Technical Note

Probable Maximum Precipitation in a Changing Climate: Implications for Dam Design

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Abstract: Modern dams are overwhelmingly designed under the assumption of climatic stationarity by using a static design value known as probable maximum precipitation (PMP). Therefore, it is worthwhile to explore the impact of relaxing the assumption of stationarity and recalculating design PMP values by using currently practiced procedures enhanced by numerical modeling or observational climate trends. This study reports the findings of nonstationary PMP recalculations at three large dam sites in the United States (South Holston Dam in Tennessee, Folsom Dam in California, and Owyhee Dam in Oregon). The results indicate that currently accepted PMP values are significantly increased when future changes in dew points from observational trends or numerical models are taken into account. It is plausible that such future changes in these meteorological thresholds, had they been known among the engineering community when PMPs were designed, would have received the necessary attention regarding the future uncertainty of stationary PMP values as a dam ages. **DOI: 10.1061/(ASCE)HE.1943-5584.0001021.** *© 2014 American Society of Civil Engineers.*

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Introduction

Because of the numerous interactions involved in storm formation, extreme storms almost always have precipitation potential beyond what was observed (Abbs 1999). Extreme rainstorms do not always exhibit meteorological conditions reaching the highest atmospheric potential of the time and geographic location of their occurrence. Therefore, it is useful for scientific and applied investigations to analytically force the atmospheric conditions of historically significant rainfall events to their upper boundary to discover their precipitation potential (Rakhecha et al. 1999). This procedure is commonly called storm maximization, a method used to derive probable maximum precipitation (PMP). The National Oceanic and Atmospheric Administration has compiled a catalog of such extreme rain events in the United States that were maximized in some consistent fashion and publicly released as hydrometeorological reports (HMRs) (U.S. Dept. of Commerce 1999; Fig. 1). These PMP values, based entirely on historical data and the assumption of a stationary climate system, have experienced extensive societal application over the last few decades, particularly for design, operations, and risk assessment of large water infrastructures, such as dams, levees, and urban drainage systems (Rakhecha and Singh 2009).

The implications of the currently available twentieth-century PMP values being representative (or not) of the 21st century are profound. The cost associated with large water infrastructures necessitates lengthy life spans (>100–500 years). Thus, nonstationary PMPs caused by climate shifts over such long periods will likely alter failure risks for these statically designed structures (Kunkel et al. 2013; Milly et al. 2008). Currently practiced PMP estimation methods maximize an observed (from historical records) extreme precipitation event 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 from the maximum daily dew point records (Rakhecha and Singh 2009). Historically, the W_{max} derived from dew point has been based on predam records. However, the Clausius-Clapeyron relationships suggest that the atmosphere can hold more water vapor as temperature increases (Dai 2006). In fact, the water-holding capacity of air increases by approximately 7% per 1.8°F (1°C) warming. This implies that storms, whatever the type, are likely to be supplied with increased moisture, which will produce more intense precipitation events in a warming climate (Trenberth 2011).

Current climatic trends point to a 2°F per 100-year increase in dew points in most regions of the United States (Robinson 2000). Most global climate models indicate a 20–30% increase by common era (CE) 2100 in maximum precipitable water caused by greenhouse gas emissions (Kunkel et al. 2013). Beauchamp et al. (2013) reported a 6% increase in PMP values by CE 2070 from projected increases in atmospheric humidity simulated by a global climate model for a specific watershed in Canada. Thus, a natural question that remains open today is, "How representative are static twentieth-century PMP values of the 21st century?"

Beyond nonstationary climate forcings, there are several physically compounding issues that undermine the representativeness of current PMP values derived from the most extreme twentieth-century storms. The currently practiced method of storm maximization that has been adopted from the derivation of twentieth-century PMP values is based on precipitable water (Rakhecha and Singh 2009). Abbs (1999) has investigated the validity of relying on precipitable water, commonly known as the HMR or World Meteorological Organization approach, and has identified possible reasons why certain HMR-PMP values have been exceeded by recently observed extreme storm events, such as the 1996 flood in Sydney, Australia.

Although the storm maximization approach has provisions for separation of the orographic (terrain) forcing from the moisture convergence (frontal lifting) forcing before transposition of a

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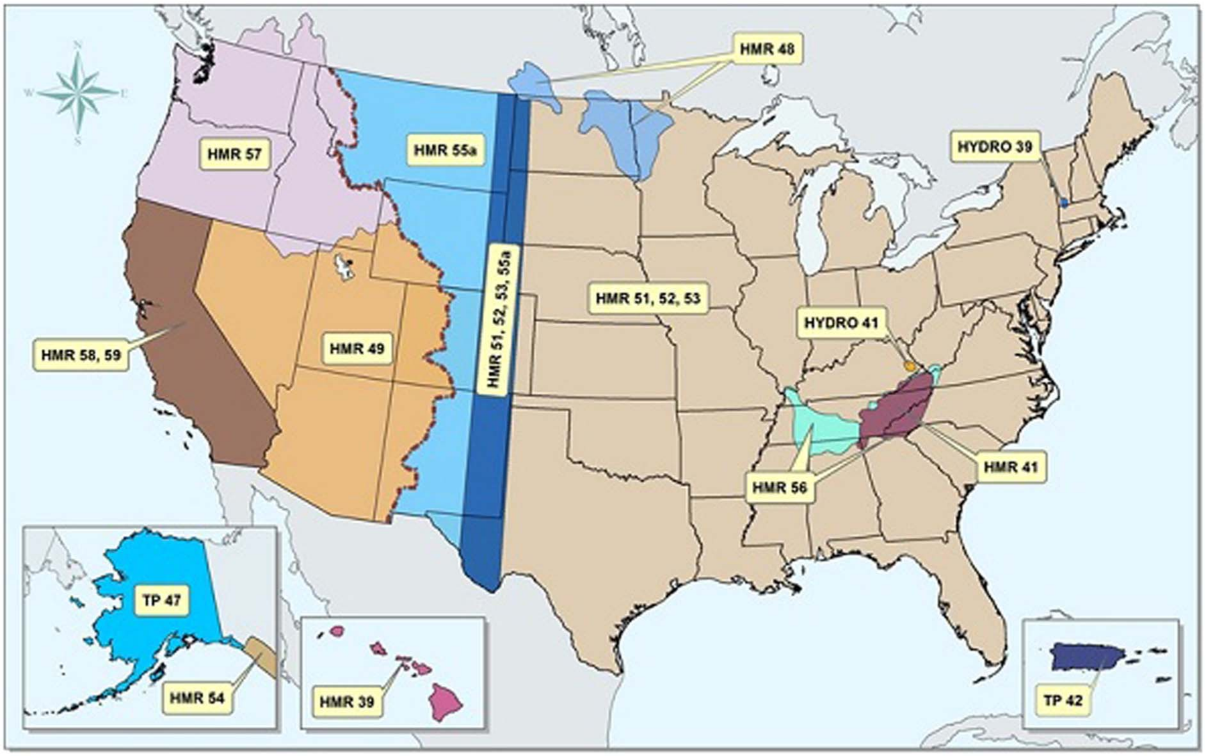

F1:1 **Fig. 1.** Regions of application for HMR-PMP reports (reprinted from U.S. Dept. of Commerce 2012)

PMP value to another area with a different duration and area, recent atmospheric modeling studies show that a linear HMR approach produces a significant bias. In some cases, the HMR-PMP values have been found to be underestimated as well (Woldemichael et al. 2012; Ohara et al. 2011; Tan 2010). Whereas most studies, such as the three previously cited and Chen and Bradley (2006), estimate PMP by assuming a saturated atmospheric column, the earlier study of Abbs (1999) estimated PMP by increasing temperature while keeping relative humidity constant to ensure dynamic equilibrium of the storm system. Thus, as a first-cut exploration to understand the representativeness of HMR-PMP values in the 21st century, it is useful for the engineering community to investigate, in hindsight, the extent to which HMR-PMP values could have been altered with a priori knowledge of future nonstationary climate forcings.

The vital science question that motivated this study is, "To what extent are universally accepted, stationary probable maximum precipitation values, as published in hydrometeorological reports, representative of current and future climate behavior given our current understanding of changes to climate?" To the best of knowledge, none have explored the extent to which PMP values are altered by using a replication of the procedures outlined in the hydrometeorological reports coupled with future climate data from numerical modeling tools or observational analyses of climatic trends. These climate differences can be caused by both top-down phenomena such as heat entrapment from greenhouse gases and bottom-up influences such as land use/land cover (LULC) change. Studies have recently looked at the effects of LULC changes in the postdam construction era on climate (e.g., Yigzaw et al. 2013; Lo and Famiglietti 2013) and global effects of the changes in climatic statistics on air moisture content. Changes in land use or land cover can significantly alter the hydroclimatology of an area from changes in permeability, evapotranspiration rates, and water loss through irrigation. A replication of the conventional procedures outlined in HMRs substituting nonstationary atmospheric variables for stationary values has not been performed. Therefore, this study aims to provide insight into the extent to which HMR-PMP values in large dams may have been altered since their construction by using both top-down and bottom-up modeling approaches.

The study is outlined as follows: the next section outlines in detail the procedure used in HMRs for deriving PMPs through moisture maximization of storms using dew points. Subsequently, the application of either top-down or bottom-up modeling approaches to each of the three study sites by using either an observational approach or numerical climate modeling is explained, and the study sites for revisiting the HMR-PMP estimates are shown. Finally, a discussion and conclusions based on the findings are presented.

Moisture Maximization of Storms in HMR Studies

The concept of probable maximum rainfall was first developed in the 1940s with the first publication of a series of hydrometeorological reports (Foufoula-Georgiou 1989). These reports, primarily produced by the Weather Bureau (now the National Weather Service), contain procedures detailing the intricate processes and data sets used for the derivation of PMPs. Although region-specific variables contribute to specific modeling methods used in each report, the general approach used in all HMRs is moisture maximization. This method increases atmospheric moisture to the upper possible limit for the time and location of the rainfall event. The method of moisture maximization is demonstrated by the following equation (Rakhecha et al. 1999):

$$\mathrm{PMP}_T = P_{0,\mathrm{SL}} \times \left(\frac{W_p(\max)_T}{W_p(\mathrm{observed})}\right) \quad (1)$$

where $P_{0,\mathrm{SL}}$ = maximum recorded depth of rainfall for a particular duration over a particular area of the storm location; $W_p(\max)_T$ =

maximum probable precipitable water of an air column in the transposed location based on seasonal 12-h maximum persisting 1,000-hPa dew point; and $W_p(\text{observed})$ = actual precipitable water in the moisture column of the storm being maximized (in some circumstances along the west coast, particularly, areas west of the 105th meridian, it is necessary to substitute maximum persisting 12-h sea surface temperatures in place of dew point) (U.S. Dept. of Commerce 1999). The observed precipitable water is found by using HMR tables that relate 12-h maximum persisting 1,000-hPa dew point to the available precipitable water in an air column (U.S. Dept. of Commerce 1965), or, if available, vertical soundings taken during the storm. Eq. (1) yields a PMP value at the transposed location with the same spatial and temporal values as the location of the maximized storm.

In addition to moisture maximization, both duration and areal factors must be considered when following the HMR methodology. Duration and areal factors can be obtained from the depth-area-duration curve of the appropriate controlling storm. The desired PMP duration (usually 72 h in the design of large dams) and area of the watershed in question can be interpolated from these curves for use in the PMP calculation of the transposed location (U.S. Dept. of Commerce 1999).

In areas of significant orography, elevation influences and storm separation into orographic and convergent components must also be used during moisture maximization (Rakhecha and Singh 2009). Splitting the storm rainfall into convergence-induced precipitation and orographic effects allows the storm to be transposed to locations with varying topographic features. The nonorographic component, or free atmospheric forced precipitation (FAFP), is the portion of rainfall caused solely by atmospheric conditions. This value can then be transposed to the desired location and multiplied by the orographic factor, or K factor, of that location. Eq. (2) is used to calculate K factors

$$K = M^2\left(1 - \frac{T}{C}\right) + \frac{T}{C} \tag{2}$$

where M = storm intensification factor; T = total 100-year precipitation; and C = 100-year convergence component (U.S. Dept. of Commerce 1999). Values of T and C can be found in tables in HMR 59. M varies by rainfall event and can be considered the precipitation in the most intense period of the storm divided by the storm duration. Multiplying the K factor by the FAFP-PMP reveals the PMP of the transposed location in orographic regions. Fig. 2 summarizes the overall procedure.

Nonstationary Rederivation of PMP Values

Study Regions

Three study regions were considered for the recalculation of PMP values, substituting nonstationary climate data in place of stationary data used in the HMRs: the Upper American River Watershed in California (Folsom Dam); the Owyhee River Watershed, extending across Idaho, Nevada, and Oregon (Owyhee Dam); and the Holston River Watershed, spanning parts of Virginia, North Carolina, and Tennessee (South Holston Dam). The bottom-up approach (looking at the effects of LULC on mesoscale climate and subsequent changes to PMP values) was applied to both the Upper American River Watershed and the Owyhee River Watershed, whereas a top-down approach (using observed dew point trends) was used on the Holston River Watershed.

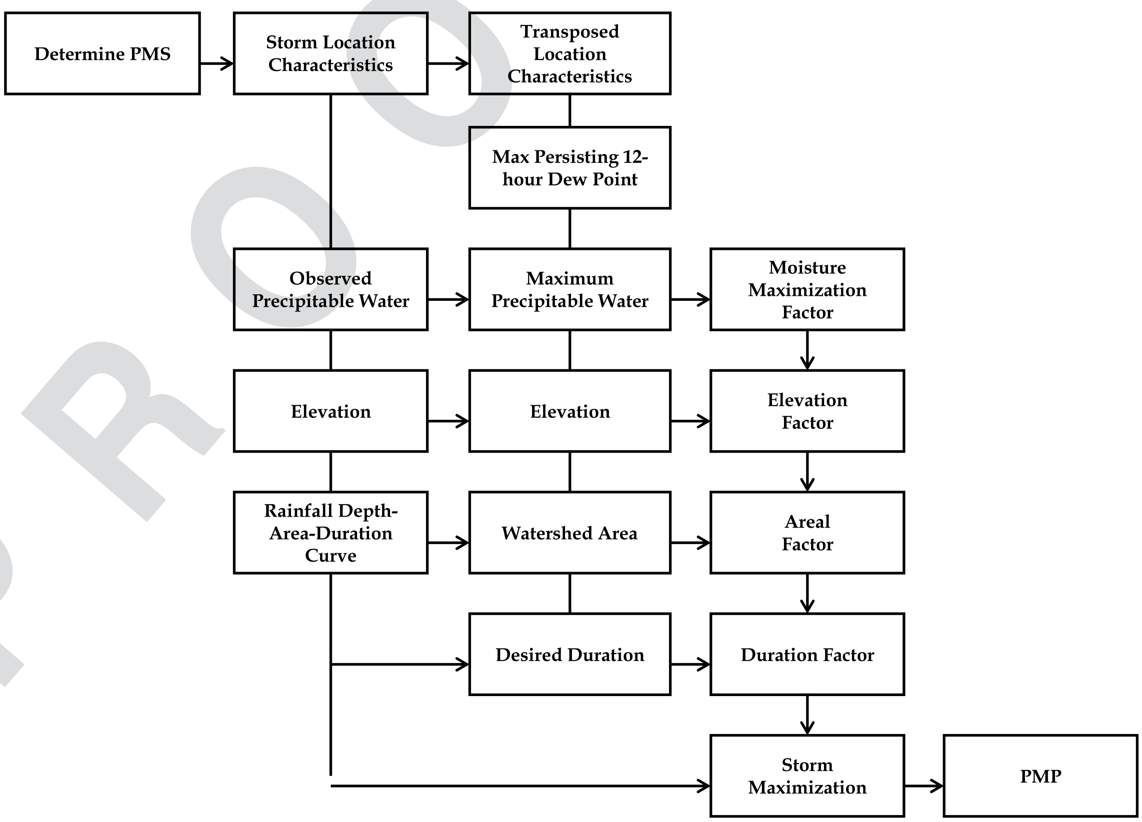

Fig. 2. Overall PMP estimation approach

A blend of both approaches at each site would be optimal, but a lack of reliable data did not allow for such an analysis.

Folsom Dam is a multipurpose dam situated 23 mi northeast of Sacramento, California. Its major intended function is flood control, but it also provides hydropower and irrigation to the surrounding region. It was constructed in 1955 along the American River and currently impounds Folsom Lake (California Dept. of Parks and Recreation 2013; Fig. 3).

Farther to the northeast of Folsom Dam is Owyhee Dam, situated in Oregon across the Idaho border from Boise (Fig. 3). The dam was constructed for use in irrigation projects. The Owyhee River drains into Owyhee Reservoir, which is fed by excess runoff from the Owyhee River Watershed (ORW). The watershed is approximately 11,588 sq mi in surface area as shown in Fig. 3 (Oregon Environmental Council 2013). The dam was completed in 1932 and was the tallest dam in the world at the time (Bureau of Reclamation 2012).

The Holston River watershed feeds South Holston Reservoir, which is an impoundment by South Holston Dam near Bristol, Tennessee. The dam was opened in 1950 and was intended primarily for hydropower and flood control, but irrigation supplied by the reservoir now delivers water to numerous surrounding croplands (Tennessee Valley Authority 2013).

Bottom-Up Recalculation Approach

A bottom-up climate modeling approach using the regional atmospheric modeling system (RAMS) (Pielke et al. 1992) was applied to two of the study regions [Upper American River Watershed (UARW) and ORW] to determine the impact of LULC change on future PMP values. Changes to land cover can have a significant effect on the water cycle caused by drainage ability, evapotranspiration, irrigation, and others and lead to a change in local climate. A storm of historical significance (January 1997) (Dettinger et al. 2004) was numerically modeled over both watersheds by using four different LULC scenarios to determine the difference in storm behavior between the scenarios. The dew point data (or more specifically, the 12-h maximum persisting dew point) from each scenario could then be extracted and used to directly simulate the HMR-PMP procedure. The LULC scenarios considered were as follows: (1) control (current land conditions of the watershed); (2) reservoir-double (an assumed land condition where the

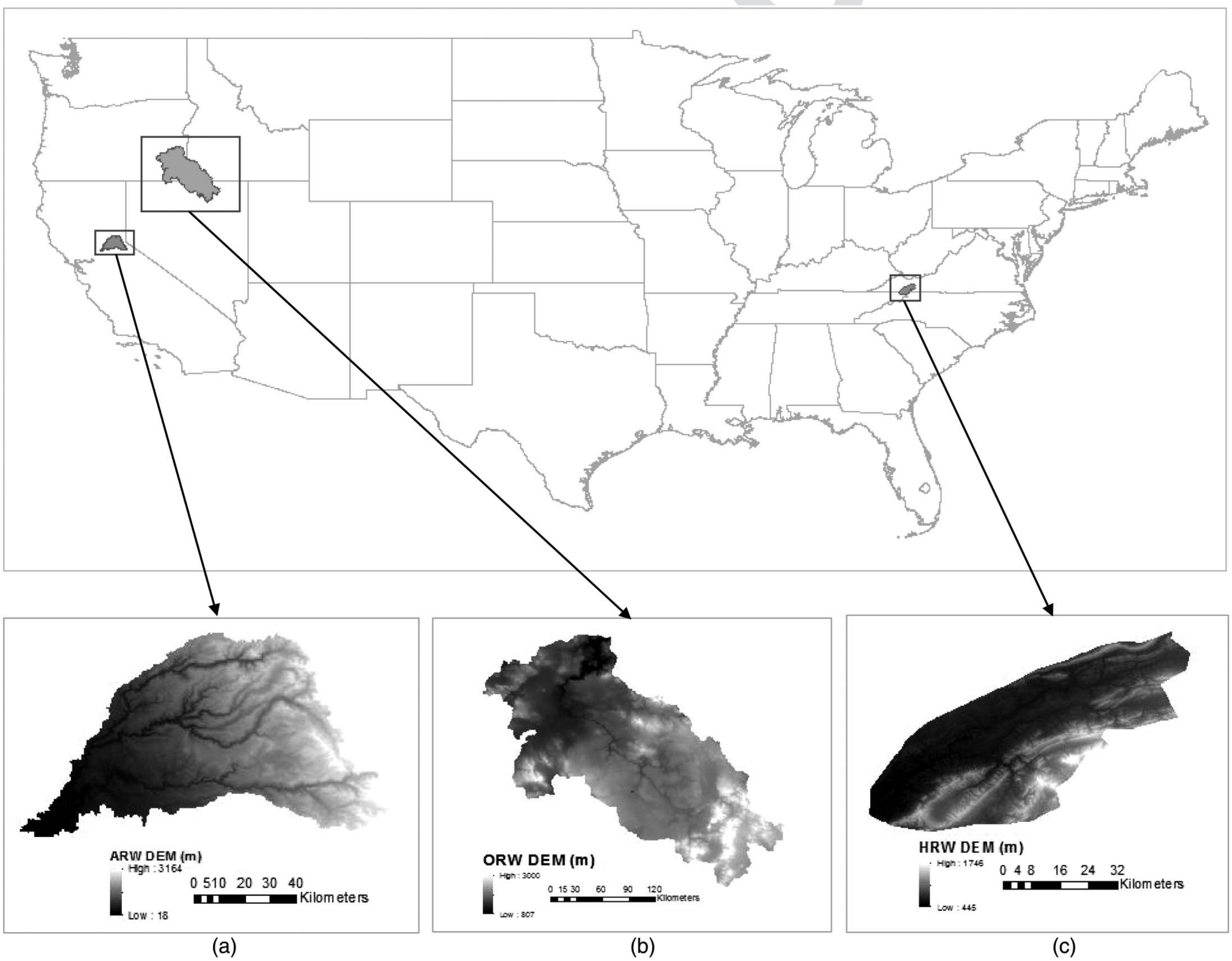

Fig. 3. Selected river impoundments and dam sites for investigation of HMR-PMP with nonstationary climate forcings: (a) American River (Folsom Dam); (b) Owyhee River (Owyhee Dam); (c) Holston River (South Holston Dam) (data from USGS 2013)

reservoir surface area is assumed to be doubled); (3) nonirrigation (a land condition where the irrigation surrounding the reservoir is assumed to be replaced with predam land cover); and (4) predam (representative of the land condition at the time of construction of the dam before the reservoir was impounded). The reservoir-double scenario is more of a hypothetical scenario that was used to explore the sensitivity of open-water evaporation on extreme precipitation rates. Conversely, the nonirrigation scenario was represented by replacing currently irrigated land surfaces with the land-use information pertaining to the predam period that was available from the HYDE database (available at http://themasites.pbl.nl/en/themasites/hyde/index.html) while keeping the reservoir intact. HYDE presents a gridded time series of land use for the last 12,000 years (Goldewijk et al. 2011). Such land data are useful in reconstructing the early-twentieth-century land-use scenario for an atmospheric modeling domain. The numerical modeling details using RAMS may be found in Woldemichael et al. (2012).

The next step after extracting the dew point data from the RAMS model for each of the two watersheds was identifying the convergence component of the January 1997 storm, which excludes all orographic influences. The orographic influences of this storm were stripped from the total rainfall so that new orographic conditions in the transposed location (in this case, the UARW) could be inserted. This was done by using the K factor [Eq. (3)], which gives the total PMP when multiplied by the convergence component. However, this was later found redundant, as the desired transposition location had similar orographic characteristics to the region of maximum rainfall that occurred at an elevation of 5,200 ft (above mean sea level). Areal and temporal adjustments were then made, followed by moisture maximization.

Based on the RAMS modeled surface dew points for the period of December 15, 1996, to January 2, 1997 of the storm, the maximum persisting 12-h surface dew point for each of the four scenarios (control, reservoir-double, nonirrigation, and predam) was obtained and compared to the 12-h maximum persisting 1,000 mb dew points for December. By using the precipitable water tables reported in the HMRs, the values of total precipitable water corresponding to both stationary and nonstationary dew points were found. By using the moisture maximization equation and an areal reduction factor (and following the flowchart outlined in Fig. 2), the nonstationary PMP for each of the LULC scenarios was calculated for Folsom Dam and Owyhee Dam. Please see Stratz (2013) for the methodological details.

Top-Down Recalculation Approach

Unlike in the UARW or ORW, the HMRs pertaining to the United States east of the 105th meridian (HMR 51; U.S. Dept. of Commerce 1978) and, more specifically, the Holston River Watershed (South Holston Dam) (HMR 51) do not specify which storm controls for various subregions. Therefore, by trial and error, the storm that produced the most conforming PMP results was found from a master list of controlling storms. The selected storm occurred in Elba, Alabama, in March 1929 (U.S. Dept. of Commerce 1965).

In contrast to the bottom-up methodology used for PMP recalculations at the UARW and ORW, a top-down approach was used to recalculate the PMP at the Holston River Watershed using observational dew point trends. Instead of looking at the sensitivity of PMPs to land-induced mesoscale climate change, an analysis of the sensitivity of PMPs to an increase in dew point alone was performed. Numerical modeling of the Elba storm for various LULC scenarios was not feasible given the absence of atmospheric forcing data dating back to 1929 to run the RAMS model. Thus, the PMP recalculation was performed on the basis of a projected trend in dew points derived from a long observational record. A study by Robinson (2000) collected nearly 40 years of dew point data across the United States from 178 stations to establish dew point trends occurring over long periods in various regions of the United States. The vast amounts of data were analyzed and indicated an increase of slightly greater than 1.8°F (1°C) over 100 years in the spring and autumn seasons. This long-term study over a widespread area is used to recalculate a nonstationary PMP for the Holston River Watershed. The maximum persisting 12-h dew point chart for March (the month of the controlling storm) was adjusted to accommodate the 1.8°F average dew point increase over a 100-year period. For convenience, a 111-year period corresponding to a 2°F increase in dew point was chosen for this calculation.

Results and Discussion

Upper American River Watershed

The recalculated PMP values for the UARW using RAMS climate model data for each LULC change scenario are shown in Table 1. The increase in PMP values using mesoscale anthropogenic climate variability is substantial. A comparison between the control and nonirrigation scenarios shows a 5.4% difference in PMP, suggesting a significant PMP intensification (i.e., magnification) caused by an influx of irrigation around the reservoir. The two highest nonstationary PMP values result from situations where both the reservoir and irrigation are in place (control and reservoir-double scenarios). This shows the impact of impounded reservoirs and irrigation on the intensification of the water cycle, leading to potentially serious nonstationarity and a rising trend in extreme precipitation. It can be inferred from the other two scenarios (nonirrigation and predam) that irrigation has a much larger impact on atmospheric intensification than reservoir size, but both contribute to a notable increase in overall PMP. Proactive accounting for postdam irrigation development appears essential for the development of more robust PMP variables for the design of large dams.

Owyhee River Watershed

The recalculated nonstationary PMP values for the Owyhee River Watershed for various LULC change scenarios are shown in Table 2. The control and reservoir-double scenarios dominate, whereas nonirrigation and predam scenarios yield the lowest change to PMP values. However, unlike the Upper American River Watershed, the nonirrigation scenario produces a higher PMP value than the predam scenario in the Owyhee River Watershed. It appears that the reservoir has a larger influence on atmospheric water

Table 1. Nonstationary 72-h PMP Values for Various LULC Scenarios for Upper American River Watershed (Using RAMS Numerical Modeling Data)

Scenario	PMP (in.)	% increase from HMR-PMP	% change from RAMS control
HMR 59 (stationary)	24.67	—	—
RAMS control	29.22	18.4	—
RAMS reservoir-double	29.53	19.7	1.1
RAMS nonirrigation	27.65	12.1	−5.4
RAMS predam	28.44	15.3	−2.7

Table 2. Nonstationary 72-h PMP Values for Various LULC Scenarios for the Owyhee River Watershed (Using RAMS Numerical Modeling Data)

Scenario	PMP (in.)	% increase from HMR-PMP	% change from RAMS control
HMR 57 (stationary)	5.38	—	—
RAMS control	14.38	167.3	—
RAMS reservoir-double	15.34	185.1	6.7
RAMS nonirrigation	12.62	134.6	-12.2
RAMS predam	11.84	120.1	-17.7

cycle intensification than does the vegetation cover in the predam era. This is a likely result of the leeward side of the mountain on which the reservoir is located. The leeward side of the mountain is dominated by LULC changes caused by the rain shadow effect, whereas the windward side experiences moisture contributions from the Pacific, which may mask any localized impact of LULC changes. Previous research supports this conclusion (Woldemichael et al. 2013b, a).

The difference between the nonstationary PMP values and HMR 57 PMP values (for the Owyhee River Watershed) is significant when compared with the Upper American River Watershed results (an increase of 167.3 and 185.1% for the control and reservoir-double scenarios, respectively, compared with an 18.4 and 19.7% increase in Folsom Dam for the same scenarios). The discrepancy can be attributed to an upper computational limit used for the in-place maximization factor (IPMF) (the insitu moisture maximization value before transposition) in HMR 57 (U.S. Dept. of Commerce 1994). The maximization factor for the LULC change scenarios using the RAMS model was 6.57, whereas a limit of 1.7 is set in HMR 57. The difference in calculated dew point when compared with maximum dew point for the time of year of the storm's occurrence in the RAMS model was substantial, leading to a large maximization factor. However, because the storm is reproduced over the ORW in the RAMS model, no transposition factor was introduced. Whereas the IPMF has an upper limit in HMR 57, the transposition factor does not. Because the IPMF and transposition factors cannot be separated for an in situ scenario, a direct comparison between HMR-PMP and RAMS-PMP for the ORW (and only the ORW) is difficult. Nonetheless, wisdom can still be obtained from the impact of LULC change on this watershed.

Holston River Watershed

For the Holston River Watershed (HRW), both HMRs 41 and 51 contribute to PMP calculations because of the orography introduced by the Appalachian Mountains. The PMP values published in these reports are not concentric isohyets as found in HMRs 57 or 59. Rather, they are shown as isolines extending from the East Coast to the 105th meridian near the foothills of the Rocky Mountains. The recalculated PMP values using a rise of 2°F per 111 years are compared with the values in HMRs 41 and 51 are presented in Table 3. The values in boldface correspond to the approximate average latitude of the HRW. These values are reduced to the area of the HRW (3,747 sq mi) and shown in Table 4. Substituting projected trends of dew point rise into the HMR procedure produced an approximately 2.4-in. 72-h PMP increase for the Holston River Watershed. This estimation is directly tied to a 2°F rise in average dew point rather than a concrete estimation for a 111-year period because of the intrinsic uncertainty in climate projections.

Table 3. Recalculated PMP Values for 10,000 sq mi over Eastern United States

Approximate latitude (east of Mississippi River)	24-h PMP (HMR)	24-h PMP (projected)	72-h PMP (HMR)	72-h PMP (projected)
39N	9.89	11.48	13.85	16.07
38N	11.48	12.69	16.07	17.77
37N	**12.69**	**14.00**	**17.77**	**19.60**
35N-37N	13.33	14.69	18.66	20.57
34N-35N	14.00	15.43	19.60	21.60
33N-34N	14.69	16.20	20.57	22.68
33N	15.43	17.00	21.60	23.81
32N	16.20	17.86	22.68	25.01
31N	17.00	18.76	23.81	26.26

Note: The values in boldface correspond to the approximate average latitude of the HRW.

Table 4. Nonstationary 72-h PMP Values for the Holston River Watershed (Using Observed Dew Point Trends)

Approximate latitude (east of Mississippi River)	10,000 sq mi PMP (HMR)	10,000 sq mi PMP (projected)	HRW PMP (HMR)	HRW PMP (projected)
39N	14.5	16.1	19.3	21.4
38N	16.1	17.8	21.4	23.7
37N	**17.8**	**19.6**	**23.7**	**26.1**
35N–37N	18.7	20.6	24.9	27.4
34N–35N	19.6	21.6	26.1	28.8
33N–34N	20.6	22.7	27.4	30.2
33N	21.6	23.8	28.8	31.7
32N	22.7	25.0	30.2	33.3
31N	23.8	26.3	31.7	35.0

Note: The values in boldface correspond to the approximate average latitude of the HRW.

Conclusions

The key findings of the hindsight investigation of HMR-PMP values with nonstationary climate forcings can be summarized as follows:

1. Irrigation has the largest LULC impact on PMP intensification. Removing irrigation from the RAMS control scenario lowered the PMP by 5.4% for the UARW and by 12.2% for the ORW.
2. Using atmospheric modeling–derived persisting dew point indicates that PMPs for dams on the leeward side of mountains are more affected by LULC change than those located on the windward side.
3. Observed trends in dew point records point to a noteworthy rise in PMP values for watersheds east of the 105th meridian should current dew point trends continue. A 2.4-in. (10.1%) 72-h PMP increase may be expected for the HRW for a 2°F rise in average dew point.

These findings have profound implications for the aging water resources infrastructure of the United States. The aging of existing hydraulic infrastructure designed under the assumption of PMP stationarity is now of significant concern. An additional compounding risk, particularly for dams, stems from natural aging and loss of storage through sedimentation, a topic that is relatively much better understood (Graf 1999, 2006; Graf et al. 2010), for the 85% of the U.S. dams that will be more than 50 years old in 2020 (Hossain et al. 2009). Gradual loss of storage reduces the routing potential of a flood wave and makes the downstream flood risk posed by the probable maximum flood, which is derived from PMP, more enhanced. Thus, the implications of the recalculation of nonstationary PMP values should now trigger a discussion on how best to leverage this understanding for better risk assessment and adaptation.

It is highly recommended that a reevaluation of existing and aging dams designed with static HMR-PMP values be performed, taking into account projected climate trends attributed to global warming and predicted LULC changes in the postdam era, both of which are known to affect extreme rainfall processes. Also, prospective dams should be constructed with the assumption of a dynamic PMP variable. The purpose of the dam (e.g., hydropower, irrigation, recreation) gives a relatively accurate indication of the LULC changes that will take effect after completion, which can be taken into account proactively during design stages together with the impacts expected from global warming trends should they continue into the future.

Global climate projections attributed global warming or observational trends also need consideration during PMP development. The progression of historical climate behavior can be used to approximate climate conditions over the intended lifetime of a dam. The future climate conditions that produce maximum PMP values should be used in conjunction with expected LULC change to produce a PMP variable more representative of the nonstationarity of the climate system.

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