Comparison of PMP-Driven Probable Maximum Floods with Flood Magnitudes due to Increasingly Urbanized Catchment: The Case of American River Watershed

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ABSTRACT: Since historical (predam) data are traditionally the sole criterion for dam design, future (postdam) meteorological and hydrological variability due to land-use and land-cover change cannot be considered for assessing design robustness. For example, postdam urbanization within a basin leads to definite and immediate increase in direct runoff and reservoir peak inflow. On the other hand, urbanization can strategically (i.e., gradually) alter the mesoscale circulation patterns leading to more extreme rainfall rates. Thus, there are two key pathways (immediate or strategic) by which the design flood magnitude can be compromised. The main objective of the study is to compare the relative contribution to increase in flood magnitudes through direct effects of land-cover change (urbanization and less infiltration) with gradual climate-based effects of land-cover change (modification in mesoscale storm systems). The comparison

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is cast in the form of a sensitivity study that looks into the response to the design probable maximum flood (PMF) from probable maximum precipitation (PMP). Using the American River watershed (ARW) and Folsom Dam as a case study, simulated peak floods for the 1997 (New Year's) flood event show that a 100% impervious watershed has the potential of generating a flood that is close to design PMF. On the other hand, the design PMP produces an additional 1500 $m^3 s^{-1}$ peak flood compared to the actual PMF when the watershed is AU1 considered 100% impervious. This study points to the radical need for consideration future land-cover changes up front during the dam design and operation formulation phase by considering not only the immediate effects but also the gradual climatic effects on PMF. A dynamic dam design procedure should be implemented that takes into account the change of land–atmospheric and hydrological processes as a result of land-cover modification rather than relying on historical records alone.

KEYWORDS: Dams; Land use and land cover; Urbanization; Imperviousness; Probable maximum precipitation; Probable maximum flood

1. Introduction

The transformation of forestland to urbanized impervious areas can change the runoff generation potential of a given area in a watershed on a large scale. Increases in population, economic opportunities, and migration can also result in greater urbanization (DeFries and Eshleman 2004; Cohen 2003). In general, human activities are the most land-cover-altering factors that lead to a change in the distribution of runoff patterns (Alberti 1999).

Under a normal hydrological cycle process, precipitation that falls on an area goes through the processes of infiltration, evapotranspiration, and runoff (Konrad and Booth 2005; Dunne and Black 1970). Once a natural area becomes impervious, because of urbanization, some of the hydrological cycle components, such as infiltration and runoff, are highly affected. More direct runoff and less infiltration are the immediate responses to urbanization (Gregory et al. 2006; Yang et al. 2011), while an imbalance in the water cycle is also observed as groundwater recharge decreases because of less infiltration. According to a study by Scanlon et al. (Scanlon et al. 2005), the change of rangeland into agricultural land in Amargosa Desert (Nevada) and in the high plains (Texas) has changed the direction of groundwater flow from upward to downward. This was attributed to change in soil property and an increase in evapotranspiration from irrigated lands.

The above response of the water cycle to land-cover change is immediate and can be treated as "tactical." There is a more gradual response, akin to climatic change, that can also be a response of water cycle to land cover changes. Such a change can be called "strategic" and is described through the following example. Presence of a dam (here used interchangeably with artificial reservoirs) can facilitate urbanization both on the upstream and downstream side. Construction of dams is still one of the socioeconomic solutions that are adapted by most developing countries (Biswas and Tortajada 2001). In recent decades, the climatic impact of change of land use and land cover (LULC) on local, regional, and global climate has been the subject of intensive research (Woldemichael et al. 2012; Degu et al. 2011; Hossain et al. 2011; Yang et al. 2011; Mishra et al. 2010; Niehoff et al. 2002). Impacts of LULC changes on the hydrological process via atmospheric processes (changes in rainfall patterns) appear to be less understood, even though the impacts on the atmospheric process per se have been relatively better studied (see Cotton and Pielke 2007 for a comprehensive review). At a minimum, there can be a spatial shift and storm modification in rainfall patterns due to the presence of artificial reservoirs and their associated LULC change (Woldemichael et al. 2012). Most of the time, the modification is in the form of an increase, resulting in a corresponding increase in peak flow (Gross and Moglen 2007). The recurrence interval and intensity of flood events also increase as a result of LULC transformation combined with the increased AU2 frequency of LULC change–driven precipitation patterns (Wahren et al. 2009), and a subsequent impact on dam design flood parameters is expected (Rodriguez-Iturbe 2000).

Thus, there are two ‘‘competing’’ scales and pathways via which the future pattern of hydrological response to precipitation and reservoir inflow can be altered. One is the tactical (immediate) terrestrial pathway of less precipitation infiltrating and resulting in more direct runoff. The other is the strategic (gradual) and atmospheric pathway of more intense precipitation patterns from LULC change–driven mesoscale storm patterns, which can also result in more direct runoff. Because the former pathway is already better understood by the hydrologic community, the interrelation between change in LULC and regional weather/climate patterns now needs to be an added consideration for future sustainable development of impounded river basins. The scale at which LULC changes impact atmospheric patterns varies based on the process that is affected. In general, such impacts are less observed in larger scales (Blöschl et al. 2007). The atmospheric process can be affected to a larger extent than hydrological processes as these hydrological processes are bounded by physical watershed boundary unlike atmospheric processes (Woldemichael et al. 2012; Yigzaw et al. 2012). The worst case is when both the atmospheric and hydrologic processes are significantly ‘‘synergized,’’ resulting in a catastrophic flood over the watershed. Some studies (Vörösmarty et al. 2004) have shown that the impact of LULC change sometimes outweighs, in some cases, the impact of global climate change modeled by general circulation models (GCMs).

This study underscores the special importance dams have for society. In the United States alone, there are more than 75 000 dams capable of storing almost one AU3 year's mean runoff of the nation (Graf 1999). Around the world, the World Commission on Dams (WCD) estimates about 45 000 large dams built over the last 80 years. It is estimated that half of the world's rivers have at least one dam somewhere AU4 along the reach (WCD 2000). Thus, for dams in particular, the competing pathway to modification of hydrological process during the postdam period is the cornerstone of any technique for assessing future resilience of dam–urban infrastructure.

Bronstert et al. (Bronstert et al. 2002) examined flooding as a result of changes in land use and climate in Germany. They used regional climate models (RCMs) and the Water Flow and Balance Simulation Model of the Eidgenössische Technische Hochschule (WaSiM-ETH) hydrological model (Schulla 1997). Changes in meteorological parameters, as a result of climate change, highly affected the runoff generation pattern of the catchment under study. On the other hand, runoff from high-intensity AU5 precipitation was significantly affected by the land-cover condition than precipitation of less intensity. In this regard, the city of Can Tho, Vietnam, is a good example where a combination of runoff increase due to urbanization and climate change has now posed a great challenge for flood management (Huong and Pathirana 2011).

Since historical (predam) data are traditionally the sole criterion for dam design, future (postdam) meteorological and hydrological variability due to land-use and land-cover change cannot be considered for design robustness. The stationarity assumption implicit in such historical data used for dam design is being challenged (Woldemichael et al. 2012; Yigzaw et al. 2012; Degu et al. 2011; Douglas and Fairbank 2011; Hossain et al. 2011; Milly et al. 2008; Stedinger and Griffis 2008), forcing the consideration of future artificial reservoirs and LULC change in this design process. In a U.S. federal dam design handbook for small dams, the likely combination of both or at least such pathway was reported to be catastrophic in a Texas watershed, where the peak flow had increased eightfold from the design value during the postdam period (USBR 1987).

This study is an extension to Yigzaw et al. (Yigzaw et al. 2012) that analyzed of the impact of Folsom Dam over the American River watershed (ARW). In Yigzaw et al. (Yigzaw et al. 2012), the impact of different probable maximum precipitation (PMP) values (obtained from numerical atmospheric model reported in Woldemichael et al. 2012) on probable maximum flood (PMF) has been studied. The question addressed in that study was as follows: How do reservoirs and/or LULC change modify extreme flood patterns, specifically probable maximum flood through local atmospheric feedback mechanisms? Study of PMP/PMF is necessary as flood used for dam design is PMF (or a fraction of it), which is decided by the designer's criteria AU6 and the risk assessment (FEMA 2004). The results from Yigzaw et al. (Yigzaw et al. 2012) have shown that the size of reservoirs has marginal impact on PMF modification. However, there is a considerable modification in the PMF between predam and postdam periods. Irrigation practice downstream of Folsom Dam was also found to impact the value of PMF. Yigzaw et al. (Yigzaw et al. 2012) had clearly studied the strategic pathway via which the PMF patterns can get modified in the postdam period. A key missing element was the study of the tactical (terrestrial) pathway and comparing it with the strategic pathway to understand the relative contribution of each and the potentially worst-case scenario (when both pathways synergize to create the most catastrophic flooding into the reservoir).

The main objective of the current study is therefore to answer the following questions: 1) To what extent does urbanization of a watershed increase peak flood via the tactical–terrestrial pathway? 2) Is an intensively urbanized watershed with normal (nonimpacted) precipitation storm (i.e., tactical pathway) more catastrophic than a watershed impacted by an increase in probable maximum precipitation due to LULC change–driven atmospheric processes (i.e., strategic pathway)? 3) What is the potentially worst-case scenario of flooding when there is synergy between both pathways to magnify the impact of one on the other? Answering these questions can strengthen the need to consider future land development and urbanization plans to the dam design procedure.

Section 2 of this paper introduces the study area and its attributed characteristics. In section 3, methodology, model used, and data type and sources are explained. Results, discussion, and conclusions are provided in section 4.

2. Study area

The study area selected is the ARW above Folsom Dam, California. Folsom Dam was constructed by the U.S. Army Corps of Engineers (USACE) in 1956 for multiple purposes at a location 32 km northeast of the city of Sacramento (USBR 1999). The total watershed area contributing to the reservoir is 4823 km^2 (USACE 2005) (Figure 1, bottom). Since its construction, flood protection of downstream areas (e.g., the city of Sacramento) has improved. However, changes in flood frequency and intensity have also changed during most of the postdam period.

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However, catastrophic floods have occurred in 1964, 1986, and 1997. These floods have put the downstream area of Sacramento at higher risk and posed considerable economic loss (Cowin et al. 2011). More importantly, these floods events have also forced engineers to reevaluate the design flood (National Research Council 1999) and ultimately redesign auxiliary spillway for Folsom Dam (USBR 2007). Currently, Sacramento remains one of the most flood-prone cities (ranked second next to New Orleans after the occurrence of Hurricane Katrina) in the United States (O'Neill 2006). Most regions of Sacramento County are protected from flood by the Folsom Dam, levee, bypass, and canal structures (Cowin et al. 2011). Design flood parameters of these flood control structures have been exceeded most of the time (James and Singer 2008; NRC 1999).

The LULC of ARW is characterized to be mostly forest land based on unsupervised classification of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) (Fry et al. 2011; Homer et al. 2007; Vogelmann et al. 2001). Most of the LULC changes occur downstream of Folsom. Figure 1 shows LULC of the study area in 1992 (bottom-left panel), 2001 (bottom-middle panel), and 2006 (bottom-right panel). Less change is observed in the upstream area, while urbanization has intensified around Fair Oaks and city of Folsom. The fact that the watershed is less urbanized makes it more suitable for our study to consider realistic future scenarios of LULC change and imperviousness under population pressure and economic development.

3. Data and methodology

3.1. Methodology

3.1.1. General approach

The objective of this study is to illustrate how urbanization in an impounded watershed can affect flood generation into an artificial reservoir. To achieve this, hypothetical but realistic future land-use and land-cover scenarios are considered for ARW. First, the actual LULC was used to simulate floods with actual observed precipitation storms and PMP. Here urbanization is represented in a form of impervious area that affects only infiltration rate and soil moisture recharge. It is clear urbanization does not result in 100% imperviousness: for example, in city parks and other recreation areas. However, since different percentages of imperviousness are used in an incremental way, the maximum impervious fraction for urban landscapes has been considered to be 100% for a quantitative illustration of its effect.

Gridded representation of the watershed at a scale of 0.125° (~12.5 km) was used (Figure 2). Precipitation and other input data are distributed in a similar manner. A given fraction of an area contributing to runoff generation is assumed to be impervious. Since the hydrological model used for simulation used grids to represent the watershed, the impervious areas considered were uniformly distributed over the

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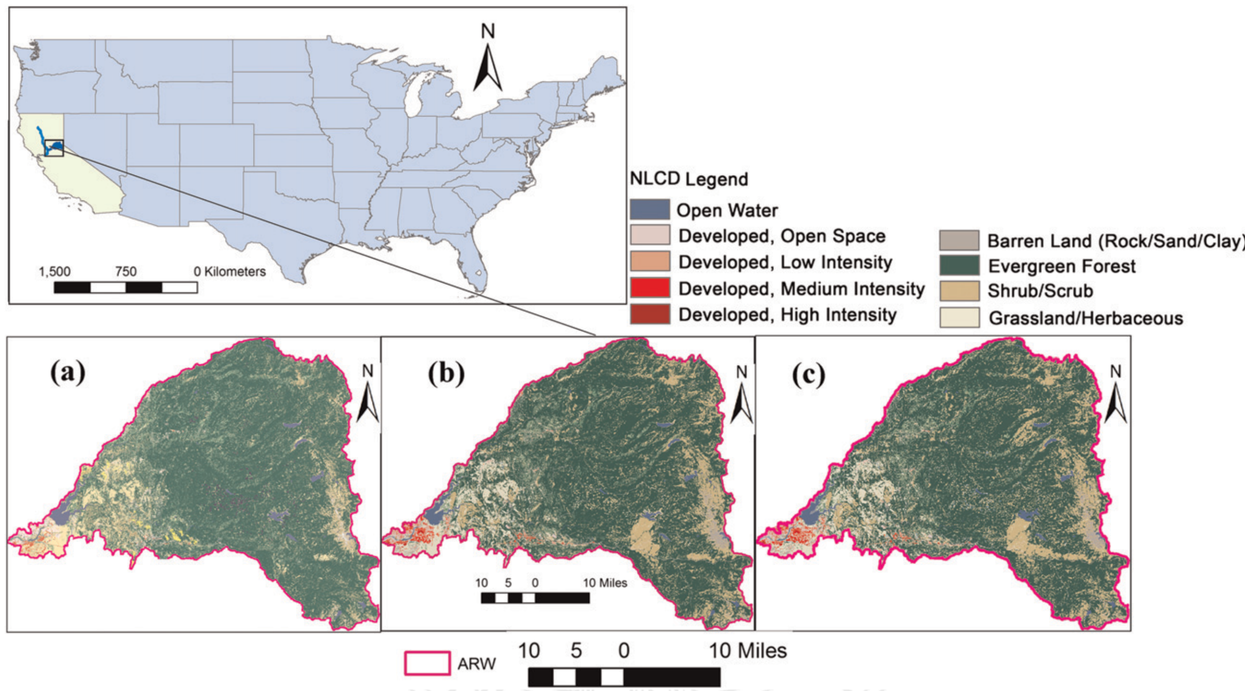

Figure 1. ARW location and land use and land cover for the years (a) 1992, (b) 2001, and (c) 2006 from the National Land Cover Dataset (NLCD).

Fig. 1 live 4/C

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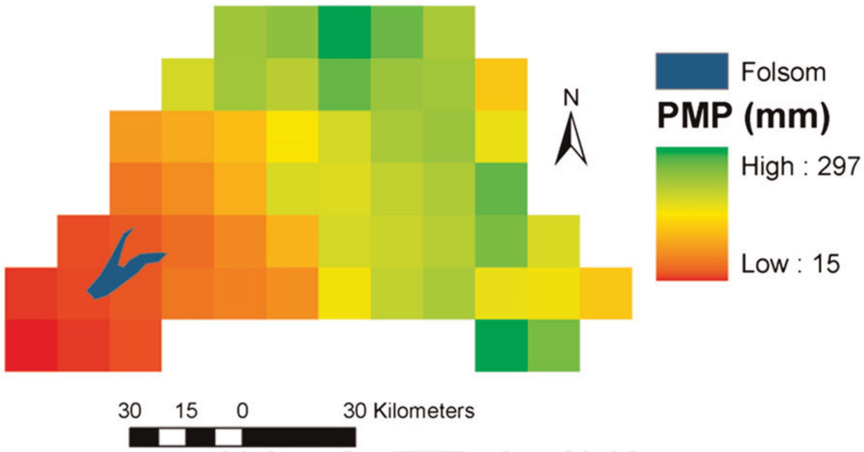

Figure 2. Gridded daily precipitation representation over ARW.

watershed. The runoff generation code of the model was modified to consider infiltration only for the area that is not impervious. For example, for an assumed grid of 20% impervious area, only 80% of the area is considered in the infiltration equation while the 20% contributes to a 100% direct runoff. This fraction was varied between 10% and 100% to simulate the corresponding floods into the reservoir. These areas are assumed to be effective impervious areas (EIA) that result in direct runoff without any infiltration (Yang et al. 2011).

3.1.2. Hydrological model

The Variable Infiltration Capacity (VIC) model (Liang et al. 1994; Liang et al. 1996) was used to simulate the runoff fluxes distributed over the watershed. This model is coupled to a routing model (Lohmann et al. 1996) to generate streamflow at a location near Fair Oaks, which is the location for calibration and verification. The VIC model allows variable infiltration and evaporation over a given area (grid cell) for different vegetation cover and topography. The spatial resolution used to represent the study area was 0.125° (~12.5 km), while a daily temporal scale was used for both runoff flux and routing. A finer temporal resolution was not possible for this case because the routing model had the limiting temporal unit of 24 h (Lohmann et al. 1996), which can be a limitation to demonstrate a clear sensitivity of hydrography for changing peak floods. The model was calibrated using observed flow at Fair Oaks, California (for details, see Yigzaw et al. 2012). The years of 1997 and 1999 are used for calibration and verification, respectively. Performance
T1 metrics of the calibrated and verified model are shown in Table 1.

3.2. Data

Gridded precipitation and other meteorological data (temperature and wind speed) with daily temporal and 0.125° (~12.5 km) spatial resolution are used as inputs into the VIC model. The data were obtained from the Surface Water Modeling

Fig. 2 live 4/C

Table 1. VIC model performance metrics (Yigzaw et al. 2012).

	Calibration period (1996/97–98)	Validation period (1998–99)
Nash Sutcliffe	0.74	0.58
PBIAS	−35.0%	−19.0%
R^2	0.77	0.65
RSR	0.5	0.65

group at the University of Washington from their website (http://www.hydro.washington.edu/Lettenmaier/Data/gridded/), the development of which is described by Hamlet and Lettenmaier (Hamlet and Lettenmaier 2005). Other input data of soil, vegetation parameter, and vegetation library are obtained from the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml).

A previous study by Woldemichael et al. (Woldemichael et al. 2012) reported simulated PMPs over ARW using an atmospheric model called the Regional Atmospheric Modeling System (RAMS; Cotton et al. 2003; Pielke 2001; Pielke 1992) at an hourly time scale and about 3-km spatial scale. The PMP data were based on the strategic pathway of atmospheric process change assuming different LULC change scenarios over ARW (most of them downstream of Folsom Reservoir). Yigzaw et al. (Yigzaw et al. 2012) extended the study of Woldemichael et al. (Woldemichael et al. 2012) by converting the PMP data into simulated PMF hydrograph data for the same LULC change scenarios.

In this study, PMP values were used to simulate PMF using actual (current–post-2000 condition) LULC and various hypothetical but future realistic impervious scenarios. The PMP hyetograph was fixed, and the reader should refer to Yigzaw et al. (Yigzaw et al. 2012) for more details. Observed precipitation patterns were simulated by the numerical model used in Woldemichael et al. (Woldemichael et al. 2012) to yield a space–time distributed format needed for simulation by VIC to PMF. The study period selected was from 25 December 1996 to 10 January 1997. This period coincides with a significant flood event that occurred in Sacramento more popularly known as the New Year's flood that led to significant revision of Folsom Dam's design and operation specifications. To understand the impact of urbanization objectively, only the peak flood magnitudes are compared for different impervious scenarios.

4. Results and conclusions

4.1. Different impervious scenario with actual precipitation storms

Peak floods for actual and hypothetical impervious areas scenario were simulated using the hydrological model VIC coupled to a routing model (Figure 3). It is apparent that a 100% impervious area would generate the maximum flood response from a given catchment. Land cover has a significant impact in peak flow seasonality, volume, and sediment process over a watershed (García-Ruiz et al. 2008). Transformation of natural vegetated land into impervious land increases direct runoff by decreasing infiltration in to the soil. An increase in impervious area as a result of urbanization also affects the time of concentration (attributed to increase in flow velocity), provided that flow regimes are large enough to avoid flow

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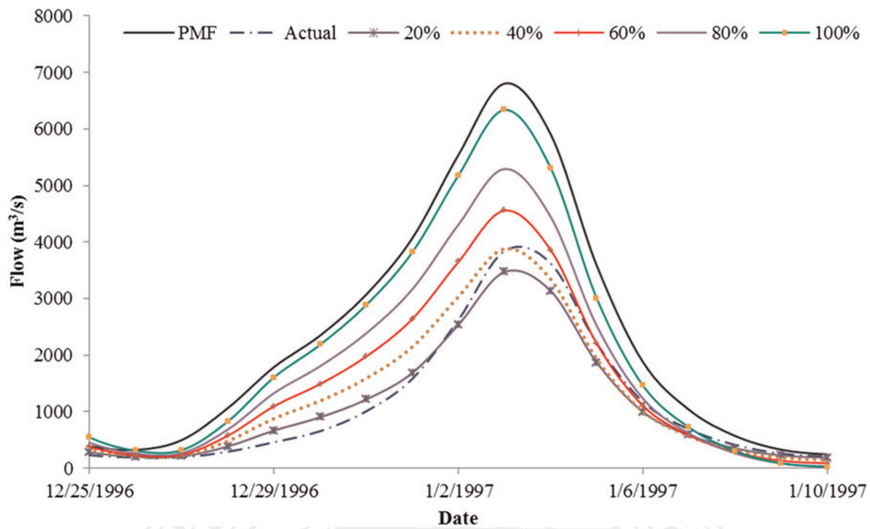

Figure 3. Simulated flow for different impervious area fractions over ARW.

obstruction (Haan et al. 1994, 75–76). A faster runoff response of upstream area means an increase in the reservoir inflow rate. This can be a major problem for reservoir and spillway operation in cases when such flow rates were not considered possible during dam design phase.

Figure 3 shows simulated flow for different hypothetical impervious area percentages over ARW for the 1997 flood event period. The peak flow for actual LULC simulated using an observed (New Year's event) precipitation storm is close to the hypothetical scenario with 40% impervious area. One of the key reasons for this apparent discrepancy is likely the antecedent soil moisture of actual LULC, which can result in an expanded saturated soil (nonimpervious) area with saturated soil moisture and hence infiltration excess phenomenon (Bronstert et al. 2002). This also underscores the high degree of nonlinearity that a watershed exhibits in transforming rainfall to peak flood magnitude. Since a uniform distribution of impervious area is used in the simulation, there is also a discrepancy in the development of saturated soil between the hypothetical scenarios and the actual LULC. This highlights the effect a spatial distribution of LULC might have on runoff generation. The general response of the watershed for larger percentage impervious area is understandable as most watersheds show sensitivity in increase of flood starting from an impervious area as small as 3% (Yang et al. 2010).

One of the objectives of this study was to demonstrate if an increase in imperviousness of a watershed generated more peak flood from an observed storm event than the PMF derived from PMP under the current LULC scenario. Comparison of the simulated peak for a 100% impervious area and the PMF from the actual LULC shows that the two flood peaks are indeed very close (Figure 3). This shows that there is a greater risk in urbanizing upstream areas within an impounded basin when the PMP-type event occurs under a scenario of increasing imperviousness. If the PMP event (which has not considered future LULC in its estimation) is to occur on an area that is transformed because of urbanization, the resulting flood is

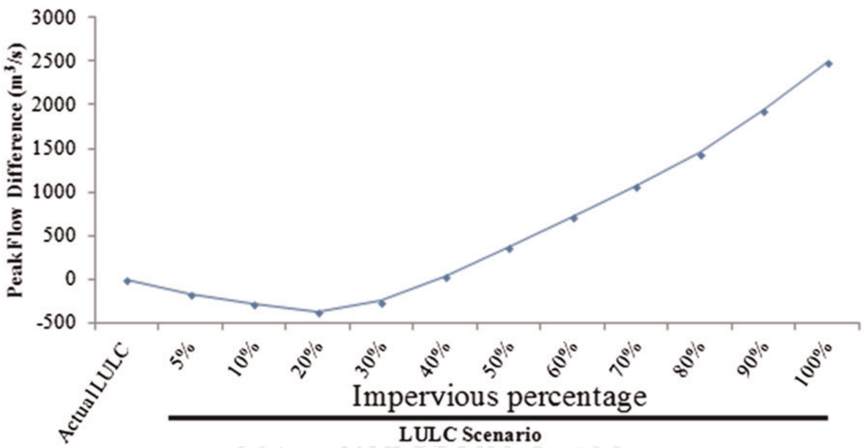

Figure 4. Flow difference for observed precipitation storm event and different impervious area fractions over ARW.

unexpected and catastrophic for downstream areas. This finding highlights the need to consider future LULC development in conjunction with PMP changes from LULC change scenarios for deriving the worst possible peak flood magnitude for high hazard dams (USBR 1987). Figure 4 shows the difference in peak flow for different impervious percentages. Larger impervious areas resulted in a higher increase of peak flow over the watershed. For example, for 40% and 90% impervious areas, there is a 0.01 and 0.4 $m^3 s^{-1}$ increase, respectively, over a 1-km^2 watershed area (Table 2). The change is clearly linear in nature.

4.2. Considering different impervious scenarios with probable maximum precipitation

This case represents a combination of PMP and increase in urbanization (impervious area) to identify the worst possible peak flood magnitude. Woldemichael et al. (Woldemichael et al. 2012) and Yigzaw et al. (Yigzaw et al. 2012) showed that LULC change downstream of an artificial reservoir has an impact on PMP and PMF, respectively. In this study, LULC changes (of increasing imperviousness) were made within the watershed. Figure 5 shows the plot of flows simulated using PMP and different impervious area percentage. However, the flows are shown as a comparison between the peak flood magnitudes obtained using the observed storm (not PMP) and varied imperviousness. The goal of this comparison was to

Table 2. Change in peak flow per watershed area.

	LULC scenario					
		Percentage impervious area				
	Actual LULC	20%	40%	60%	80%	100%
Peak flow difference ($m^3 s^{-1}$)	—	−370	39	715	1452	2496
Difference per watershed area (km^2)	—	−0.08	0.01	0.15	0.30	0.52

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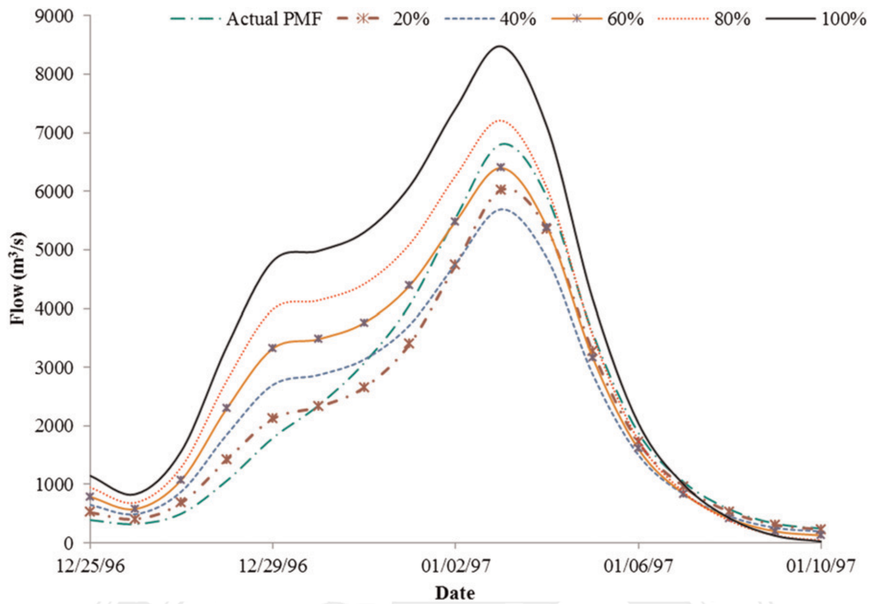

Figure 5. Simulated PMF values for different impervious area fractions over ARW.

understand the additional level of "extreme" nature that the notion of a PMP can add to an urbanizing watershed. Figure 5 shows that there is an increase of more than 2000 $m^3 s^{-1}$ in peak discharge for 100% imperviousness between the observed storm and the PMP. For areas that are less than 100% impervious, higher discharges were still observed. This happens as, in most PMP phenomena, the infiltration capacity is always likely to be exceeded by precipitation intensity.

T3 F6 The worst flood risk can occur if LULC change impacts both hydrological and atmospheric processes together and create a synergy. Table 3 and Figure 6 summarize flood peaks for different LULC and precipitation-type scenarios. The peak results show that the peak flood due to the observed precipitation storm and 100% impervious area can be generated with a 60% impervious area and the PMP (cf. Figures 2, 4). A PMP-scale storm event over a 100% impervious watershed, which represents the most efficient runoff producing scenario, resulted in about 1500 $m^3 s^{-1}$ more peak flood magnitude. This is an indication of the how the combination of LULC modification and PMP alteration can yield the worst-case scenario of flooding for designing a dam. Such comparisons provide a reference for engineers to proactively consider future anticipated LULC scenarios vis-à-vis LULC-driven PMP changes during the design phase of a large dam project.

Table 3. Summary of peak floods for different LULC and precipitation type.

		Runoff ($m^3 s^{-1}$)					
			Percentage impervious area				
Date	Precipitation type	Actual LULC	20%	40%	60%	80%	100%
3 Jan 1997	Observed	3841	3471	3880	4557	5293	6337
	PMF	6803	6022	5691	6396	7207	8475

Fig. 5 live 4/C

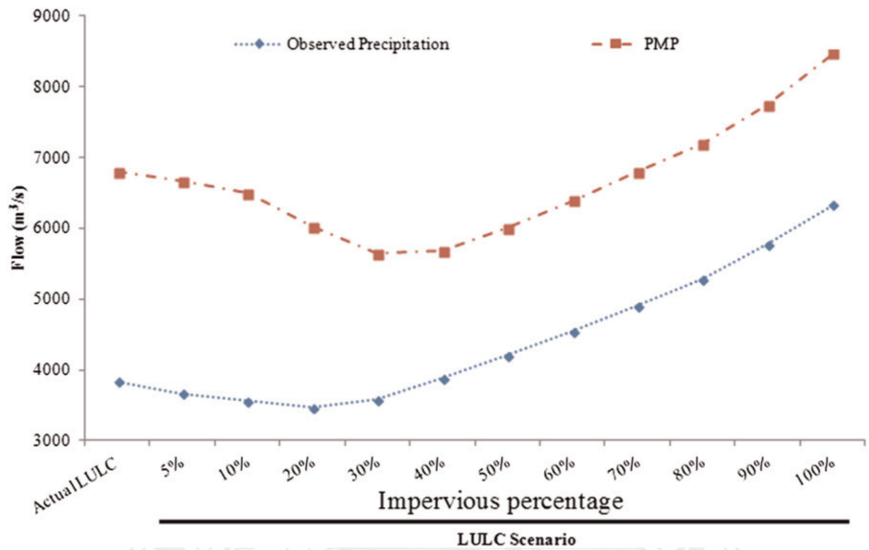

Figure 6. Comparison of impact of impervious area on observed precipitation and PMP over ARW.

This study considered two key pathways (immediate/tactical and gradual/strategic) by which the design flood magnitude can be compromised during the postdam phase. The key objective of the study was to compare the relative contribution to increase in flood magnitudes through direct effects of land-cover change (urbanization and less infiltration) with the more gradual climate-based effects of land-cover change (modification in mesoscale storm systems). The study was cast in the form of a sensitivity study that looked into the response to the design probable maximum flood (PMF) from probable maximum precipitation (PMP). Though the idea that PMP/PMF is never to be exceeded seems to be realistic, there should be an adjustment in to their estimation and hence the design parameters used for dams. Our study pointed to the radical need for consideration future land-cover changes more upfront during the dam design and operation formulation phase by considering not only the immediate terrestrial effects but also the gradual climatic effects on PMF. A dynamic dam design procedure should be implemented that takes in to account the change land–atmospheric and hydrological processes as a result of land-cover modification.

Transformation of LULC upstream of artificial reservoirs can increase the flood generation potential of the watershed. A storm with a high frequency of occurrence can have the same effect of a low-exceedance probability flood if urbanization has rapidly altered large portions of a watershed in a short period. Thus, there is a great danger to human lives and other economic losses from floods that are beyond the capacity of control mechanisms such as dams and levees. The interaction between land surface and atmosphere also leads to potential increase in PMP and PMF in the postdam phase. Sediment transport and yield pattern are also affected as a result of such interrelationships. Better understanding of the impact of one component on the other and incorporating such knowledge into water resources management is vital for our ever-changing world that is increasingly relying on dams. Urbanization is unavoidable with increase in population, economic opportunities, and migration patterns. The importance of this paper is to the engineering community and decision makers that are involved in the development of water resources (specifically artificial reservoirs).

The engineering community should always pursue design procedures that embrace future changes in climate, hydrology, and LULC patterns. A dynamic design procedure that considers multiple competing scenarios in the future to identify the worst-case peak flood magnitude is likely to yield a more robust design than one that relies purely on historical records and the assumption of stationarity.

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References

Alberti, M., 1999: Urban patterns and environmental performance: What do we know? *J. Plann. Educ. Res.,* **19,** 151–163.

Biswas, A. K., and C. Tortajada, 2001: Development and large dams: A global perspective. *Water Resour. Dev.,* **17,** 9–21.

Blöschl, G., and Coauthors, 2007: At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrol. Processes,* **21,** 1241–1247, doi:10.1002/hyp.6669.

Bronstert, A., D. Niehoff, and G. Bürger, 2002: Effects of climate and landuse change on storm runoff generation: Present knowledge and modelling capabilities. *Hydrol. Processes,* **16,** 509–529.

Cohen, J. E., 2003: Human population: The next half century. *Science,* **302,** 1172–1175, doi:10.1126/science.1088665.

Costa, M. H., A. Botta, and J. A. Cardille, 2003: Effects of large-scale changes in land cover on the
AU7 discharge of the Tocantins River, southeastern Amazonia. *J. Hydrol.,* **283,** 206–217.

Cotton, W. R., and R. A. Pielke Sr., 2007: *Human Impacts on Weather and Climate.* Cambridge University Press, 288 pp.

——, R. L. McAnelly, and T. Ashby, 2003: Development of new methodologies for determining extreme rainfall. University of Colorado Department of Natural Resources Rep., 143 pp. [Available online at http://rams.atmos.colostate.edu/precip-proj/overnow/index.html.]

Cowin, M. W., and Coauthors, 2011: 2012 Central Valley flood protection plan. California Department of Water Resources Central Valley Flood Management Planning Program Rep., 162 pp.

DeFries, R., and K. N. Eshleman, 2004: Land-use change and hydrologic processes: A major focus for the future. *Hydrol. Processes,* **18,** 2183–2186.

Degu, A. M., F. Hossain, D. Niyogi, R. A. Pielke Sr., J. M. Shepherd, N. Voisin, and T. Chronis, 2011: The influence of large dams on surrounding climate and precipitation patterns. *Geophys. Res. Lett.,* **38,** L04405, doi:10.1029/2010GL046482.

De Michele, C., G. Salvadori, M. Canossi, A. Petaccia, and R. Rosso, 2005: Bivariate statistical approach to check adequacy of dam spillway. *J. Hydrol. Eng.,* **10,** 50–57, doi:10.1061/
AU8 (ASCE)1084-0699(2005)10:1(50).

Douglas, E. M., and C. A. Fairbank, 2011: Is precipitation in northern New England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. *J. Hydrol. Eng.,* **16,** 203–217, doi:10.1061/(ASCE)HE.1943-5584.0000303.

Dunne, T., and R. D. Black, 1970: An experimental investigation of runoff production in permeable soils. *Water Resour. Res.,* **6,** 478–490, doi:10.1029/WR006i002p00478.

Fry, J., and Coauthors, 2011: Completion of the 2006 National Land Cover Database for the conterminous United States. *Photogramm. Eng. Remote Sens.,* **77,** 858–864.

García-Ruiz, J. M., and Coauthors, 2008: Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. *J. Hydrol.,* **356** (1–2), 245–260, doi:10.1016/j.jhydrol.2008.04.013.

Gregory, J. H., M. D. Dukes, P. H. Jones, and G. L. Miller, 2006: Effect of urban soil compaction on infiltration rate. *J. Soil Water Conserv.,* **61,** 117–124.

Gross, E. J., and G. E. Moglen, 2007: Estimating the hydrological influence of Maryland state dams using GIS and the HEC-1 model. *J. Hydrol. Eng.,* **12,** 690–693, doi:10.1061/(ASCE)1084-0699(2007)12:6(690).

Haan, C. T., B. J. Barfield, and J. C. Hayes, 1994: *Design Hydrology and Sedimentology for Small Catchments.* Academic Press, 588 pp.

Hamlet, A. F., and D. P. Lettenmaier, 2005: Production of temporally consistent gridded precipitation and temperature fields for the continental United States. *J. Hydrometeor.,* **6,** 330–336.

Homer, C., and Coauthors, 2007: Completion of the 2001 National Land Cover Database for the conterminous United States. *Photogramm. Eng. Remote Sens.,* **73,** 337–341.

Hossain, F., A. M. Degu, D. Niyogi, S. Burian, J. M. Shepherd, and R. A. Pielke, Sr., 2011: Climate feedback–based considerations to dam design, operations and water management in the 21st century. *J. Hydrol. Eng.,* **17,** 837–850, doi:10.1061/(ASCE)HE.1943-5584.0000541.

Huong, H. T. L., and A. Pathirana, 2011: Urbanization and climate change impacts on future urban flood risk in Can Tho city, Vietnam. *Hydrol. Earth Syst. Sci. Discuss.,* **8,** 10 781–10 824, doi:10.5194/hessd-8-10781-2011.

James, L. A., and M. B. Singer, 2008: Development of the lower Sacramento valley flood-control system: Historical perspective. *Nat. Hazards Rev.,* **9,** 125–135, doi:10.1061/(ASCE)1527-6988(2008)9:3(125).

Konrad, C., and D. Booth, 2005: Hydrologic changes in urban streams and their ecological significance. *Amer. Fish. Soc. Symp.,* **47,** 157–177.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land surface water and energy fluxes for GSMs. *J. Geophys. Res.,* **99** (D7), 14 415–14 428.

——, E. F. Wood, and D. P. Lettenmaier, 1996: Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications. *Global Planet. Change,* **13,** 195–206.

Lohmann, D., R. Nolte-Holube, and E. Raschke, 1996: A large-scale horizontal routing model to be coupled to land surface parameterization schemes. *Tellus,* **48A,** 708–721.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, 2008: Stationarity is dead: Whither water management? *Science,* **319,** 573–574, doi:10.1126/science.1151915.

Mishra, V., K. A. Cherkauer, D. Niyogi, M. Lei, B. C. Pijanowski, D. K. Ray, L. C. Bowling, and G. Yang, 2010: A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper Midwest United States. *Int. J. Climatol.,* **30,** 2025–2044.

National Research Council, 1999: Improving American river flood frequency analyses. National Research Council Commission of Geosciences, Environment and Resources, 113 pp.

Niehoff, D., U. Fritsch, and A. Bronstert, 2002: Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *J. Hydrol.,* **267,** 80–93.

O'Neill, K. M., 2006: Levee troubles: The cost of making the Sacramento Valley into an agricultural giant. *Sacramento Hist. J.,* **1** (1–4), 73–104.

Pielke, R. A., Sr., 1992: A comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.,* **49,** 69–91.

——, 2001: *Mesoscale Meteorological Modeling.* 2nd ed. International Geophysics Series, Vol. 78, Academic Press, 676 pp.

Rodriguez-Iturbe, I., 2000: Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. *Water Resour. Res.,* **36,** 3–9.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehy, 2005: Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biol.,* **11,** 1577–1593, doi:10.1111/j.1365-2486.2005.01026.x.

Schulla, J., 1997: *Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen.* Zürcher Geographische Schriften, Heft 69, XX pp. AU9

Stedinger, J. R., and V. W. Griffis, 2008: Flood Frequency Analysis in the United States: Time to Update. *J. Hydrol. Eng.* doi:org/10.1061/(ASCE)1084-0699(2008)13:4(199).

USACE, 2005: Stochastic modeling of extreme floods on the American River at Folsom Dam: Flood-frequency curve extension. U.S. Army Corps of Engineers Hydrologic Engineering Center Rep. RD-48, 54 pp.

USBR, 1987: Design of small dams. U.S. Bureau of Reclamations Water Resources Tech. Publ., XX pp. AU10

——, 1999: Hydraulic model study of Folsom Dam spillway performance and stilling basin abrasion. U.S. Bureau of Reclamations Water Resources Research Laboratory Rep., XX pp. AU11

——, 2007: Folsom Dam safety and flood damage reduction (DS/FDR) action. Folsom Joint Federal Project, XX pp. AU12

Vogelmann, J. E., S. M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel, 2001: Completion of the 1990's National Land Cover Data Set for the conterminous United States. *Photogramm. Eng. Remote Sens.,* **67,** 650–662.

Vörösmarty, C., and Coauthors, 2004: Humans transforming the global water system. *Eos, Trans. Amer. Geophys. Union,* **85,** 509–514.

Woldemichael, A. T., F. Hossain, R. A. Pielke Sr., and A. Beltrán-Przekurat, 2012: Understanding the impact of dam-triggered land-use/land-cover change on the modification of extreme precipitation. *Water Resour. Res.,* **48,** W09547, doi:10.1029/2011WR011684.

Yang, G., L. C. Bowling, K. A. Cherkauer, B. C. Pijanowski, D. Niyogi, 2010: Hydroclimatic response of watersheds to urban intensity: An observational and modeling-based analysis for the White River basin, Indiana. *J. Hydrometeor.,* **11,** 122–138.

——, ——, ——, and ——, 2011: The impact of urban development on hydrologic regime from catchment to basin scales. *Landsc. Urban Plan.,* **103,** 237–247.

Yigzaw, W., F. Hossain, and A. Kalyanapu, 2012: Impact of artificial reservoir size and land use/land cover patterns on estimation of probable maximum flood: The case of Folsom Dam on American River. *J. Hydrol. Eng.,* doi:10.1061/(ASCE)HE.1943-5584.0000722.