Physically Based Estimation of Maximum Precipitation over American River Watershed, California

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Abstract: A methodology for maximum precipitation (MP) estimation that uses a physically based numerical atmospheric model is proposed in this paper. As a case study, the model-based 72-h MP was estimated for the American River watershed (ARW) in California for the December 1996–January 1997 flood event. First, a regional atmospheric model, MM5, was calibrated and validated for the December 1996–January 1997 historical major storm event for the ARW, on the basis of the U.S. National Center for Atmospheric Research (NCAR) reanalysis data to demonstrate the model capability during the historical period. Then, the model-simulated historical storm event was maximized by modifying its boundary conditions. The model-simulated precipitation field in the ARW was successfully validated at nine individual rain gauge stations in the watershed. The computed basin-averaged precipitation was somewhat higher than observations obtained by the spatial interpolation of the rain gauge observations. This result suggests a limitation of the spatial interpolation of ground rain gauge observations because they are mostly located in valleys, and the distribution of precipitation is highly heterogeneous over the mountainous terrain of the ARW. Next, to maximize precipitation over the watershed, the initial and boundary conditions in the outer nesting domain of the atmospheric model were modified. In this demonstrative study, the boundary conditions were modified by three methods: (1) maximizing the atmospheric moisture by setting the relative humidity at 100%; (2) maintaining the atmospheric boundary conditions corresponding to the state of the heaviest precipitation (maintaining equilibrium conditions); and (3) spatially shifting the atmospheric conditions to render the atmospheric moisture flux to hit the watershed. Because these modifications significantly increased the precipitation over the ARW, they clearly show the importance of wind and moisture conditions at the boundary of the atmospheric modeling domain. These different maximization methods produced similar 72-h precipitation depths, which were 549 mm by the combination of 100% relative humidity and equilibrium high precipitation conditions at the outer boundary of the model domain, and 541 mm from shifting the historical atmospheric conditions to the south by 5.0°. Accordingly, the 72-h maximum precipitation over the ARW was estimated to be approximately 550 mm. Although this study presents only a demonstrative maximization work, it shows that the presented modeling approach can be a potential alternative to standard probable maximum precipitation (PMP) estimation without depending on the linear relationships required in the standard PMP method. Also, because the proposed modeling approach is based on the initial and boundary atmospheric conditions from a synoptic scale that may be obtained from the NCAR/National Centers for Environmental Prediction reanalysis data for the historical period and from the general circulation model (GCM) climate projections, it can account for any nonstationarity that may be present in the hydro-climate system. **DOI:** 10.1061/(ASCE)HE.1943-5584.0000324.

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Introduction

Flood frequency analysis has been a standard tool for designing flood protection structures. However, as evidence of global climate change is emerging [Intergovernmental Panel on Climate Change (IPCC) 2007], the fundamental assumption on the stationarity of the atmospheric and hydrologic processes, is being questioned (e.g., Milly et al. 2008). All standard statistical tools for the long-term flood frequency analysis require stationarity that underlies statistics, such as the time average value, staying constant. Climate change itself implies nonstationarity because of the evolution in time of the Earth's hydro-climate system. Therefore, the analyses that solely rely on historical records and their sample statistics may no longer be suitable for making inferences on the future behavior of the hydro-climate conditions over a watershed. In this context,

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there is a need for physically based methods for the development of estimates of future floods over a watershed. With such a physically based numerical modeling approach that may use synoptic atmospheric data for its initial and boundary conditions in model simulations at watershed scale either from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data for the historical period or from the general circulation model (GCM) climate projections, it may be possible to account for the time-evolving hydro-climate dynamics over a watershed with the change in the global climate system, thereby accounting for any possible nonstationarity in the climate system.

An alternative concept to the purely statistical flood frequency analysis for the design of hydraulic structures may be the probable maximum precipitation (PMP) approach to flood estimation. The widely accepted definition of PMP is a physical upper bound of possible precipitation over a given size of storm area at a particular location at a certain time of the year [Hansen et al. 1982; World Meteorological Organization (WMO) 1986]. However, a purely statistical approach to PMP estimation where a certain number of standard deviations of a maximum precipitation depth are considered above the mean of the maximum depth (Hersfield 1961) is also used in some hydrologic engineering practice.

Although PMP implies the "probabilistic" limitation of the heaviest precipitation, it has been mainly determined by the "physics" of the weather system. Since the term PMP was recognized in the late 1950s (American Meteorological Society 1959), U.S. agencies such as National Weather Service (NWS), Weather Bureau (USWB), and Army Corps of Engineers (USACE) were involved in the improvement of the PMP estimation. To compute the PMP, a general storm is generally generated by a mass conservation model (e.g., Myers 1967; WMO 1973). The modern methodology for the PMP estimate includes several techniques such as moisture maximization, storm separation, and enveloping.

The original PMP estimation methodology does not account for the orographic effect on precipitation. In fact, since the first PMP estimation by the original method was published (USWB 1961) for California, a few precipitation events have exceeded the PMP estimations, particularly for short durations, indicating that the original method is not applicable over the mountainous region such as Sierra Nevada (Bergeron 1965; Hobbs 1989). The most widespread approach for orographic PMP is a technique called *storm separation* (Miller et al. 1973; Hansen et al. 1988). In the storm separation technique, it is assumed that the orographic effect of the maximum precipitation can be evaluated independently from a nonorographic storm. As such, the orographic PMP estimation can be obtained by applying an empirical relationship called *orographic factor* to the nonorographic (or convergence) PMP estimation.

In the standard PMP estimation approach, the moisture convergence component of precipitation is maximized before the orographic factor is applied. One of the most common techniques to maximize the historical extreme event is called *moisture maximization method* (WMO 1986). This method maximizes the observed or generated extreme precipitation by the ratio $W_{\max}/W$, where W is the actual precipitable water in the atmosphere and $W_{\max}$ is the maximum precipitable water estimated by the maximum daily dew point temperature of the corresponding month. However, Papalexiou and Koutsoyiannis (2006) pointed out that the moisture maximization method is highly sensitive to the available observation data. To mitigate this data-dependency weakness of the PMP estimation, techniques based on the multiple extreme event data, such as enveloping (Corrigan et al. 1999) or a probabilistic method (Papalexiou and Koutsoyiannis 2006), have been proposed and used.

The aforementioned traditional methodology has been applied in many regions of the world, but the assumptions in the standard PMP estimation method remain arguable. First, it is questionable that the orographic component can be linearly separated from the convergence component while the Earth's atmosphere is a highly nonlinear system. Second, it is also uncertain that the precipitation is linearly related to the precipitable water in the atmosphere. Third, it is unknown whether the precipitation distribution stays the same as the atmospheric moisture is increased. Furthermore, the spatial representation of the precipitation field over a watershed may cause significant uncertainty in the standard PMP estimation. To compute the PMP for a watershed, the climatologic spatial distribution of the precipitation is typically adopted, but such synoptic scale of precipitation dynamics may be insufficient for the watershed-scale PMP. Thus, it is necessary to develop a scientifically sound methodology that can systematically compute the upper physical bound of precipitation.

A numerical modeling approach that accounts for the various effects of the nonlinear atmospheric system in an orographic region may provide an objective PMP estimate without any assumptions and statistical linear relationships. Abbs (1999) used such a numerical atmospheric model, the Colorado State University Regional Atmospheric Modeling System, in Australia and tried to evaluate various effects on PMP estimation. In her study, the numerical atmospheric model was used just to determine the sensitivity of the atmospheric state variable (temperature) and the orographic effect on the maximization factor to improve the standard methodology. This paper presents a more straightforward use of a regional-scale atmospheric model for PMP estimation is proposed. That is, the modeled precipitation field will be maximized by changing the model initial and boundary conditions at the outer model domain during a historical extreme storm event. Through various approaches to maximize precipitation over the targeted watershed, the American River watershed (ARW), it is attempted to determine the physical upper bound of the precipitation by using numerical simulations from a regional atmospheric model, which does not need the assumptions required in the standard PMP estimation methods. In this study, the value computed by this methodology will be called *maximum precipitation* (MP) to distinguish it from the traditional PMP.

The maximum precipitation over the ARW is evaluated by maximizing the historical extreme precipitation, corresponding to the December 1996–January 1997 historical flood event, as a demonstrative case in this study. This is the first step toward developing a comprehensive methodology for the physically based estimation of maximum precipitation. The comprehensive methodology, when completed in the future, will be based on all the observed historical and GCM-projected severe precipitation events. Accordingly, to achieve the aforementioned MP, one may take the following steps in a comprehensive methodology:

1. Identify historical extreme events over a specified watershed;
2. Reconstruct historical extreme storm events over the studied watershed through a numerical regional atmospheric model that will use the synoptic initial and boundary atmospheric conditions that correspond to the identified historical severe events, from NCEP/NCAR reanalysis data;
3. Maximize regional atmospheric model-simulated historical extreme storms over the studied watershed by modifying the corresponding synoptic atmospheric initial and boundary conditions, to be obtained from the NCEP/NCAR reanalysis data;
4. Identify future extreme precipitation events from an analysis of all the available GCM climate projections over the studied region;

5. Construct extreme storm events over the studied watershed through a numerical regional atmospheric model that will use the initial and boundary atmospheric conditions that correspond to the identified future severe events, from GCM climate projections data;
6. Maximize regional atmospheric model-simulated future extreme storms over the studied watershed by modifying the corresponding synoptic atmospheric initial and boundary conditions, to be obtained from the GCM climate projections data; and
7. Develop a maximum precipitation estimate based on an analysis of all the maximized historical and future precipitation events over the specified watershed.

Because this study is a first step to achieve the previously described comprehensive methodology to estimate maximum precipitation over a watershed, only one very significant historical extreme precipitation event (the most significant flooding in recent history of California) is addressed. However, through this single event, it is possible to demonstrate the basic concepts of the proposed methodology to maximize precipitation over a watershed. Accordingly, this paper covers the first three items in the previously described procedure.

On the basis of historical atmospheric data, the atmospheric conditions that have rendered extreme precipitation over the ARW during the December 1996–January 1997 historical flood event are analyzed. Then, the MM5 regional atmospheric model is applied to the ARW to reconstruct the selected storm event to validate the model performance during the historical event period. As a numerical regional atmospheric model, MM5 (fifth generation mesoscale model) (Grell et al. 1994), developed by NCAR and the Pennsylvania State University (Anthes and Warner 1978), is selected. Because it is based on the nonhydrostatic framework, the MM5 can dynamically downscale the global atmospheric data to an appropriate spatial resolution that is fine enough to capture the effect of steep topography. For this study, the initial conditions (IC) and boundary conditions (BC) for the model simulations are prepared on the basis of the NCAR historical global reanalysis atmospheric data. The NCAR reanalysis data is a synthesized historical observation database by using a global atmospheric model and is available from the late 1940s to the present with the temporal resolution of 6 h. Because the spatial resolution of the NCAR reanalysis data is approximately 280 km over California, to perform the necessary analysis at the watershed scale, it is necessary to downscale these data to the scale of a few kilometers over the targeted watershed. Therefore, the reconstruction of the severe storm event by using the MM5 is equivalent to the dynamic downscaling of the historical global reanalysis atmospheric data to watershed scale at 3-km spatial grid resolution. The MM5 modeling system is calibrated and validated by comparing its simulations against the available historical observations in terms of precipitation. Finally, the model-simulated historical extreme precipitation during the December 1996–January 1997 flood event is maximized by modifying the IC and BC with respect to atmospheric moisture and duration and by spatially shifting the IC and BC conditions to obtain physically based estimates of the MP.

American River Watershed

The proposed methodology here for the estimation of maximum precipitation is demonstrated over the American River watershed, California. A map of the ARW above Folsom Dam is shown in Fig. 1. The American River drains approximately 5,440 km^2 along the western slope of the Sierra Nevada mountain range in northern California and contributes significant flows to the Lower Sacramento River region. The area has a well-developed drainage system composed of three principal streams: North Fork, Middle Fork, and South Fork, which flow generally westward. There is considerable variation in vegetative cover over the watershed, ranging from light- to medium-density cover at low elevations, heavy cover over most of the medium elevations, moderate to light cover over the high elevations, and practically no cover in severely glaciated areas around the high peaks. The elevations range from 3,170 m at the headwater to approximately 60 m at the Folsom Dam. Flows from the watershed form a flood plain covering roughly 445 km^2 at the confluence of the Sacramento and American Rivers. The flood plain includes most of the developed portions of the City of Sacramento and virtually the entire Natomas Basin, an agricultural reclamation area adjacent to the two rivers that is rapidly being urbanized (USACE 2006).

Folsom Dam is on the main stem of the American River, approximately 47 km upstream from its confluence with the Sacramento River. It is a multipurpose dam operated by the U.S. Bureau of Reclamation as a part of the Central Valley Project (CVP). The dam regulates runoff from approximately 4,817 km^2 of drainage area, and the reservoir has a total (full-pool) capacity of approximately 1.2 billion cubic meters. The designated flood space in the Folsom Reservoir was originally authorized at 493 million cubic meters. On the basis of current agreements between the Bureau of Reclamation and the Sacramento Area Flood Control Agency (SAFCA), it now varies in the range of 493–826 million cubic meters (maximum balanced control space).

Historical Extreme 72-h Precipitation

Before the systematic flood recording on the American River started in 1905, several extreme events and floods in the last half

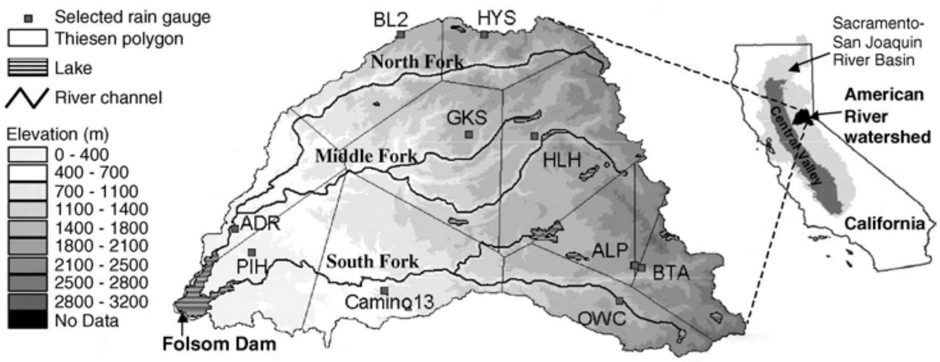

Fig. 1. Map of ARW

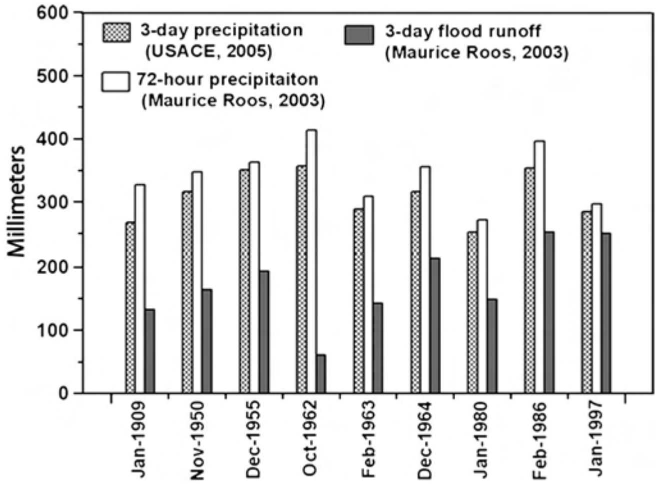

Fig. 2. Comparison of estimated maximum 72-h (3-day) precipitation and flood runoff, American River watershed (USACE 2005; Roos 2003)

of the nineteenth century (1850, 1862, 1867, 1878, 1881, and 1891) caused damage in the Sacramento area (Weaver 1962; Roos 2003). Since the extreme flood event in 1862, substantial efforts have been directed toward major levee projects to mitigate the effect of flooding. For the aforementioned events in the last half of the nineteenth century, the depth of the 72-h precipitation event was estimated in the range of 323–373 mm (12.7–14.7 in.).

Fig. 2 shows the 72-h (3-day) basin-average precipitation and runoff based on the field measurements for the nine highest precipitation events at the ARW during the twentieth century. It can be seen from this figure that there are significant differences in the reports of USACE (2005) and Roos (2003). This may be attributable to the selection of the rain gauges and to the methods of areal averaging. Meanwhile, it is obvious that the relationship between precipitation and runoff is not direct because of the complicated hydrologic conditions, such as initial soil moisture and snow storage in the mountain range. For example, the precipitation event in 1962 was the largest in the record, but the actual runoff was the smallest among the historical extreme events, as shown in Fig. 2. The precipitation event in 1997 was the second heaviest among the nine precipitation events, but its runoff was as large as the largest runoff event of 1986. In this study, the high runoff event of 1997 was selected for analysis and precipitation maximization because the final goal of the study is to estimate maximum flood (runoff), but this paper will not cover the hydrologic response of the ARW. It is also beneficial to select a recent flood event such as the 1997 event because of the richness of data in the watershed. In this study, only the 72-h MP will be discussed because it is a representative duration for the major floods that brought significant damage to the discussed region. However, the methodology presented here can be repeated for other durations (such as 24 h, 12 h, and so on) to obtain the depth-duration curves as needed.

Several PMP estimations for the ARW have already been available, considering the importance of flood protection for the Sacramento City and Sacramento–San Joaquin River delta area. The first PMP value published in *Hydrometeorological Rep. No. 36* (USWB 1961) over the ARW was estimated as 800 mm (31.48 in.). Then, Corrigan et al. (1999) revised it to 726 mm (28.57 in.) using more-recent techniques for the orographic effect. According to the recent work by the USACE (2001), the 72-h PMP in the ARW was 752 mm (29.6 in.). The historical records in Fig. 2 shows that the existing PMP estimations are nearly double the precipitation depth in the historical maximum event.

MM5 Calibration and Validation Results

The regional atmospheric model, MM5, must be calibrated and validated before using it to maximize the precipitation field. To figure out the best combination of the MM5 model options, the atmospheric conditions over Northern California during the 2-month period of December 1, 1996, through January 31, 1997, were simulated by using the MM5. In this calibration process, the best model options for cumulus parameterization, cloud microphysics, and atmospheric boundary layer were determined by comparing modeled versus observed precipitation over the ARW during December 1996, the first half of the simulation period. Then, using the second half of the simulated atmospheric conditions (January 1997), the model-simulated precipitation was validated by comparing its simulations against the observed counterparts at the ARW.

By using available precipitation data, the best combination of physical options for MM5 were determined. Because the hourly increment precipitation data are necessary to check the temporal accuracy of the model simulation, the monthly operated ground rain gauge stations were excluded. As such, 10 California Data Exchange Center (CDEC) stations and one California Irrigation Management Information System (CIMIS) station, operated by California Department of Water Resources (DWR), were selected for this study. PRISM (parameter-elevation regressions on independent slopes model) is one of the most comprehensive spatially distributed processed precipitation data sets developed by Oregon State University (Daly et al. 1994). It provides interpolated ground precipitation data over the United States at 4-km spatial resolution from 1895 to present. However, because PRISM has only monthly data, it was used only for the comparisons of the monthly basin-average precipitation volume and its spatial distribution over the ARW. The satellite data and other synthesized precipitation databases were examined, but they were not used in this study because of their coarse spatial resolutions. Weather radar data from NCDC (National Climatic Data Center), NEXRAD (next generation radar), were also examined. However, many of the data frames were missing, and even the available frames showed unexpectedly little precipitation over Sierra Nevada during the 1997 storm. Although there are several reasons for it, these frames seem to be disfigured by the attenuation effect of the radiation through the series of high water content storm cells in this event. As such, it was concluded that the ground rain gauge and PRISM data were the only reliable sources for the model calibration and validation during major storm events such as the 1997 storm.

Table 1 shows the various combinations of model options for MM5 in this study. Combinations of physical options are labeled Cases 1 to 8. In this study, Grell scheme (Grell et al. 1994) and

Table 1. Combinations of Model Options in MM5

Case number	Cumulus parameterization	Microphysics processes	PBL schemes
1	Kain-Fritsch 2	Mixed-phase (Reisner 1)	MRF
2	Grell	Mixed-phase (Reisner 1)	MRF
3	Kain-Fritsch 2	Reisner graupel (Reisner 2)	MRF
4	Grell	Reisner graupel (Reisner 2)	MRF
5	Kain-Fritsch 2	Mixed-phase (Reisner 1)	Gayno-Seaman
6	Grell	Mixed-phase (Reisner 1)	Gayno-Seaman
7	Kain-Fritsch 2	Reisner graupel (Reisner 2)	Gayno-Seaman
8	Grell	Reisner graupel (Reisner 2)	Gayno-Seaman

Table 2. Monthly Precipitation over ARW during December 1996–January 1997 by PRISM and MM5 Simulations

		PRISM	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
December 1996	Precipitation (mm)	704	702	726	697	724	695	702	689	706
	Difference (%)	—	−0.29	3.14	−0.97	2.96	−1.26	−0.29	−2.13	0.40
January 1997	Precipitation (mm)	591	685	696	641	659	703	718	682	681
	Difference (%)	—	15.81	17.79	8.42	11.47	18.95	21.44	15.43	15.21

Kain-Fritsch 2 (Kain and Fritsch 1993) scheme were investigated for the cumulus parameterization. Grell scheme is based on the rate of destabilization or quasi-equilibrium and is a simple single-cloud scheme with updraft and downdraft fluxes and compensating motion that determines the heating/moistening profile. Kain-Fritsch scheme uses a sophisticated cloud-mixing scheme to determine entrainment/detrainment and removes all available buoyant energy in a relaxation time. Kain-Fritsch 2 is a new version of the Kain-Fritsch scheme that includes shallow convection. For the planetary boundary layer (PBL) schemes, medium-range forecast (MRF) PBL (Hong and Pan 1996), and Gayno-Seaman PBL (Ballard et al. 1991; Shafran et al. 2000) options were examined. MRF PBL scheme is an efficient scheme based on a Troen-Mahrt representation of the countergradient term and K-profile in the well-mixed PBL, as implemented in the NCEP MRF model. Gayno-Seaman PBL is based on Mellor-Yamada turbulence closure. It is distinguished from others by the use of liquid-water potential temperature as a conserved variable, allowing the PBL to operate more accurately in saturated conditions. For the cloud microphysics options, mixed-phase (Reisner 1) and Reisner graupel (Reisner 2) schemes were examined. In the mixed-phase scheme (Reisner et al. 1998), supercooled water process is added to the microphysics processes including dry, stable precipitation, warm rain, and simple ice to allow for the slow melting of snow. However, it does not contain graupel or riming processes. Reisner graupel (Reisner 2) scheme is based on mixed-phase scheme, but graupel and ice number concentration prediction equations are added. In this study, cloud-radiation scheme (NCAR 2005) for a radiation scheme and five-layer soil model (Dudhia 1996) for the surface scheme were selected. In the model calibration process, selection of the physical options in MM5 was optimized to render the best fit when compared to the PRISM data, as MM5 has a variety of physical options for cumulus parameterizations, PBL schemes and diffusion, microphysics processes, and radiation and surface schemes.

MM5 simulations were carried out using these model configurations, and each simulation result was evaluated on the basis of the observed ground precipitation data. These eight cases produced simulation results that are very similar to each other with respect to spatial distribution and timing of precipitation. The monthly total precipitation was the only clear indicator of model performance.

Table 2 shows the monthly basin-averaged precipitation simulated by the eight MM5 model configurations (option combinations) along with the PRISM data. Also shown is the difference (%) between PRISM data and each model case. Case 3 combination of MM5 physical options shows the best agreement with the PRISM data. It was concluded that the combination of the Case 3 physical options is the best model configuration for MM5 in this study.

The calibrated model (model configuration, Case 3) was validated on the basis of the observed ground precipitation data at each ground station location, provided by CDEC and CIMIS data sources. Fig. 1 shows the locations of ground precipitation stations in the ARW denoted by a gray square over the digital elevation model (DEM) from the National Elevation Dataset (NED) by USGS. Fig. 1 shows that most of the stations are located around the valley with lower elevations than hilltops. Fig. 3 compares the observed and MM5-simulated (Case 3) hourly precipitation at each observation station during the December 1996–January 1997 storm event. The observed basin-averaged precipitation at the bottom-right graph of Fig. 3 was derived by the Thiessen polygons method from ground observation stations. It is seen from these comparisons that the

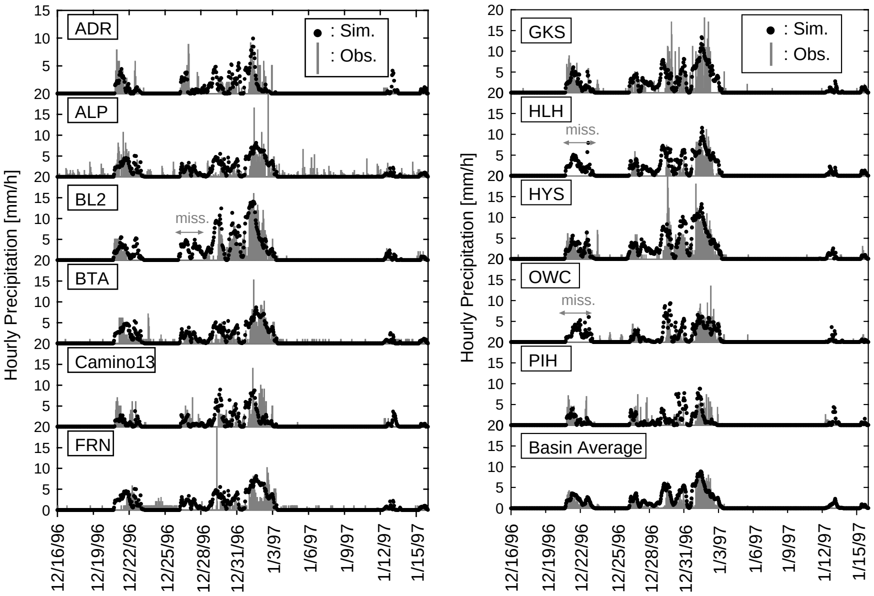

Fig. 3. Comparisons of observed and simulated (Case 3) hourly precipitation at 11 stations and hourly basin-averaged precipitation during December 1996–January 1997 storm event

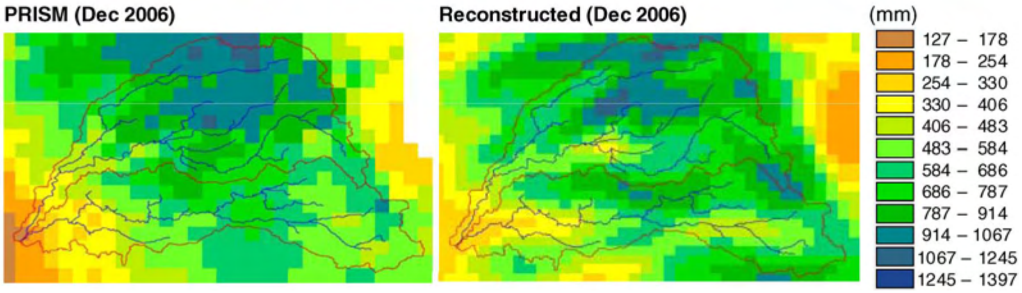

Fig. 4. Comparison of simulated MM5 precipitation fields (Case 3) and PRISM data for December 1996 over ARW

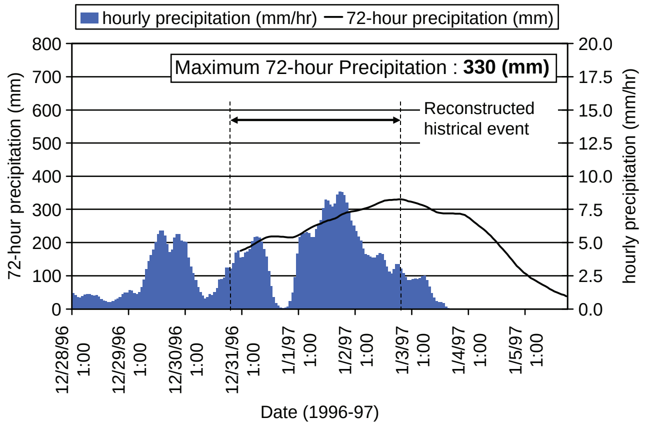

Fig. 5. Reconstructed basin-averaged precipitation and its 72-h moving sums during January 1997 event (Run 0)

observed and simulated precipitation at each location match very well at an hourly time scale. These validation results using Case 3 model configuration of physical options for MM5 form a foundation for the MP studies in the ARW.

Fig. 4 shows the comparison between the simulated monthly precipitation field by case 3 MM5 and the corresponding PRISM data over ARW for December 1996. It is seen from the maps in Fig. 4 that the spatial distribution of the precipitation for December 1996, obtained by the dynamic downscaling of NCEP reanalysis data using MM5, matches reasonably well with the PRISM data. Note that the MM5 simulation has 3-km spatial resolution, whereas the resolution of PRISM is 4 km. The MM5 simulation result shows banded precipitation structures around the ridges attributable to the orographic effects, whereas the PRISM data do not show such structures. The orographic effect on precipitation is determined by wind fields as well as topography. It is possible that PRISM may not represent well the effect of orography on precipitation fields during this period over the ARW because PRISM was developed on the basis of elevation-based interpolation considering climatological moisture movement. Such orographic effect on precipitation can be clearly discerned in the precipitation field simulated by MM5.

Maximum 72-h Precipitation

The maximum 72-h precipitation period during the December 1996–January 1997 storm event was identified on the basis of the reconstructed atmospheric data by using the MM5 with the Case 3 model configuration. First, the basin-averaged precipitation over the ARW was computed by using the reconstructed precipitation fields by MM5, as can be seen in the bottom-right graph of Fig. 3. Because the complete spatial precipitation field at 3-km resolution and 1-h time increment was reconstructed over the whole ARW, one can easily compute the basin-average precipitation. The bar graph in Fig. 5 shows the computed basin-averaged precipitation at 1-h time increments over the ARW. Then, the 72-h moving sums of the hourly basin-averaged precipitation were computed for the 2-month simulation period of December 1996 to January 1997, as shown in the line graph in Fig. 5. In this study, the 72-h period is labeled by its ending time. For example, the maximum value in the moving summation (the line graph in Fig. 5) was found at January 2, 1997, at 12:00, and the corresponding 72-h period for the maximum precipitation was therefore from December 31, 1996, at 12:00, to January 2, 1997, at 12:00. The maximum basin-averaged 72-h precipitation was evaluated as 330 mm (12.99 in.). This number corresponds to Roos's estimation of 328 mm (Roos 2003) fairly well but exceeds the USACE estimation of 285 mm (USACE 2005); both estimates are based on the ground rain gauge data.

Fig. 6 shows the identified maximum 72-h precipitation fields based on the 3 km (left) and 9 km (right) resolution simulations during the 72-h period ending on January 2, 1997, at 12:00. In Fig. 6 the contour lines of the maximum 72-h precipitation field were

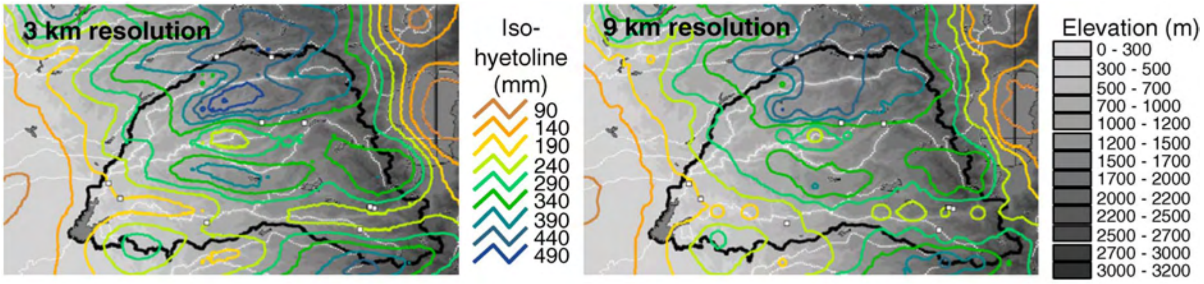

Fig. 6. Obtained maximum 72-h precipitation fields by MM5 with 3-km (left) and 9-km (right) computational grid resolutions, and topography (NED) by USGS

superimposed over the DEM (NED) by USGS. It can be seen in both graphs of Fig. 6 that the higher elevation regions around the ridges and hilltops receive higher precipitation. However, comparing the model-simulated precipitation fields of the 3-km (left map) to 9-km (right map) grid resolutions in Fig. 6, it may be seen that the orographic effect over the ARW with 9-km grid was not emphasized very well. From these results, it can be inferred that a computational grid of 3-km resolution is desirable for the dynamic downscaling in order to capture the impact of steep topography on the precipitation fields over an orographic region such as Sierra Nevada.

By examining the reconstructed precipitation fields using MM5, it became clear that the local topography played a significant role in orographic precipitation. In fact, as noted earlier, two different observation-based estimates of maximum 72-h precipitation from USACE (2005) and Roos (2003) imply that the computation of basin-averaged precipitation greatly depends on the handling of the spatial distribution among gauges. Because there is tremendous uncertainty on the precipitation values at locations in between the existing rain gauges, the discrepancy in the maximum basin-averaged precipitation of the 1997 storm between the model simulation and interpolated observation is not surprising. As such, to measure the performance of the model simulation, the comparisons against the individual rain gauges in Fig. 3 may be more appropriate than those against the basin-averaged value. Consequently, the representative severe storm event during the winter of 1997 was successfully reconstructed, as substantiated by comparisons of model simulations against observations at all rain gauge sites in the ARW (Fig. 3). The corresponding maximum 72-h precipitation was evaluated as 330 mm (12.99 in.) by using the numerical weather model, MM5.

Development of Design Storm: Precipitation Maximization for January 1997 Storm Event with respect to Boundary Conditions

In this section, to maximize the precipitation over the ARW that corresponds to the historical storm event of December 1996–January 1997, boundary conditions of the calibrated/validated MM5 are modified. Although only the maximization for 72-h precipitation over the ARW will be presented in this study, the same exercise for other durations can obviously be performed as needed. In this study, the model-simulated 72-h precipitation is maximized by: (1) moisture—keeping relative humidity (RH) in the boundary condition at 100% (Runs 1 and 3); (2) duration—creating the equilibrium boundary condition once the atmospheric moisture over the ARW reaches maximum (Runs 2 and 3); and (3) wind field—shifting the boundary condition in the latitudinal direction so that one can identify the wind field that produces the maximum precipitation over the ARW (Run 4). The third method, maximization with wind field, will be presented in the next section because it requires the analysis of the wind field in the 1997 storm event.

As a first method, atmospheric moisture in the boundary conditions of MM5 simulations was maximized so that the 72-h precipitation over the ARW can be maximized. Precipitable atmospheric moisture content may be maximized without changing the atmospheric stability by setting the RH of the boundary condition at 100%. The rest of the state variables in the boundary condition were kept as the original historical states. The propagation of the perturbation from the outer boundary was computed by the MM5 by using a series of model nesting domains during the whole storm period over the ARW. Therefore, the maximization of atmospheric moisture in the boundary condition of the numerical weather model obviously differs from the traditional "moisture maximization method" (WMO 1986) that relies on a linear formula.

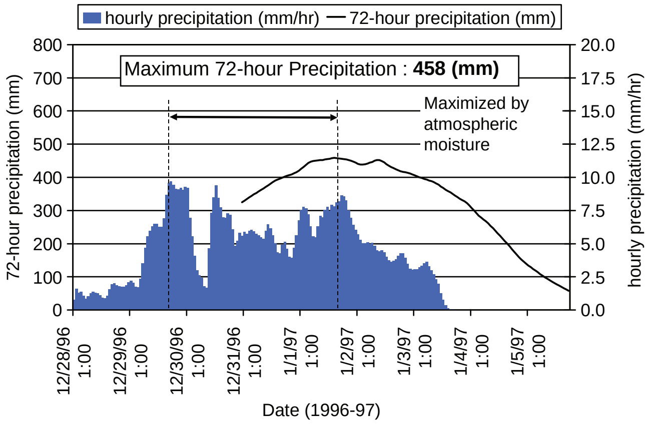

Fig. 7. Hourly basin-averaged precipitation (bar) over ARW and its 72-h moving sums (line) for 1996–1997 storm event based on MM5 with 100% RH boundary condition (Run 1)

The maximization of the 1997 storm by means of perturbing the atmospheric moisture is denoted by Run 1 in this study, and Fig. 7 shows the maximized simulated hourly basin-averaged hyetograph and its 72-h moving sums. Referring to the historical simulation labeled as Run 0 in Fig. 5, the maximum 72-h precipitation of 458 mm in Run 1 is approximately 39% more than that of Run 0. It can be seen that the first peak of hourly precipitation in Run 1 exceeds the peak of the original highest hourly precipitation in Run 0. This implies that the rainband that brought the original heaviest precipitation (Run 0) in the ARW was already nearly saturated. However, the first rain wave potentially had more capacity to carry water from the Pacific Ocean to Sierra Nevada. More interestingly, although the fully saturated atmospheric boundary condition was provided for the entire simulation period in Run 1, the precipitation ceased at 15:00 in January 3, 2007, in the ARW. It may be inferred that the wind field is as important as the atmospheric moisture to have high precipitation over the ARW. Thus, to further maximize the basin-averaged precipitation over the ARW, other state variables including the wind field need to be modified.

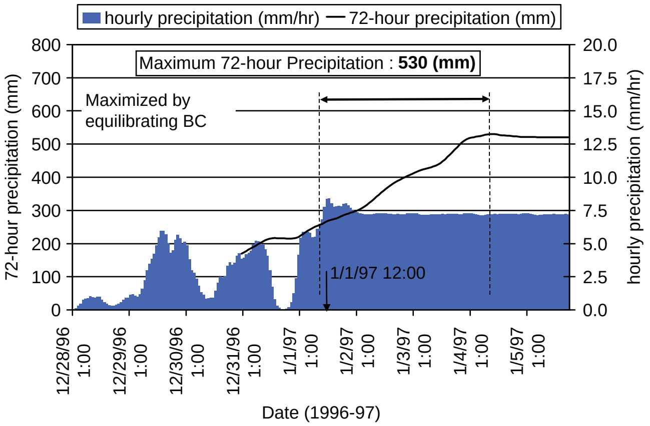

Fig. 8. Hourly basin-averaged precipitation (bar) and its 72-h moving sums (line) for 1996–1997 storm event based on MM5 with equilibrium boundary condition set at maximum atmospheric moisture state over ARW (Run 2)

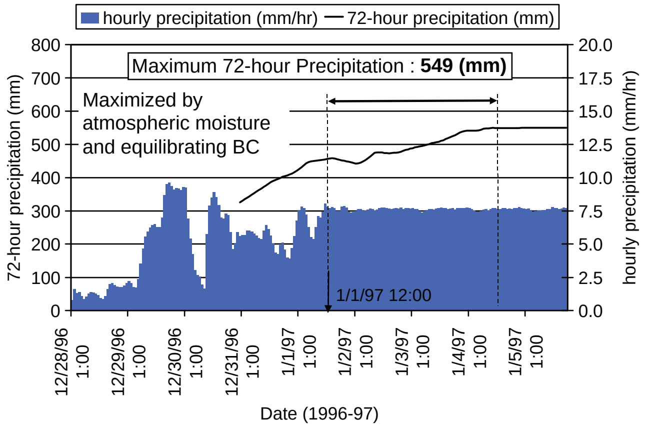

Fig. 9. Hourly basin-averaged precipitation (bar) and its 72-h moving sums (line) for 1996–1997 storm event based on MM5 with 100% RH combined with the equilibrium boundary condition at 12:00, January 1, 1997 (Run 3)

Before modifying the wind field, it was explored whether the duration of the storm can be modified in the next run (Run 2). The historical atmospheric condition over the ARW along the outer boundary was fixed once the peak precipitation depth (January 1, 1997, at 12:00) was reached over the ARW to force continuation of the historical peak precipitation conditions over the ARW. Fig. 8 shows the simulated hourly (bar graph) and corresponding 72-h (line graph) basin-averaged precipitation based on the condition of Run 2. Clearly, the hourly basin-average precipitation reaches an equilibrium at around the hourly precipitation of 7.4 mm after 12 h from 12:00 in January 1, 1997, when the boundary condition was fixed. The maximum 72-h precipitation of Run 2 was evaluated as 530 mm, which was higher than those of Runs 0 and 1. Hence, it is possible to have an equilibrium high precipitation over the ARW if the large-scale (scale of the NCAR reanalysis data) weather system is set at a steady state. A steady-state analysis is a very common approach in the nonlinear system of river channel hydraulics for design purposes. Analogously, this type of steady-state analysis may have a good engineering value for hydrologic design.

Additionally, a combination of the moisture-maximized storm case (Run 1) and equilibrium storm case (Run 2) was examined as Run 3 to further maximize the 72-h precipitation over the ARW. That is, the historical atmospheric RH of the grids at the outer boundary and within the whole initial domain during the whole storm period was changed to 100% (Run 1), and then the atmospheric condition at the outer boundary was fixed once the peak precipitation depth was reached over the ARW (January 1, 1997, at 12:00) (Run 2). Fig. 9 shows the simulated hourly and the 72-h basin-averaged precipitation based on the conditions of Run 3. The maximum 72-h precipitation of Run 3 was 549 mm, which is higher than those of the other runs. These three runs show that by modifying the atmospheric initial and boundary conditions for the calibrated/validated MM5, the basin-averaged 72-h precipitation can be maximized.

Development of Design Storm: Precipitation Maximization for January 1997 Storm Event by Shifting Boundary Conditions

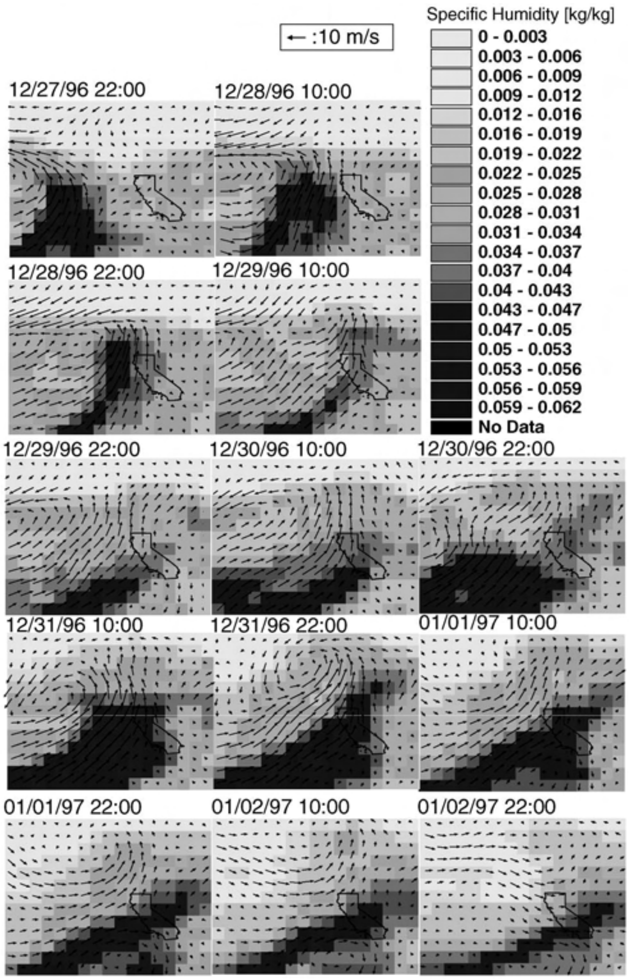

Fig. 10. Atmospheric moisture (vertical summation of specific humidity) and wind fields (at 915 mb) around Pacific Northwest and California during 1996–1997 historical storm event

The analysis in the previous section clearly indicates that the wind field and the atmospheric moisture are important for extreme precipitation events. Particularly, it was shown that the continuous moisture supply to the ARW region easily enhanced the total amount of 72-h precipitation. In this section, we will review the synoptic atmospheric state during the December 1996–January 1997 storm around California, which is at a much larger scale than the ARW, to diagnose what weather pattern has brought the heavy precipitation to the ARW. Then, another maximization methodology based on this diagnosis will be explored by using MM5 simulations.

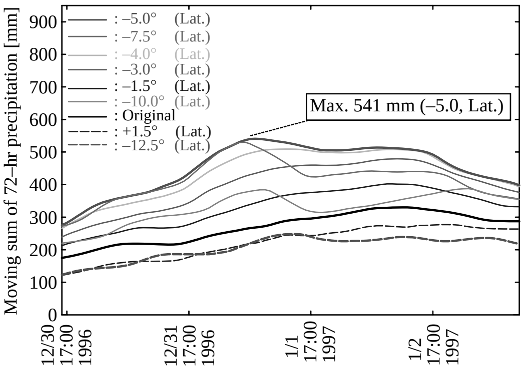

Fig. 11. Consecutive 72-h moving summation of precipitation for each shifting condition from +1.5° to −12.5° in latitude (Run 4)

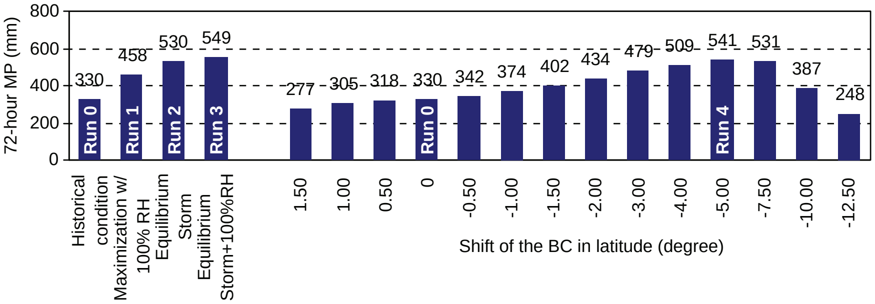

Fig. 12. Summary of estimated 72-h maximum precipitation based on January 1997 event by using three different maximization methods: atmospheric moisture (100% RH), equilibrium storm, and boundary condition shifting (Runs 0–4)

Atmospheric moisture (or precipitable water) and wind fields around the Pacific Northwest, including California, from December 28, 1996, at 22:00 to January 3, 1997, at 22:00 were derived directly from the NCAR reanalysis data and are plotted in Fig. 10. The wind fields were at 915 mb in height, and the moisture fields were derived by the vertical integration of the specific humidity through all of the vertical atmospheric layers from the land surface to the top atmospheric layer of the NCEP reanalysis data. These moisture movements in the atmosphere, often referred to as "atmospheric river" or "pineapple express," are generally considered to cause extreme storm events over Northern California (Zhu and Newell 1998). Fig. 10 shows that the precipitable water approaches California during the storm period once the wind fields change direction toward northeast after December 29, 1996, at 22:00. These large-scale processes visually show the importance of the effects of wind and moisture conditions during a storm event over California.

These historical atmospheric conditions, shown in Fig. 10, suggest that shifting the boundary conditions in space with respect to latitude may maximize the precipitation fields over the ARW. Therefore, as a final approach, the historical atmospheric boundary domain was shifted with respect to latitude to maximize the 72-h precipitation over the ARW. As such, the atmospheric moisture, wind, temperature, and stability were modified at the MM5 outer boundary on the basis of the shifted atmospheric conditions that were actually observed at the southern (or northern) part of California during the historical storm event. This case study tries to simulate how much precipitation would fall on the ARW if the storm would travel slightly northward (or southward).

Fig. 11 shows the consecutive 72-h moving sums of precipitation for each shifted condition ranging from −12.5° (southward) to +1.5° (northward) from the original observed position. Shifting the boundary conditions southward increases the maximum 72-h precipitation, whereas shifting these northward decreases it. Fig. 12 compares the maximum 72-h precipitation under the shifting of the boundary conditions, as well as from other previously described methods. The maximum 72-h precipitation was 541 mm at −5.0° shift, and this was labeled as Run 4. The result of maximum 72-h precipitation obtained by the spatial shifting of the boundary conditions (Run 4) was close to that of Run 3, the combination of equilibrium and 100% RH conditions (549 mm). Accordingly, the maximum 72-h precipitation over the ARW was estimated as 550 mm on the basis of the atmospheric conditions during the 1996–1997 historical storm event. Because the maximized precipitation depths by using the various modifications in the initial and boundary conditions of the MM5 simulations converged to a realistic number, it may be concluded that it is possible to estimate a maximum precipitation value by using a numerical weather model by maximizing the precipitation depth in multiple historical storm events that were observed over the ARW and that are projected by GCM for the future global climate.

Summary and Conclusion

To obtain physically based estimates of the MP at the ARW, a methodology using the numerical regional atmospheric model MM5 is proposed. This model-based methodology has several advantages over the traditional methodology for PMP estimation. First, because the regional atmospheric model (MM5) is capable of managing the energy and mass exchanges over the landscape (the orographic uplifting effect, the moisture convergence, and the nonlinearity of the atmosphere), this model-based PMP estimation does not require any assumptions or linear relationships of the standard PMP estimation, which is based on storm separation and moisture maximization. Second, since the model-simulated MP has minimum dependency on the rain gauge observation data, one can obtain a realistic MP estimate in a sparsely gauged basin. In fact, technically speaking, this regional atmospheric model-based approach can still function without any historical record because the historical precipitation fields can be reconstructed by downscaling the existing NCEP/NCAR reanalysis data; however, model calibration and validation are highly recommended before the precipitation maximization exercise, if the observation data are available. Third, once the model configuration (the specific combination of the model options) is specified, the precipitation field is objectively and uniquely determined. Fourth, this modeling approach can provide the fine-scale spatial distribution of the maximized precipitation, which is critical for orographic regions such as Sierra Nevada. Finally, because the proposed technology is based on the dynamic downscaling of the synoptic atmospheric conditions over a specified watershed by utilizing a regional atmospheric model, it can account both for the historical conditions by using the globally available NCEP/NCAR reanalysis data providing the historical synoptic atmospheric initial and boundary conditions, as well as for the future conditions by using the various GCM climate projections providing the future synoptic atmospheric initial and boundary conditions. Within this framework, the proposed modeling methodology can accommodate any nonstationarity that may be present in the climate. Furthermore, because it can accommodate as large a combined historical/future sample as available by using GCM simulations and NCEP/NCAR data, it can accommodate both the critical dry and wet periods in the past and in the future. Accordingly, it is believed that the proposed methodology can minimize the over- or underestimation of maximum precipitation over a watershed as the sample size increases by the ever-increasing GCM simulations of the global climate.

In the case study of the ARW, the numerical regional atmospheric model MM5 was calibrated and validated on the basis of the available observation data before the maximization estimations under various alternative approaches in order to determine the best combination of physical options for the MM5 model components. The comparisons against the spatially interpolated monthly data for precipitation fields (PRISM) and 11 individual rain gauges' hourly data demonstrated the reliability of the model in Northern California. However, the effect of topography on precipitation fields (the orographic effect), which can be seen from the MM5 precipitation simulation results at 3-km grid resolution, suggests that the basin-averaged precipitation obtained solely from the ground observation stations may underestimate the true basin-average precipitation.

To develop a design storm, the 72-h precipitation depth was maximized with respect to boundary conditions and spatially shifting atmospheric conditions. These physically based maximization estimates clearly show the importance of wind and moisture conditions at the boundary of the model domain. Fig. 12 summarizes the results of the computed 72-h maximum precipitation estimates based on the 1997 storm event by using three different maximization methods: (1) the approach based on atmospheric moisture (100% RH) (Runs 1 and 3); (2) the approach based on equilibrium conditions (equilibrium storm) (Runs 2 and 3); and (3) the approach based on boundary condition shifting (Run 4). The maximum 72-h precipitation was estimated as 549 mm by the combined method of the equilibrium and 100% RH atmospheric conditions at the outer boundary of the model domain, and as 541 mm by the shifting atmospheric conditions southward by 5.0°. From these results, it seems that under the atmospheric conditions of the 1997 storm event, the 72-h maximum precipitation must be around 550 mm over the ARW. Comparing against the existing PMP values: 800 mm (USWB 1961), 726 mm (Corrigan et al. 1999), and 752 mm (USACE 2001), which are nearly twice as high as the historical most severe storm events over the ARW (USACE 2005; Roos 2003). This study's model-based MP estimate of 550 mm indicates that the traditional methodology may significantly overestimate the PMP. In other words, this study's MP estimate implies that the physical upper bound of the 72-h precipitation over the ARW may be somewhere below the existing PMP values. Hence, this study's MP estimation method may provide significant relief to the flood mitigation strategies for the Sacramento–San Joaquin River delta.

The precipitation maximization over a watershed by using a numerical weather model is not yet established, and this study should be interpreted as a first step in this direction. At this stage of the development, it is yet to be shown how well the proposed methodology will work under varying storm durations (other than the 72-h duration), varying atmospheric conditions of recorded historical severe storm events, and varying atmospheric conditions of future severe storm events, whose synoptic conditions are simulated by GCM. As such, the reported study is just a first step in the substantial future work that remains for the development of a physically based maximum precipitation methodology over any specific watershed.

This study demonstrated how the initial and boundary conditions of a numerical atmospheric model can possibly be modified to obtain estimates of the maximized 72-h basin-averaged precipitation over the ARW. Within this framework, although the possibility of underestimation of the MP still remains, it is encouraging that the various maximum precipitation estimates obtained by different methods converged to a realistic value. Hence, it is concluded that a methodology for the estimation of design storms over a watershed that is based on a numerical weather model such as MM5 holds significant promise.

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