood frequency analysis of the American River at Sacramento from a 500-year recurrence interval to a 70-year recurrence interval in 1998 (NRC 1999). In fact, there were a number of floods that occurred prior to the start of systematic stream flow measurement in 1905 (Ohara et al. 2011). The revised flood frequency analysis has shown that the Sacramento levees, in their current form, are likely unable to



F1:1 **Fig. 1.** American River Watershed (ARW) location and topography withstand the new 100-year flood (1% exceedence probability) (NRC 1999).

Hydraulic Features of Folsom Dam

The operation of Folsom Dam has been managed by USBR since the completion of its construction by USACE. The dam is a compound type of dam, which consists of a 425-m-long and 103-m-high gravity section with a crest elevation of 146 m and two auxiliary embankment dams extending on both sides (USBR 2007b). The total area contributing to Folsom Lake is about 4,823 km^2 (USBR 2007b; USACE 2005). The main purposes of the dam are power generation, flood control, and water supply (USBR 1999). At full pool level, the dam can accommodate a flood close to 1.2 billion m^3 (Ohara et al. 2011). From this storage 132 million m^3 is surcharge, 492 million m^3 is joint use, and 598 million m^3 is active storage (USBR 2007b). Flood-control capacity is enhanced by releasing flows during low reservoir level, which provide storage for annual floods (USBR 1999). The spillway is gate controlled with eight gates in total, five main and three emergency gates. These spillway gates have the capacity of discharging 16,000 m^3/s (USBR 2007b). A levee system with a capacity of about 3,250 m^3/s protects Sacramento from flooding. The dam impounds flow of the American River at the junction of its tributary North Fork and South Fork (see Fig. 1) (USACE 2005). A joint project called Folsom Dam Joint Federal Project (JFD) is currently underway by the USBR, USACE, Sacramento Area Flood Control Agency (SAFCA), and California's Department of Water Resources (DWR) to increase the flood-management capacity of the Folsom Dam.

Methodology

General Approach

The general approach used in this study is hydrologic modeling of the ARW that can realistically capture the terrestrial response of rainfall as runoff and stream flow. We used a calibrated hydrological model to simulate PMF values for the PMP values that were simulated by Woldemichael et al. (2012) using a numerical atmospheric model, RAMS. The PMP simulations pertained to the period of December 1996 to January 1997 when a catastrophic storm that flooded Sacramento took place (hereafter referred to as the 1997 event). Fig. 2 shows a schematic presentation of the steps used in the PMP processing for PMF generation for the ARW. By keeping the relative humidity at 100%, Woldemichael et al. (2012) generated different PMP results from the atmospheric model corresponding to various LULC scenarios. For each LULC scenario, the corresponding atmospheric variables and land surface (elevation, soil moisture, vegetation index, LULC, and sea surface temperature) data were used in RAMS to generate PMP values. These PMP results were obtained at daily time step and a 0.0298-degree (~3 km) spatial grid resolution. Since the hydrologic model used for PMF generation used a 0.125-degree spatial (~12.5 km) grid resolution, the higher resolution PMP values from atmospheric model had to be aggregated to the daily time step (Fig. 2). Further details on PMP and PMF scenarios are provided in the Model Calibration and PMF Simulation section.

Hydrologic Model

The hydrologic model, called variable infiltration capacity (VIC) (Liang et al. 1994; Liang et al. 1996), coupled to a stream flow routing model (Lohmann et al. 1996) was used to simulate stream flow in the ARW. VIC is a large-scale, semi-distributed hydrologic model. The basic assumption used in this model is that the infiltration capacity of soil layers is variable. It evolved from a single soil layer to multiple soil layers model. The current available model (VIC-3L) has the ability to model three and more soil layers, which allows for soil moisture diffusion between layers (Cherkauer et al. 2003). VIC-3L allows spatial variability of vegetation and evaporation in a grid cell. A separate model, which is referred to simply as a routing model (Lohmann et al. 1996), takes the runoff and base flow simulated by VIC-3L at each simulation grid and routs it as stream flow. The modeling is done in two steps. First, the meteorological forcing inputs are used to simulate runoff and snow fluxes for each grid that are representing the watershed. Then, the routing model routs these fluxes from each grid to a stream flow at a given location, Fair Oaks in this study.

Once the runoff is simulated by VIC-3L, the routing model uses a linearized Saint-Venant equation to generate a stream flow at a specified station (Lohmann et al. 1998). Fig. 3 shows the meteorological forcing and other input variables files used for VIC-3L and the coupled routing model. Fig. 4 shows the representation of the American River network in the form of flow direction. The scale used in the coupled model depends on the availability of input data. These input data include precipitation, minimum temperature, maximum temperature, and wind speed on a given spatial scale (grid by grid). The finest data resolution readily available for the continental United States from the University of Washington are of 0.125 degree and daily temporal scale. VIC-3L was therefore

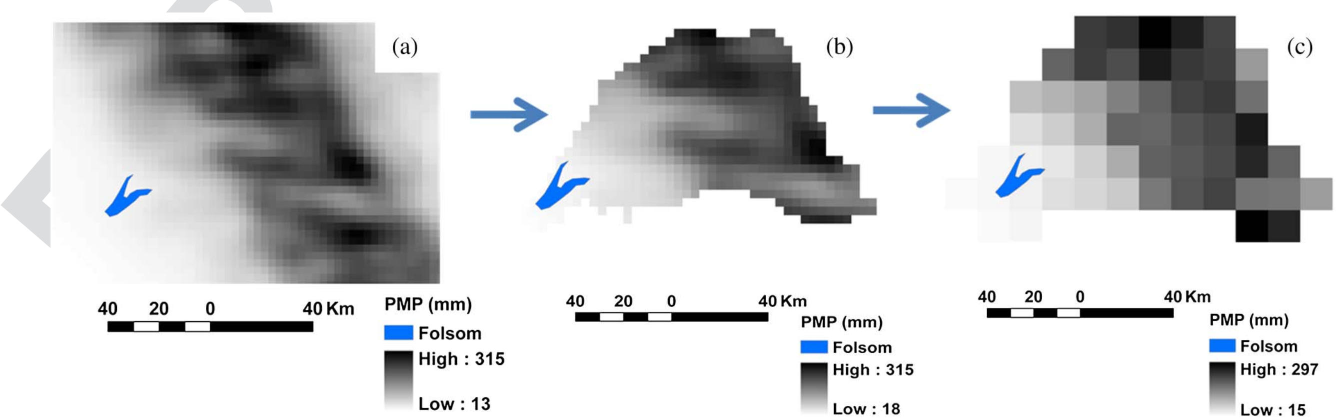


Fig. 2. Schematic presentation of PMP preparation from RAMS result for the hydrologic model (VIC-3L) (a) RAMS PMP domain; (b) RAMS PMP extraction over ARW; (c) RAMS PMP data aggregated to 0.125 degree over ARW for VIC-3L modeling

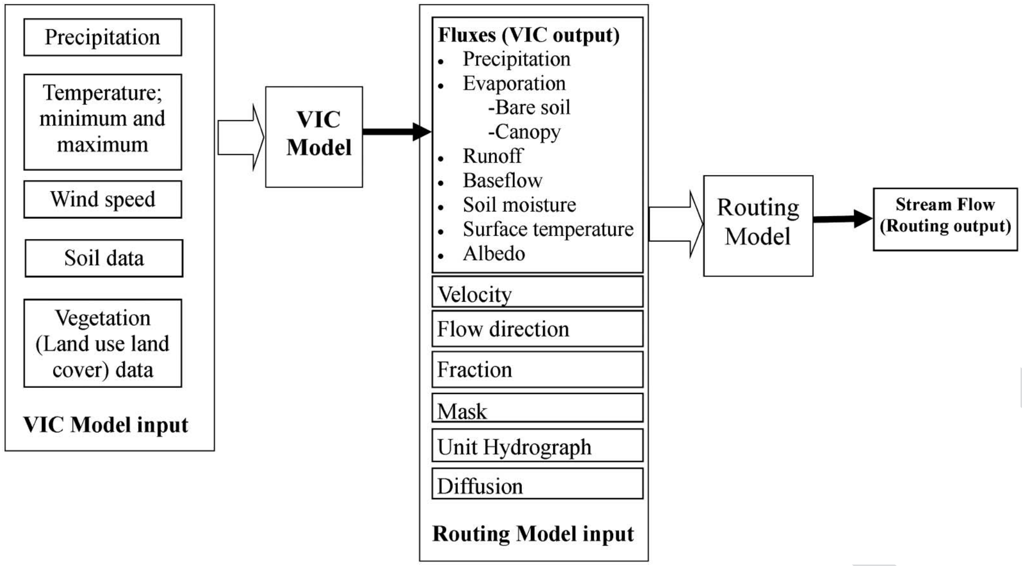


Fig. 3. Input–output files for VIC-3L and the stream flow routing model

applied at the daily timescale. While an hourly time step would have captured the peak from the watershed better than a daily time step, the stream flow routing model, which routs the runoff fluxes, has a minimum of a daily time step (Lohmann et al. 1996). Thus, the timestep for simulation in VIC-3L is daily. The 0.125-degree representation of the watershed overestimates the polygon-based watershed area (4,823 km^2) by about 43%. However, the VIC-3L model did not consider the outer grids in the contribution to the flow downhill (i.e., the fraction of the flow contribution for these peripheral grids is zero). Using such an approach, the overestimation of the contributing area of the basin is reduced to 29%.

Data

Daily gridded meteorological data at 0.125-degree (~12.5 km) resolution were used that are obtained from the Surface Water Modeling group at the University of Washington from their web site at http://www.hydro.washington.edu/Lettenmaier/Data/gridded/, the development of which is described by Hamlet and Lettenmaier (2005). Soil and vegetation data together with vegetation library were obtained from the University of Washington web site (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml). The digital elevation model from the U.S. Geological Survey (USGS), National Elevation Dataset (NED) seamless data warehouse at about 30-m resolution, were used to delineate the ARW and generate flow direction at a 0.125-degree scale (Fig. 4). Measured flow data for verification (of model choice), calibration, and independent validation were obtained from the U.S. Geological Survey (USGS) National Water Information System for the gaging station USGS No. 11446500 at Fair Oaks (Figs. 1 and 4).

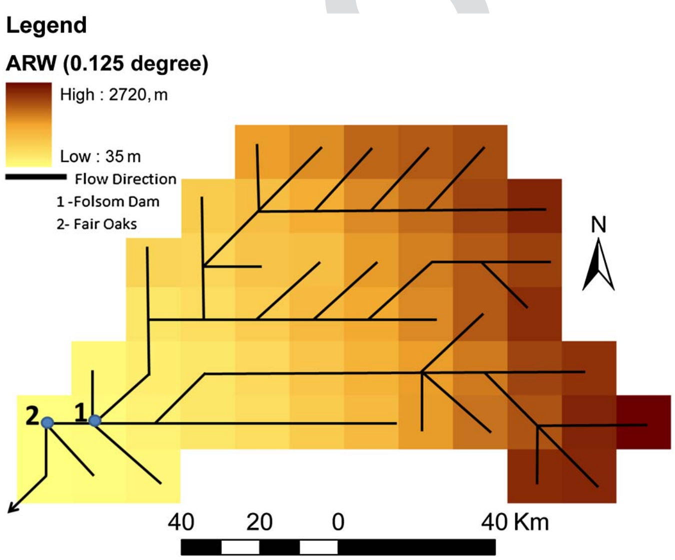
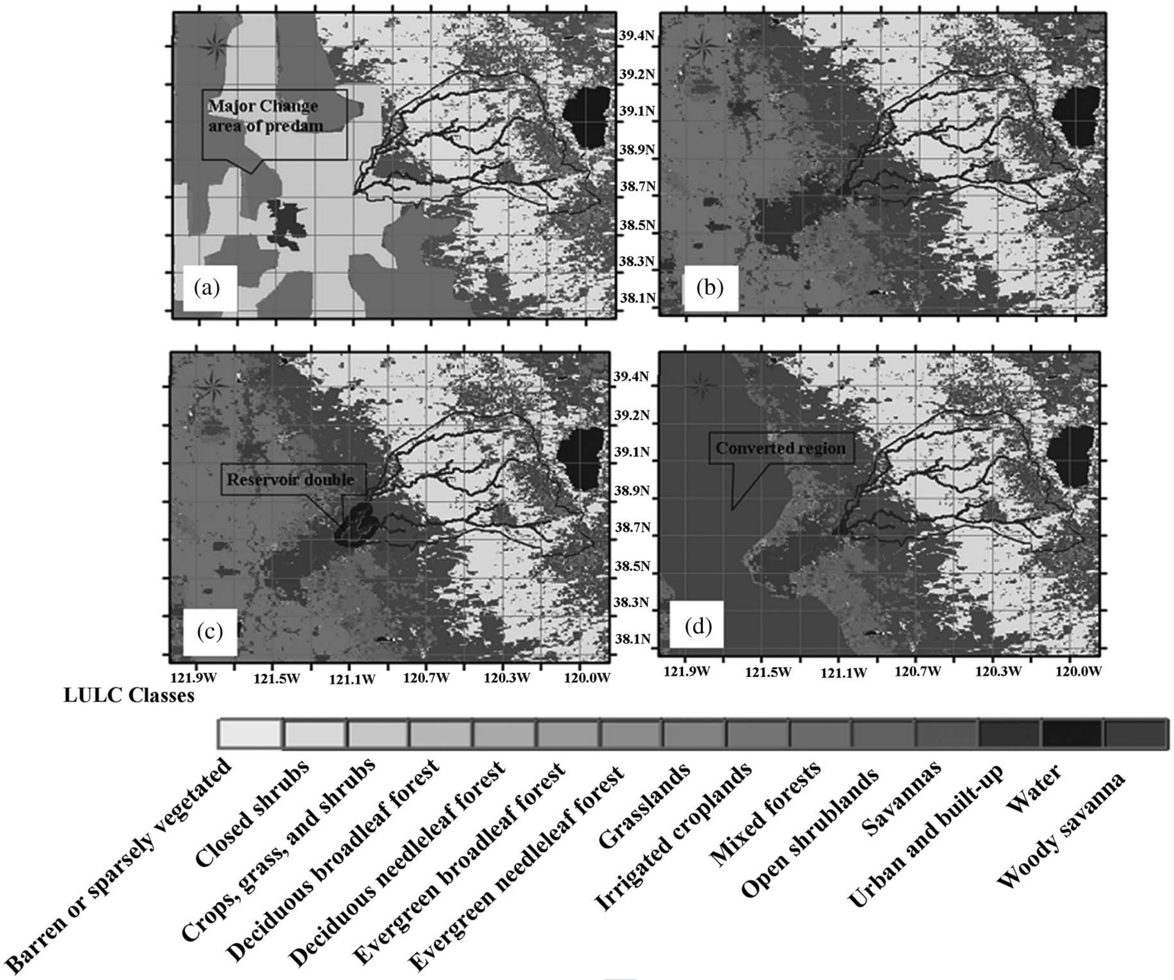


Fig. 4. Flow direction for American River Watershed (ARW) at 0.125-degree grid resolution

Model Calibration and PMF Simulation

Woldemichael et al. (2012) considered four scenarios for simulation of PMPs from LULC-driven atmospheric feedbacks (Fig. 5). The scenarios considered were predam, control, reservoir-double, and nonirrigation. Predam scenario is considered to reflect the LULC and reservoir size (which is nil before Folsom construction) prior to 1956. In the predam scenario, the PMP simulated in Woldemichael et al. (2012) were a result of meteorological and land surface characteristics that were believed to represent the pre-1955 period. The control scenario represented the 2003 LULC condition of the ARW and surrounding region; while the reservoir-double scenario was the case where the size [from surface area of 11,140 acres (USBR 2007b] of the reservoir was hypothetically doubled from that used in the Control scenario. The last scenario Nonirrigation considered the irrigation developments that occurred during the postdam era and converted them to the predam land use. The irrigation development considered is downstream of Folsom, which has resulted from the water supply of the reservoirs, such as Folsom. The LULC patterns around ARW of these four scenarios according to the Olson global ecocystem (OGE) classification are shown in Fig. 5. For each of these LULC scenarios, PMP for the period spanning December 15, 1996, to January 4, 1997, was simulated using the RAMS atmospheric model. Equations of continuity, momentum, heat, and moisture are the bases for RAMS (Pielke 2001). It is specifically tailored for modeling microscale dynamical systems, cloud microphysical processes, and land-atmosphere interactions. Thus, RAMS is considered ideal for



F5:1 **Fig. 5.** Different scenarios used in this study [developed from Olson's global ecosystem (OGE) by Woldemichael et al., (2012)]: (a) predam; (b) con-
F5:2 trol; (c) reservoir-double; (d) Nonirrigation conditions

the objectives of this study. A detailed description of RAMS is provided by Pielke (1992) and Cotton (2003).

PMF hydrographs were simulated by VIC-3L using the corresponding PMP time series for each scenario. Rainfall data was aggregated to the daily time step for use in the VIC-3L model. The LULC used in VIC-3L model for each PMF run was consistent with the LULC used for deriving the pertinent PMP. Table 3 summarizes the key features of each PMP scenario that was used to generate the corresponding PMF for ARW. For more details on the calibration, validation, and setting up of RAMS over the ARW region, the reader is referred to Woldemichael et al. (2012). Stream flow simulation over ARW was performed for the period between January 1990 and December 2000 at a location that was close to Fair Oaks (Fig. 4). The decade-long simulation helped in understanding the water balance prediction performance of the VIC-3L model. Also, the long simulation period allowed sufficient spin-up time for the VIC-3L to reach a stable equilibrium condition for an event-based simulation. For an event-based simulation of flood events for generation of PMF, calibration of the VIC-3L model was performed against stream flow gaged at Fair Oaks. This gaging station is located downstream of the Folsom Dam (Figs. 1 and 4). The first half of this period (1997–1998) was used for calibration while the other half (1998–1999) was used for independent validation of stream flow simulation.

The effect of the Folsom dam (and a few smaller dams) upstream was also addressed in this calibration step. The smaller dams upstream of Folsom are predominantly used for silt (sediment) trapping rather than flow regulation, and therefore, were assumed to have minimal impact on the stream flow simulation. Folsom Dam, on the other hand, has the expected impact of delaying the peaks and magnitudes during flood events, resulting in a mismatch between simulated and measured flow at Fair Oaks. To improve further the stream flow simulation downstream of the Folsom Dam, two options were considered. As a first option, the modified Puls method of reservoir routing was performed to rout the flood to Fair Oaks. The elevation-area–storage curve for Folsom reservoir, which is required for inflow routing through the spillway, was obtained from the USGS reservoir sedimentation database (RESSED) (http://www.ida.water.usgs.gov/ressed/) based on a reservoir sedimentation survey made in 2005. As a second option, the flow direction data used in the stream flow routing algorithm (Lohmann et al. 1996) was manually readjusted to reflect the actual river network and the dam location more closely. Among the two options, the flow direction readjustment (second option) yielded more accurate results at Fair Oaks gaging point [Fig. 6(a)].

Independent validation shown in Fig. 6(b) shows satisfactory performance of this calibrated VIC-3L model. Fig. 7 shows a close-up of the performance of VIC-3L in simulating the 1997 flood event that was selected for generation of PMF from various LULC scenarios. In general, the calibrated model was found to overestimate the flood peak magnitude by only 0.9%. This is considered acceptable given that the model used a daily time step

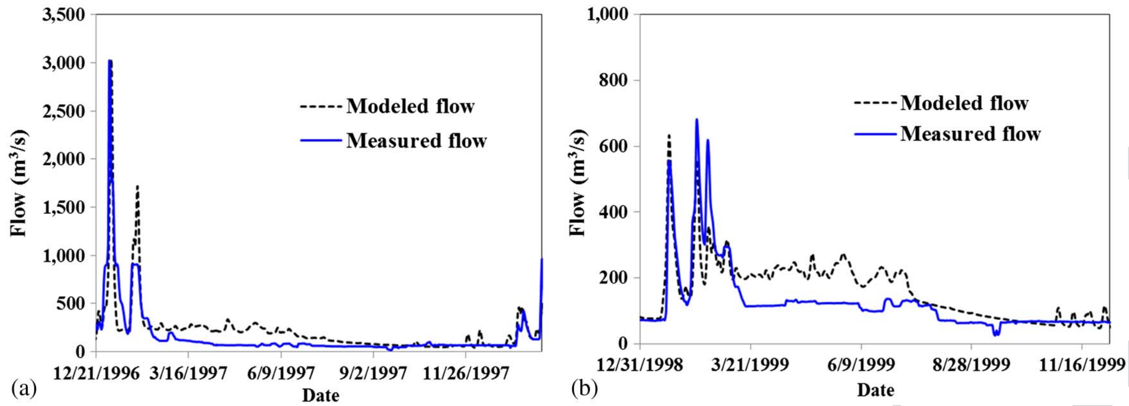


Fig. 6. Simulated and measured flow comparison for (a) calibration period; (b) independent validation period

for simulation of stream flow. In addition, the objective of this study is to establish the relationships LULC change and reservoir size have on PMF. Table 1 shows the performance of the VIC-3L model using measures, such as Nash Sutcliffe efficiency (Moriasi et al. 2007), percent bias (PBIAS), coefficient of determination (R^2), and root mean squared error (RMSE)-observation standard deviation ratio (RSR) (Moriasi et al. 2007; Krause et al. 2005; Benaman et al. 2005) for daily discharge values. Nash Sutcliffe efficiency is defined by a value (between 1 and $-\infty$) that is residual variance normalized by the variance of the observed data (Moriasi et al. 2007; Krause et al. 2005). Coefficient of determination (R^2) describes the correlation between the modeled and observed data (Moriasi et al. 2007). Parameters varied during calibration and their corresponding values for final simulation are provided in Table 2. While there is a modest amount of bias in the simulation of stream flow, other measures demonstrated that VIC-3L is able to represent the hydrological processes of the ARW satisfactorily (Table 1).

Results and Conclusion

This case study looked into the impact of modification of PMP on PMF due to changes in dam-driven LULC and reservoir size for Folsom Dam on the American River watershed (ARW). The regional atmospheric model (RAMS) simulated PMP values for different LULC, and reservoir-size scenarios were obtained from the study of Woldemichael et al. (2012). A hydrological model coupled to a routing model was setup over ARW. The coupled model was calibrated using measured stream flow data at Fair Oaks. The analysis period considered is from December 15, 1996 to January 4, 1997, which included the 1997 catastrophic Sacramento flood event.

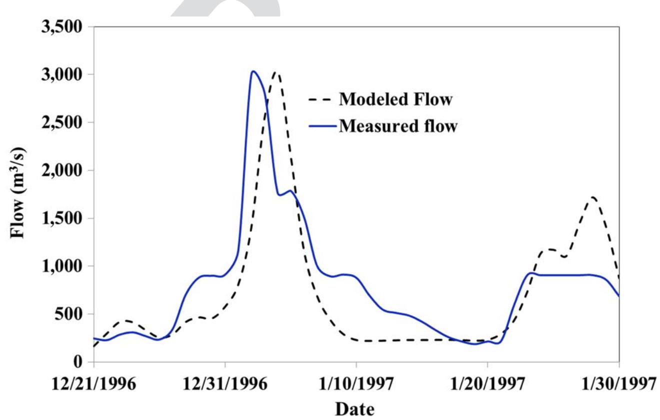


Fig. 7. Simulated and measured flow at Fair Oaks for the 1997 flood event

Table 1. Assessment of Stream Flow Simulation by VIC-3L (Coupled to Routing) Model

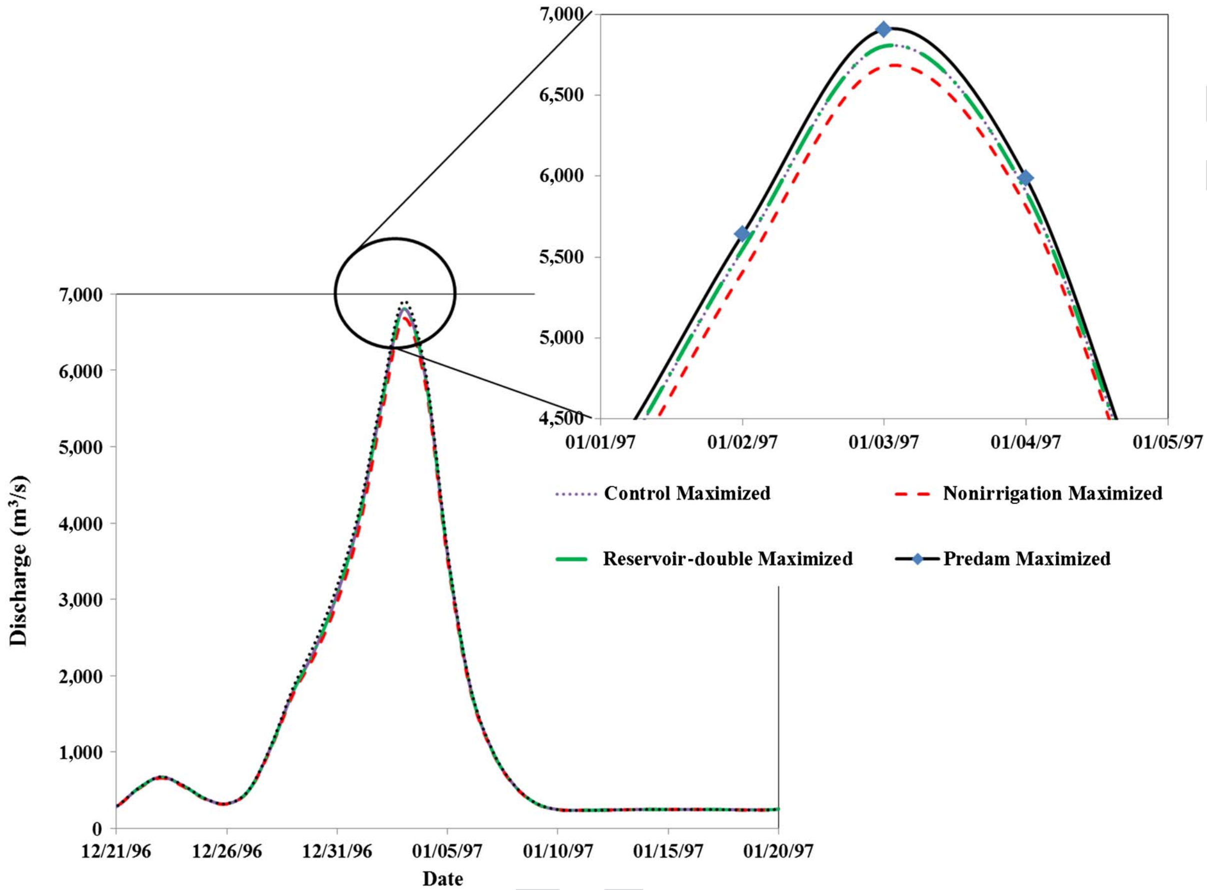
Model	Calibration period (1996/1997–1998)	Validation period (1998–1999)
Nash Sutcliffe	0.74	0.58
PBIAS	−35.0%	−19.0%
R^2	0.77	0.65
RSR	0.5	0.65

Table 2. Calibrated Model Parameter Values

Parameter	Value at calibration	Recommended range in VIC
b_{inf} (infiltration parameter)	0.175	>0 to ∼0.4
W_s (fraction of maximum soil moisture)	1.0	>0 to ∼1.0
$D_{s\,\max}$ (maximum baseflow in lower soil layer)	19	>0 to ∼30
D_s (fraction of $D_{s\,\max}$)	0.175	>0 to ∼1.0

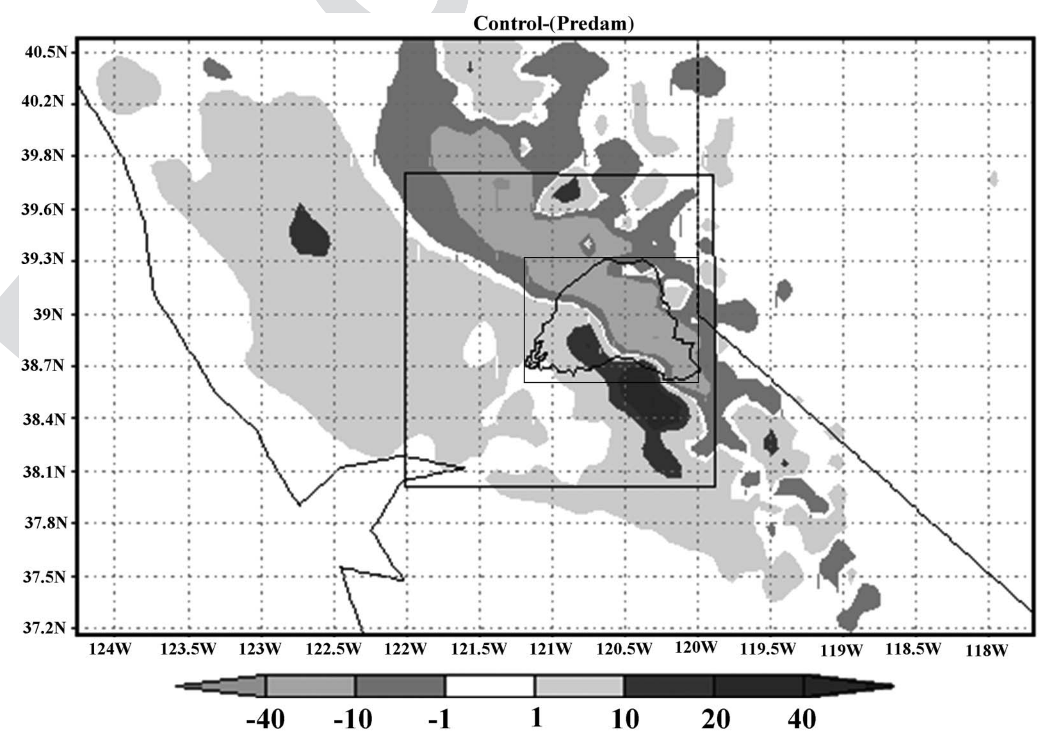
Table 3. Land Use Land Cover (LULC) Scenarios Used for PMP-driven PMF Simulation

LULC group	Reservoir size group	PMP scenarios	Description
1955 LULC	No-reservoir	Predam	Reservoir absent; LULC representing that of the year 1955.
2003 LULC	Current size	Control	Reservoir present; actual reservoir size and LULC representing that of the year 2003.
	Double size	Reservoir-double	Reservoir present; reservoir size double of current size and LULC representing that of the year 2003.
2003 LULC-hybrid	Current size	Nonirrigation	Reservoir present; actual reservoir size and LULC representing that of the year 2003 with all irrigation land use converted to the land use of the predam period.



F8:1 **Fig. 8.** Simulated PMF values for all cases

Fig. 8 summarizes the impact of the various LULC-driven PMP scenarios on PMF in terms of the peak flows. The peak flood for the control scenario is found to be less than that of the predam scenario by about 105 m^3/s (about 1.5%). Since a daily time step is used in the hydrological model, the timing of the peaks is unlikely to be affected. This difference is due to the decrease in simulated



F9:1 **Fig. 9.** Difference between PMP results of control and predam cases

Table 4. Impact of LULC-driven PMP Scenarios on PMF

Scenarios	PMP (mm) (72-h maximum)	PMF (m^3/s) (simulated)
Predam	346	6,908
Control	354	6,803
Reservoir-double	358	6,805
Nonirrigation	344	6,678

Note: PMF flow values pertain to the peak magnitude of the PMP-derived flood hydrograph.

maximum precipitation (PMP) in the upstream regions of ARW after the construction of Folsom Dam for the 1997 event (Woldemichael et al. 2012). PMP comparisons for the two scenarios in Fig. 9 show that there is an increase in maximum precipitation from the predam condition in the downstream areas, while there is a decrease in the upstream areas of the Folsom Dam. A PMF hydrograph pertaining to the control scenario was compared to the reservoir-double scenario. This comparison, which looks into the impact of two different reservoir sizes without any changes to the LULC, shows that reservoir size has virtually no effect on PMF simulation. Woldemichael et al. (2012) have shown that there is an increase of about only 10 mm in the 72-h total PMP values on some areas of the watershed for control and reservoir-double scenarios (Table 4). In the distributed hydrologic model of VIC-3L, this amount of PMP increase over 72 h is not found to be significant to increase the infiltration-excess based runoff in the PMF simulation. Comparison of control to the Nonirrigation scenario shows that there can be a significant decrease in PMF if there were no irrigation developments in the postdam era. This decrease is about 125 m^3/s (about 1.8%), a result close to the case of the predam and control comparison. Enhanced evapotranspiration from irrigation activities increases the precipitation and hence the flood.

Folsom Dam is located in the Mediterranean Koppen-Geiger climate zone, where large dams have been found to have experienced an increase in extreme precipitation patterns (Degu et al. 2011). In our study, the impact of LULC change on PMF modification is mostly due to shifts in patterns of precipitation for the storm used for PMP simulation. If the impounded watershed is relatively small, such shifts will likely impact neighboring watersheds. For the case of the ARW, there are two neighboring rivers—the Feather River and Mokelumne River (Fig. 10). Both these rivers contribute to the flow in the Sacramento area and therefore have implications on the downstream flood risk of urban infrastructure. Thus there is a clear need to broaden the analytical domain to include a region that is representative of the mesoscale storm modification domain. As change in LULC is inevitable with a growing population, a multidisciplinary dam design/operations approach (involving atmospheric scientists, hydrologists, and managers) is timely. In line with the current practice of dam design, this study aims to advance a platform in which atmospheric models and hydrological models could be integrated for estimation of inflow design floods (IDFs) for various realistic scenarios that are likely to impact extreme precipitation patterns. The advantage of such an approach is the ability to proactively consider specific land management practices that may compromise design or operations in the future through atmospheric feedbacks.

Storms can also develop from local changes and be supplemented by larger-scale events, such as atmospheric rivers (ARs). For example, in California alone, all the major storms that brought more than 300 mm/day precipitation in the twentieth century were associated with a well-developed AR (Dettinger 2011). Such storms have resulted in increased risk for civil infrastructures like dams and downstream cities (as was the case for the 1997 event that flooded the Sacramento Valley). The May 2010 flood in Nashville and the October 2010 flood in the Carolinas are also linked to ARs (Ralph and Dettinger 2011). Outside of the United States, for instance, ARs have been responsible for the 10 major floods that occurred in the United Kingdom since 1970 and several other places in North Africa and Central America (Ymanjaro 2011). It is currently not known how such intense AR storms get modified by the extensive anthropogenic changes to the land surface during their propagation inland. In particular, the far reaching LULC changes triggered by dams, such as irrigation and urbanization,

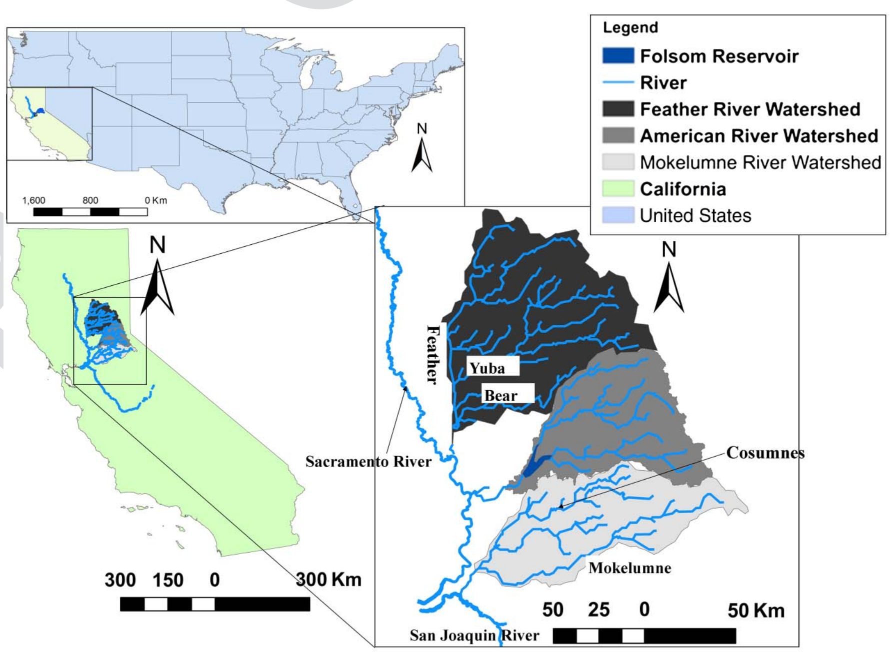


Fig. 10. ARW neighboring watersheds of Feather River and Mokelumne River

which are already known to modify mesoscale precipitation patterns, have not been investigated for their impact on the evolution of ARs. The irrigation development that has resulted from the supply of Folsom Dam and the surrounding urbanizations (cities and communities) have modified the precipitation and flood-flow pattern in the ARW.

In summary, the broader implications of this study are multifaceted and concern flood risk in urban areas, design, operation and maintenance of dams, and water supply management. With an ASCE infrastructure report card grade of D, 70% of the dams in the United States are used for flood control, hydroelectric power generation, irrigation, recreation, and water supply (ASCE 2009). Moreover, the average age of U.S. dams is 51 years, and the total estimated rehabilitation costs near $51 billion. It is crucial to consider the potential impacts of LULC-driven changes in extreme precipitation to improve the functional resilience of dams. Dams' impact on the local land use and land cover and other activities should be considered in a dynamic way such that current and future influences are included in risk assessment and mitigation measures.

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