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Climate change, urbanization, and optimal long-term floodplain protection

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[1] This paper examines levee-protected floodplains and economic aspects of adaptation to increasing long-term flood risk due to urbanization and climate change. The lower American River floodplain in the Sacramento, California, metropolitan area is used as an illustration to explore the course of optimal floodplain protection decisions over long periods. A dynamic programming model is developed and suggests economically desirable adaptations for floodplain levee systems given simultaneous changes in flood climate and urban land values. Economic engineering optimization analyses of several climate change and urbanization scenarios are made. Sensitivity analyses consider assumptions about future values of floodplain land and damageable property along with the discount rate. Methodological insights and policy lessons are drawn from modeling results, reflecting the joint effects and relationships that climate, economic costs, and regional economic growth can have on floodplain levee planning decisions.

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1. Introduction

[2] Climate change has received considerable attention in recent decades. Most studies have examined the potential impacts of various climate change scenarios on hydrology, the environment, water, agricultural, and various other human activities. More recently, studies examining the ability and economics of human adaptation to climate change have been undertaken [*Venkatesh and Hobbs*, 1999; *Stakhiv*, 1998; *Yao and Georgakakos*, 2001; *Simonovic and Li*, 2003; *Vanrheenen et al.*, 2004; *Tanaka et al.*, 2006]. Occasionally, the economic and hydrologic impacts of climate change have been compared with those of population growth over long periods [*Vörösmarty et al.*, 2000; *Lund et al.*, 2003].

[3] Climate change could worsen flooding problems in some regions [*Schreider et al.*, 2000; *Milly et al.*, 2002], while continued urbanization of floodplains will increase potential flooding damages and vulnerability. An important trade-off that long-term floodplain management must address is how to balance the long-term potential for increasing flood damages with the benefits of human and natural uses of floodplains over long periods of time. Cities and urban land use decisions can endure for hundreds, even thousands of years. It behooves flood control engineers and urban planners to consider the long-term changes in economic and environmental conditions likely to affect the long-term performance of long-lived infrastructure and land use systems. This paper illustrates the importance of such a long-term perspective and presents a limited approach for exploratory examinations of flood control systems in a growing urban region. The study examines some effects of urbanization and climate change on levee system adaptation for long-term flood management using a simplified representation of urban floodplain management for California's lower American River near Sacramento to explore economic, engineering, and hydrologic interactions. The long-term floodplain management problem is formulated as an optimization problem solved by dynamic programming (DP). Illustrative results, analyses, limitations, and conclusions are presented.

2. Problem

[4] Climate change is typically a relatively slow and uncertain process that occurs in a larger context of human demographic, technological, and economic change. Climate changes, their uncertainty, and other changes in the human context together shape slow or abrupt human adaptive responses. In the case of flooding, climate change could affect the frequency of floods while urbanization could increase flood vulnerability and the magnitude of potential damages. As human use of floodplains and structural and nonstructural flood control efforts adapt over time to these changing conditions, significant economic and social consequences can arise. Adaptations must seek to buffer climate change effects along with changing demands for flood damage reduction and mitigation. To explore these adaptations from an economic perspective, we examine two issues: (1) how floodplain management can adapt economically to changing flood frequency combined with floodplain urbanization and (2) how levee height and setback can be changed over time to economically accommodate

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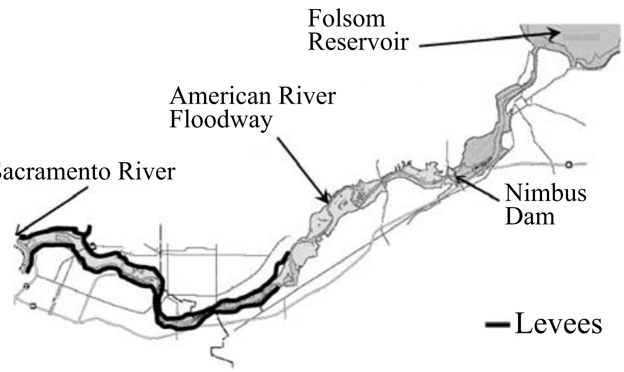

Figure 1. Map of the Sacramento metropolitan area and lower American River flood control.

changes in climate and urbanization for floodplain management. We examine these issues in the context of a simplified example based preliminarily on the lower American River, California. The analysis and results offer new insights and improve understanding of the adaptation problem faced by urbanizing floodplains without presuming to solve the very complex and real flooding challenges faced by the greater Sacramento area in their entirety.

[5] Sacramento, California, located at the confluence of the Sacramento and American Rivers, is one of the nation's most flood-prone cities. It is vulnerable to flooding from the Sacramento River along the length of its western edge and by the lower American River running through its middle as it bisects the city from east to west (Figure 1). To the east above Sacramento on the American River, Folsom Reservoir captures inflow from its North and South Forks, providing about 1.21 billion m^3 of total storage capacity, of which between 0.49 and 0.82 billion m^3 are reserved for flood control during the winter flood season. Immediately below Folsom Dam, the lower American River is confined by high ground that flattens as the river progresses downstream through denser metropolitan areas. The core of metropolitan Sacramento lies south of the lower American River, behind levees. Large tracts of floodplain north of the lower American River (North Natomas) are currently urbanizing behind levees [*National Research Council* (*NRC*), 1995]. This analysis focuses on this northern Sacramento metropolitan area behind the north bank of the lower American River.

[6] Over time, as the Sacramento region's economy grows, population and urban property values exposed to potential flooding are expected to increase. Population projections for the greater Sacramento area by 2100 are as high as four million [*Landis and Reilly*, 2002], a twofold increase over today's population of about 2 million. Flooding potential for this region is likely to increase due to climate change [*Lettenmaier and Gan*, 1990; *Miller et al.*, 2003] as well as from increased population and economic activity in the floodplain brought on by regional growth.

[7] Although the Sacramento region has a wide array of structural and nonstructural options to consider for managing flood risks, we focus this analysis on levee decisions for long-term protection of the floodplain and the changing economic risk trade-offs involved in levee decisions when land values, costs and flood climate are changing. We approximate the mediating effects of Folsom Reservoir operation in regulating unregulated flood flows from climate change by applying the method developed by *Goldman* [2001] to estimate regulated flood frequency curves downstream of Folsom Dam, but do not consider changes in reservoir outlet structure, flood storage capacity, or operations in this work. The decision variables evaluated with the DP model are levee height and floodway width (levee setback) over time. Raising existing levee heights entails a significant and irreversible construction expense, but is an expandable incremental option. Broadening the floodway makes more room for the river [*Van Stokkom et al.*, 2005], expands flood conveyance capacity and provides recreational benefits with less risk of geotechnical failure and potentially lower cost than having levees of great height. However, it entails different costs and reduces the economic benefits from land now incorporated into the floodway.

[8] In retaining a focus on levee planning, upstream reservoir control options are not examined explicitly in this model, but have been studied by others [*Yao and Georgakakos*, 2001]. Part of the California water system, Folsom Reservoir has several uses other than flood control and any operational changes would have important implications for the larger regional water and flood management system. Downstream Sacramento River options, conditions, and their backwater effects also are neglected. Options to reduce flood damage potential such as building codes, zoning, and flood warning and evacuation systems are similarly ignored for now [*Lund*, 2002]. Integrating a wider range of floodplain management options would be desirable but is beyond the scope of this study.

3. Components of Risk-Based Optimization Modeling for the Lower American River Levee System

[9] Risk-based optimization is used to preliminarily evaluate the economic desirability of levee height and setback changes for the lower American River over a long period of climate change and urbanization. The DP model has the following components and assumptions, which, like any model, unavoidably simplify the basin's true situation.

3.1. Flood Frequency and Levee Failure Probability

[10] Flood frequency analysis, as traditionally practiced, assumes that annual maximum floods are stationary, independent, identically distributed random processes. However, in the context of climate change, annual maximum floods in this study are treated dynamically. Three climate scenarios of 3-day unimpaired annual maximum inflow to Folsom Reservoir are considered, two of which are developed from historical flood flow records and one from a general circulation model study of global climate change. A 3-day period was identified as the critical duration for flood inflows to Folsom Reservoir because typically a very heavy flow event will take 2–3 days to fill flood storage at Folsom Reservoir [*Goldman*, 2001; K. T. Redmond, American River flood frequencies: A climate-society interaction, http://meteora.ucsd.edu/cap/kelly_flood.html]. Development of the three climate scenarios is explained next.

[11] The stationary history scenario assumes the 3-day annual maximum inflow to Folsom Reservoir is an independent and identically distributed random variable that follows a lognormal distribution. Annual 3-day maximum

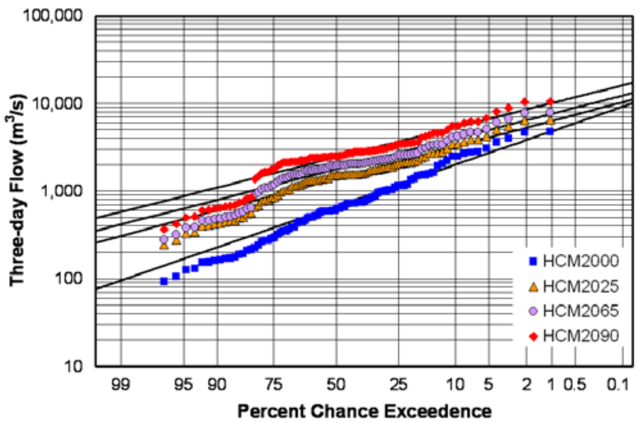

Figure 2. Historical and HCM flood scenario data for three future periods fitted to lognormal distribution curves.

inflows at Folsom Reservoir for 93 years (1905 through 1997) were fitted to a lognormal distribution using the least squares error (LSE) criterion. Figure 2 shows the fitted lognormal distribution curve for the historical record, yielding a stationary mean of 1006 m^3/s and standard deviation of 1180 m^3/s. The resultant "historical" distribution parameters (horizontal line in Figure 3) are taken to represent the year 2000 unregulated flood frequency curve.

[12] The historical trend scenario assumes the mean and standard deviation of the 3-day annual maximum flood are increasing over the planning period as observed in the historical record. Changing flood frequencies were estimated using a lognormal distribution with linear trend model [*Stedinger and Crainiceanu*, 2001] as follows:

$$\ln(Q_t) = \mu + \beta(t - \bar{t}) + \varepsilon_t \qquad (1)$$

where $\bar{t} = (T + 1)/2$ and T is the flood record length, ε_t follows a normal distribution $N(0, \sigma^2)$, and μ and β are parameters describing the linear trend. Applying equation 1 to the historical flood record, linear trend parameters were estimated using regression analysis to be $\mu = 9.983$, $\beta = 0.00206$ and $\sigma = 0.964$. However, the regression analysis showed no strong statistical evidence of a trend ($\beta \neq 0$) in the historical data so that flood risks estimates from the lognormal with trend model may be unreliable. The historical trend (HT) scenario developed from the historical record is included in the study as an alternative interesting climate change scenario to explain increasing annual flood peaks observed since 1950. While an assumed historical trend is plausible, there is no agreement on what has caused greater flood peaks since 1950 [*NRC*, 1995, 1999].

[13] The mean and standard deviation of the 3-day annual maximum inflow at Folsom Reservoir for the HT scenario were calculated for each time step from the lognormal distribution mean and standard deviation values from the trend line shown in Figure 3. Consequently, at the beginning of the analysis in year 2000, the HT scenario has a flood frequency mean and standard deviation (trend line values) greater than the mean and standard deviation assumed for the stationary scenario (see Figure 3).

[14] The third flood climate scenario is the HCM scenario, derived from temperature and precipitation changes predicted by the second Hadley Centre coupled ocean-atmosphere general circulation model (HadCM2 run 1) [*Miller et al.*, 2003]. HadCM2 run 1 assumes a 1 percent annual increase in mean global CO_2 relative to present conditions and results in a relatively wet and warming climate trend for California. Hydrological streamflow estimates derived from downscaling results from HadCM2 run 1 to the watershed scale and applying them in precipitation runoff simulations [*Miller et al.*, 2003] provide the basis for developing the trends in the mean and standard deviation of future flood inflows into Folsom Reservoir for the HCM scenario. *Miller et al.* [2003] developed 30 years of daily flows for the North Fork American River at North Fork Dam for three different future periods. To estimate changing flood frequency curves at Folsom Reservoir for the HCM scenario, peak inflows at Folsom for the whole basin were developed from information about peak floods at North Fork Dam using Miller's HadCM2 run 1 hydrology.

[15] Folsom Reservoir regulates runoff from about 4,820 km^2, receiving drainage from all three forks of the American River [*NRC*, 1995]. For simplicity, it is assumed climate change would result in uniform temperature and precipitation changes across the American River watershed above Folsom. The three tributaries are each about 130 km long and their respective flood peaks arrive almost simultaneously at Folsom Reservoir (http://meteora.ucsd.edu/cap/kelly_flood.html). *NRC* [1999] showed a linear relationship between cumulative annual peak inflows to the North Fork Dam and cumulative annual peak inflows to the Folsom Reservoir. On the basis of these three conditions, we approximate climate change unimpaired flood flows at Folsom from the GCM-derived hydrology for the North Fork American River using a perturbation scheme described next.

[16] For each future climate change period, a time series of 3-day annual maximum inflows to Folsom were constructed in three steps. First, perturbation ratios for flood inflows to North Fork Dam from Miller were calculated by dividing the 3-day annual maximum inflows under climate change by the simulated historical flood flows without climate change. The 30 years of simulated historical flood flows at North Fork Dam were then sorted into six frequency groups (<18, 18–34, 34–50, 50–66, 66–82%,

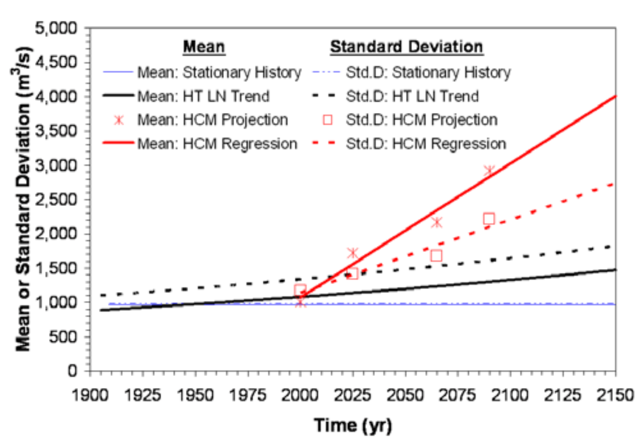

Figure 3. Means and standard deviations of the 3-day annual maximum inflow frequency distribution into Folsom Reservoir for three climate scenarios.

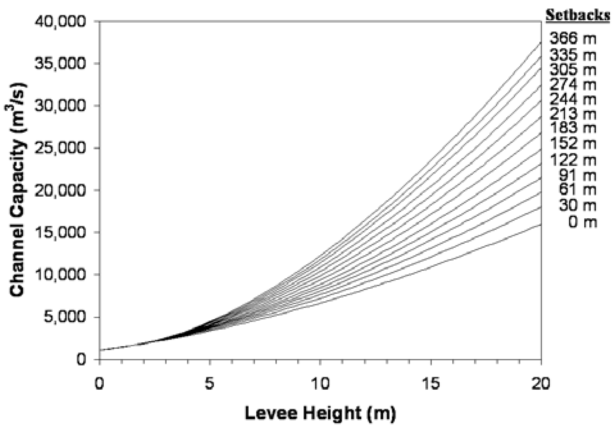

Figure 4. Stage-discharge rating curves for the lower American River at 12.5 km up from the confluence with the Sacramento River (7.75 river mile) for 13 levee setbacks.

and >82%) based on their flood flow frequency. Next, an average perturbation ratio value was calculated for each frequency group. Lastly, the appropriate average perturbation ratio was applied to each year's historical 3-day annual maximum inflow at Folsom (flood record) corresponding to this year's frequency group to generate climate change flood inflows at Folsom Reservoir.

[17] The constructed flood flow series for each of the three projected HCM climate change periods (2025, 2065, and 2090) was fitted to a lognormal distribution by minimizing the summed squared errors. These are shown in Figure 2 along with the stationary history scenario marked "Historical", representing the year 2000 level flood frequency curve. Thus, from bottom to top in Figure 2, the sets of points and their fitted lognormal curves represent flood frequency distributions for 2000, 2025, 2065, and 2090. The means and standard deviations of these four flood series were regressed against their year levels to form a continuous climate change HCM scenario where both flood flow mean and deviation increase linearly over the coming century along the plotted regression lines shown in Figure 3.

[18] The resultant annual linear increase in flood frequency parameters for the HCM scenario is 19.6 m^3/s for the mean (1.83% of the year 2000 flood mean) and 10.6 m^3/s for the standard deviation (0.93% of the year 2000 standard deviation). The mean, 1072 m^3/s, and standard deviation, 1142 m^3/s, calculated from the regression equations for year 2000 are used for the base year in the DP model. The HCM scenario is no more believable than other climate change scenarios and is perhaps somewhat extreme, but was chosen to demonstrate the approach and insights into potential climate change flood hydrology effects on planning decisions in the analysis.

[19] Levee failure for the decision analysis model is assumed to occur only with levee overtopping and results in floodplain inundation. Actual levee failure can involve other factors not included in this analysis, such as the duration of flooding [*NRC*, 1995]. For a given channel with a levee setback and height, overtopping flow was found from stage-discharge rating curves (Figure 4) derived from HEC-RAS hydraulic modeling of the river [*USACE*, 2002a].

[20] The overtopping flow is discharged by Folsom Reservoir. To estimate the probability of its exceedence under a given climate scenario (equivalent to the failure probability of the levee configuration under that scenario), we adapt a method developed by *Goldman* [2001] to transform the unregulated flood inflow frequency curve at Folsom into a regulated flood frequency curve at the downstream levee location. The approach combines information about the frequency of a given unregulated peak inflow with information about the ability to control that inflow to a desired objective release (the most likely unregulated versus regulated flow relationship for a given flood pool, operating policy, and outlet structure), to produce the regulated flow frequency curve for the downstream location. Here, we take the smallest unregulated inflow value associated with the downstream levee's overtopping flow (for a particular state) from the unregulated versus regulated flow relationship for Folsom Dam developed by Goldman. This unregulated value exceedence probability, taken from the 3-day annual maximum inflow lognormal distribution for the given climate scenario and time period, becomes the exceedence probability for the overtopping flow. For example, an overtopping levee flow of 3200 m^3/s at the downstream levee location would, most likely, be produced by an unregulated 3-day inflow to Folsom of 6740 m^3/s or greater. The exceedence probability for a 6740 m^3/s 3-day inflow under the stationary history climate scenario is 0.6%, and thus becomes the probability of levee failure by overtopping.

[21] In this analysis, 2001 Folsom Reservoir operating rules have been assumed. Although reservoir operating rules are likely to change over such a long period, this simplification allows the study to focus adaptation on the downstream levee system. A more comprehensive regional study would be required to more explicitly incorporate a more complex representation of Folsom Reservoir operations. Actual reservoir operators with forecasts might see different peak reservoir outflows for similar inflow volumes that occur with different patterns or forecasts. However, operators know that 3-day inflows beyond some critical value would cause downstream levee overtopping. Since flood frequency downstream of Folsom is an input for the DP model, future studies of upstream decisions, such as Folsom operations, could employ this study's representation of downstream damages and levee decisions.

3.2. Flood Hydraulics

[22] Simulations with an existing HEC-RAS hydraulic model using regulated 3-day annual maximum flows provided rating curves for locations on the lower American River, over a range of levee setbacks and a total reach length of about 35 km. Thirteen levee setbacks were examined for each of 159 cross sections to create the stage-discharge relationships shown in Figure 4. Steady flow simulation was done since appropriate operation of Folsom Reservoir can cut the flood peak and result in steadier flow downstream.

[23] This study examines levee setbacks from 0 to 366 m (Figure 4) along 21 km of the north bank of the lower American River heading upstream from the confluence with the Sacramento River. Most of the remaining north bank of the lower American River below Folsom runs through high ground. On the south bank, the levee directly abuts downtown Sacramento, making setback increases

almost impossible on this side. Consequently, setback decisions in the modeling analysis are only applied to the north bank levee.

[24] HEC-RAS simulations employed a fixed bed analysis, assuming no geomorphologic change over the study period. A Manning's n value of 0.045 to 0.05 was used for the overbank and 0.035 in the channel. Downstream boundary conditions were set at normal hydraulic depth. An index point 12.5 km up from the confluence with the Sacramento River (river mile 7.75) was used to evaluate the whole reach. The north bank elevation at this cross section is 9.3 m above mean sea level and has been taken as the levee bottom elevation. Figure 4 contains the resulting stage-discharge rating curves at the index point cross section. In the DP model, overtopping flows for various setbacks and levee heights are calculated from the rating curves using bilinear interpolation.

3.3. Benefit and Cost Functions

[25] One of the most difficult steps in planning is summarizing society's values into a scalar-valued ranking function to allow comparison of engineering alternatives [*James*, 1965]. In this study, economically optimal floodplain management seeks to maximize the difference between benefits and costs, in this case, between the annualized economic value of land use and the expected annual flood damage and mitigation costs. Expected flood damage functions were estimated from recent flood damage studies [*USACE*, 2002b]. Flood damage occurs in the model when flow stage exceeds levee height. Average year 2000 damage was estimated to be $11.2 billion if all land in Sacramento City and Natomas is flooded. This damage is huge but plausible given approximately $40 billion in damageable property in these areas [*NRC*, 1995; http://meteora.ucsd.edu/cap/kelly_flood.html].

[26] Implementation costs of management decisions are estimated from the literature and discussions with local flood engineers. The current value of floodplain land protected by the levee is assumed to be $49,422/ha yr ($20,000/acre yr) while the value of floodway land by the river is $2,471/ha yr ($1,000/acre yr). When the floodway is expanded, land protected by the levee is reduced. The loss or gain of land is equal to the levee setback change so that increasing the levee setback reduces the annual land value benefit, and vice versa. Levee construction costs usually vary with rivers and locations along them. Foundation preparation costs can vary widely. In California, a rough cost of compact fill is $5 per cubic yard, provided fill material is nearby. Levee construction costs can range from $5 to $10 million per mile depending on their size and foundation work (R. Mayer and G. Hester, personal communications, March 2005). Here we have assumed soils for levee construction and augmentation are available and estimated the average unit cost for levee construction to be $35.3/m^3 ($1/ft^3) to account for other potential costs for levee construction. Given an assumed trapezoidal levee cross section, construction cost becomes a quadratic function of levee height. In addition, higher levees also occupy additional land due to their trapezoidal shape, slightly reducing usable urban land. When the levee is moved (setback changes), a fixed cost of $100 million is applied to represent the costs for site acquisition, legal services, design and consulting, displacements, etc.

[27] The lower American River urban area is rapidly expanding. Several growth rates for floodplain land values were examined. Damageable property values were assumed to increase at the same rate as floodplain land values. Flood warning systems are already quite good for this area. Nonetheless potential human life loss due to flood hazard is critically important, but difficult and controversial to model, and is not evaluated in the objective function. A real 6.5%/year discount rate has been assumed.

4. Model Formulations and Solution Methods

[28] Flood protection in leveed flood control systems has been formulated with various optimization models [*Lund*, 2002; *Olsen et al.*, 2000; *Simonovic and Li*, 2003]. To incorporate dynamic changes in climate and urbanization over time requires a structurally flexible and computationally efficient model. Dynamic programming (DP) was tested against and chosen over an alternative linear optimization formulation that uses a Markov chain representation of decision tree risk states [*Olsen et al.*, 2000] for computational advantages.

[29] The dynamic programming formulation uses time t as the decision stage, levee setback and height at the beginning of current period as state variables $\overrightarrow{S_t}$, and the next period's levee setback and height as decision variables $\overrightarrow{X_t}$. For a stage benefit function $B_{jt}(\overrightarrow{S_t}, \overrightarrow{X_t})$, including gain or loss of floodplain land value and levee construction and damage costs, flooding state probability $P_t(j|\overrightarrow{X_t})$ over j possible flooding states (e.g., flooded versus not flooded), and real continuous discount rate r, the recursive function becomes

$$f_t\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) = \begin{cases} \max\limits_{X_t} \left\{ \left[\sum\limits_j P_t\left(j|\overrightarrow{X_t}\right) B_{jt}\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) \right] + f_{t+1}\left(\overrightarrow{S_{t+1}}, \overrightarrow{X_{t+1}}\right) e^{-r\cdot\Delta t} \right\}, & t < N \\ V\left(\overrightarrow{X_N}\right), & t = N \end{cases} \quad (2)$$

where $f_t\,(\overrightarrow{S_t}, \overrightarrow{X_t})$ is the maximized accumulated discounted benefit from time t to time N, the end of the planning period, given the state and decision at time t. Without climate change the time subscript to P can be removed. Without urbanization and real construction cost changes over time, the time subscript on the benefit function can be removed. Discounting is handled at each stage with incremental continuous discounting on the second term. We have assumed climate change and urbanization will persist for N periods, followed by a stationary climate, an end to urbanization, and consequently no further changes in optimal levee decisions. For an infinite horizon problem the future value at the end of the Nth period becomes

$$V\left(\overrightarrow{X_N}\right) = \left[\sum_j P_N\left(j|\overrightarrow{X_N}\right) B_{jN}\left(\overrightarrow{X_N}\right) \right] \frac{e^r}{e^r - 1} \quad (3)$$

Table 1. Base Case Parameters for DP runs

Parameter	Value
Optimization	
Planning horizon, years	150
Stage length, years	1
Levee height limit, m	19.8
Levee	
Top width, m	4.9
Side slope	3
North bank length (km)	21
South bank length, km	21
Initial setback, m	30.5
Initial height, m	4.6
Economic	
Damageable property from inundation, millions of $	11,200
Levee construction cost, $/m^3	35.3
Levee maintenance cost, $/km yr	ni[a]
Levee relocation cost, millions of $	100
Floodplain benefit, $/ha yr	49,422
Floodway benefit, $/ha yr	2,471
Discount rate	6.5%

[a]Levee maintenance costs, predominantly a fixed function of levee length, do not vary across levee states in this problem. They have therefore been ignored.

where $B_{jN}(\overrightarrow{X_N})$ is annual net benefit under flooding event j in the Nth period. The state transition equation is

$$\overrightarrow{S_{t+1}} = \overrightarrow{X_t} \quad (4)$$

The state vector $\overrightarrow{S_t} = [h_{1t}, d_{1t}, h_{2t}]$, where h_{1t} is north bank levee height, d_{1t} is north bank setback, and h_{2t} is south bank height, assuming a fixed south bank levee location. Since very high levees are impractical, a maximum levee height has also been assumed, limiting this state and decision variable to $h_{1t} = h_{2t} \leq h_{\max}$.

[30] The stage benefit function is

$$B_{jt}\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) = \begin{cases} LV_t\left(\overrightarrow{X_t}\right) - CC_t\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) & j = 0 \\ -CC_t\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) - FD_t\left(\overrightarrow{X_t}\right) & j = 1 \end{cases} \quad (5)$$

where LV_t is gain or loss of annual land value in period t resulting from levee setback change from the original setback at the beginning of the planning horizon; CC_t is levee construction cost in period t, including the fixed cost of moving a levee for state transitions that move the levee; and FD_t is flood damage potential equal to damageable property value at period t. Levee maintenance cost also could be included in CC_t, but were not in this case. For this system levee maintenance costs appear to be predominantly fixed functions of levee length, and so would not affect the outcome of these optimizations.

[31] To improve computation speed and represent the infrequency of major flood control system changes, each time step in the model represents several years. The parameters in the model have been adjusted appropriately for this coarsening of the time step. For example, if the time step represents n years, the probability of m independent failures in n years is $p_f^m\ (1\text{-}p_f)^{(n-m)}$, where p_f is the annual probability of flooding and levee failure. Thus the parameter $P_t(j|X_t)$ above becomes $1\text{-}(1\text{-}p_f)^n$, the probability of flooding during an n-year period, where $p_f = P_t(j|X_t)$ in a single year. Flood damage from flood or levee failure in a single year should be multiplied by the expected number of flood events, $n\ p_f$, for an n-year time step. The discounting factor e^{-rt} is also expanded to discount to the center of a multiyear time step interval, $e^{-r(t+\Delta t/2)}$.

[32] The DP algorithm is quite efficient. The time needed to find an optimal policy is polynomial in the number of discrete states in each time step. However, the number of discrete states needs to be quite large to obtain precise results, significantly increasing computation time. To address this constraint, discrete differential dynamic programming (DDDP) was used to reduce computation time and improve precision [*Heidari et al.*, 1971; *Yakowitz*, 1982]. DP was applied with relatively coarse state grids to find an initial global optimal solution followed by DDDP to improve the precision and computation time compared to DP alone. Results showed the initial grid size of a DP run had little influence on the final result refined with the DDDP algorithm.

5. Analyses and Results

[33] The DP model was run for a base case and various urbanization and climate change scenarios. Table 1 contains parameter values for the base case, which assumes a stationary historical flood frequency and no urban growth over the 150-year planning horizon. For each analysis, a graph illustrates how parameter changes affect the timing and size of levee raising and setback changes. Graphs of optimal levee setback and height over a 150-year horizon (Figures 5, 6, 7, and 8) show the path of optimal changes in setback distance in the upper half of each graph (measured from the top downward along the right) and in levee height in the lower half of each graph (measured from the bottom upward along the left-side primary axis). Only the north bank levee height and setback are discussed since north and south bank levee heights were identical in all runs, and no changes were allowed to the south bank levee setback.

5.1. Climate Change Effects

[34] In the first set of results examined for the three climate change scenarios without growth in urban land values (Figure 5), levee setback remains constant at 30.5 m over the planning period in all climate scenarios. While levee height in the stationary history (SH) scenario increases

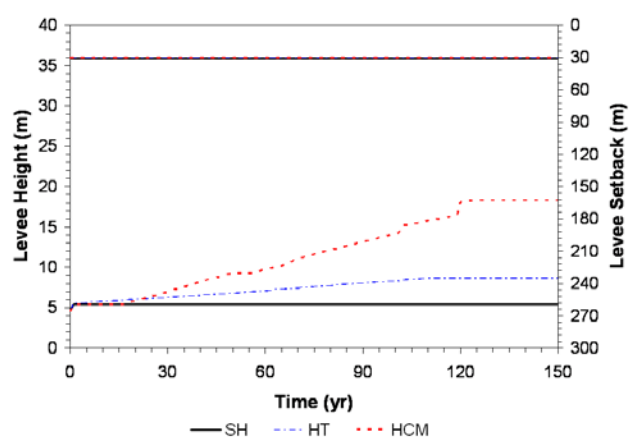

Figure 5. Climate change effects on levee setback (top right) and height (bottom left) decisions.

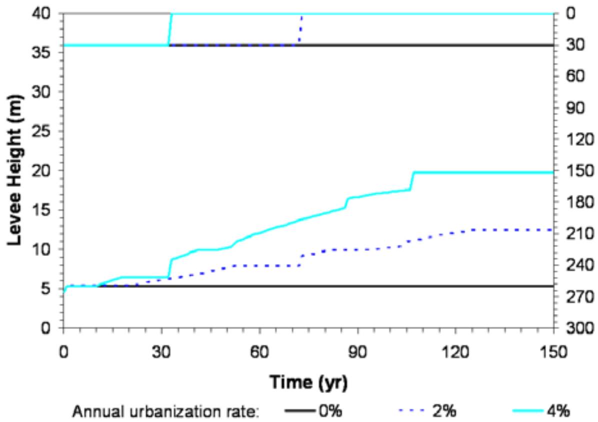

Figure 6. Urbanization effects on levee setback and height decisions.

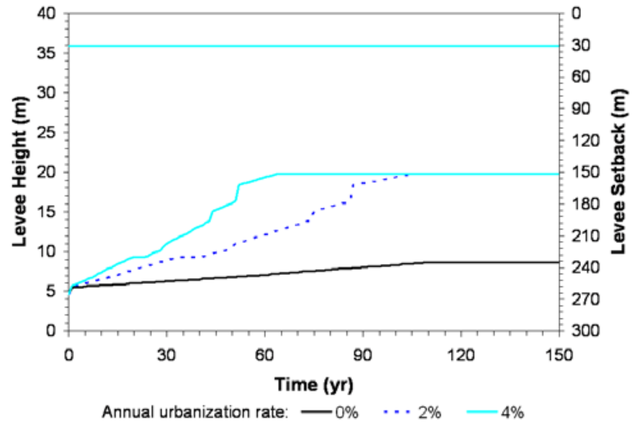

Figure 7. Combined effects of historical trend in hydrology and urbanization.

to about 5.4 m at the beginning and then remains constant, in the historical trend (HT) scenario it increases to 5.5 m at the beginning, gradually increases to 8.6 m at the 110th year, and remains unchanged thereafter. The HCM scenario (HCM) has levee height of 5.4 m at the beginning, then "no action" for about 17 years, followed by gradual increases to 9.18 m at year 50, another constant period of 7 years, gradual increases to 14.1 m at year 100, a jump to 15.1 m two years later, then another period of gradual increases to 16.5 m at year 120, followed by a quick jump to 18.3 m, with no further changes. The quite divergent decision trajectories for levee height changes reflect the impacts of different patterns of evolving flood frequency means and variances over time.

[35] A conclusion here is that steadily worsening flood frequencies for a high-value urban area lead to an economically optimal dynamic of raising levee heights. Given high costs for moving levees, increasing levee setbacks over time to make more room for increasing flooding risk is not economically optimal over the planning period in this case without growth in urban land values and damageable property.

5.2. Urbanization Effects

[36] Optimization results for three urbanization rates examined without climate change are plotted in Figure 6. With no urbanization (0%/yr increase in damageable properties and urban land values), levee setback at 30.5 m remains constant over the planning horizon. Under a modest urbanization rate of 2%/yr increase in urban land and damageable property values, levees are moved to a zero setback near year 73, while under a higher urbanization rate of 4%/yr increase, they are moved much earlier to a zero setback at about year 33.

[37] Levee height for all three cases increases to 5.4 m at the beginning. After this initial raising, levee height remains constant for the 0%/yr case. For the 2%/yr case, the levee remains at 5.4 m until year 22, gradually increases to 7.8 m at year 52, remains constant for the next 20 years, then jumps to a height of 9.2 m at year 73 when levee setback is reduced to zero, followed by gradual raising for 50 years until levee height reaches 12.4 m, when raising ceases. In the 4%/yr case, levee height has a shorter period of just 10 years at 5.4 m, rises to 6.4 m at year 17 followed by 15 years unchanged, then jumps to 8.7 m in year 33 when the setback is reduced to zero, followed by generally gradual but steep rising to 17.6 m at year 106, after which it remains unchanged.

[38] Optimal levee changes in Figure 6 demonstrate the implications of urbanization for long-term flood control planning. Under an assumed stationary historical climate, urbanization alone tends to reduce levee setbacks to increase protected land at an increased cost of having higher levees. Whenever the levee is moved toward the river, levee height is increased to compensate for the loss of flood channel capacity.

5.3. Combined Climate Change and Urbanization

[39] Worsening flood frequency tends to raise levees and maintain or increase setbacks and land in the floodway over time, while urbanization tends to raise levees and move them closer to the river. The combination of these two tendencies, when a maximum levee height limitation exists, produces a different long-term levee design strategy. The HT and HCM climate scenarios were combined with the three urbanization rates to examine their effects on levee construction decisions (Figures 7 and 8).

[40] Under the HT scenario (Figure 7) and all three urbanization rates (0%/yr, 2%/yr and 4%/yr), levee setbacks never changed over the 150-year planning period. Optimal levee height under the HT climate with 2%/yr urbanization

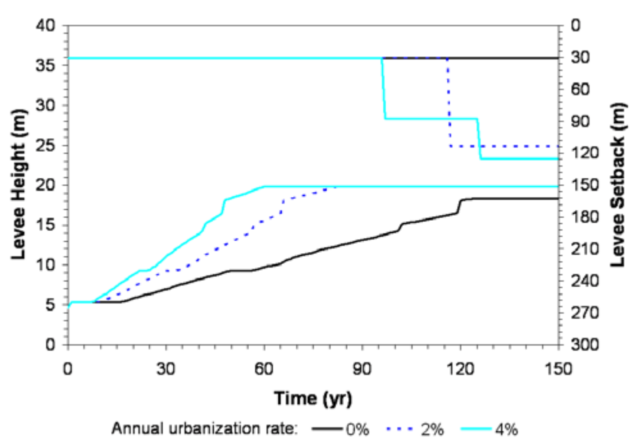

Figure 8. Combined effects of HCM climate scenario and urbanization.

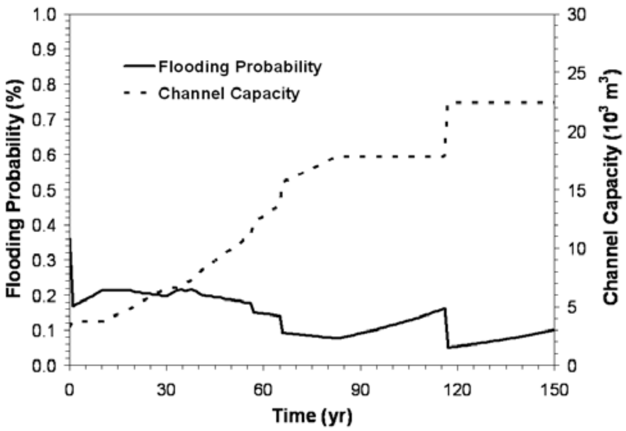

Figure 9. Sensitivity analysis for damageable property value, urban land value, and discount rate.

begins at 5.6 m and increases mostly steadily to the levee height limit of 19.81 at year 105, with rapid jumps at year 75 and 87 year. The HT scenario with 4%/yr urbanization follows a similar pattern, but more rapidly. Levee height starts at 5.7 m, increasing to the limit of 19.8 m at year 65, 40 years sooner.

[41] Under the HCM scenario (Figure 8) with urbanization, both levee height and setback change over the 150 planning horizon. For the 2%/yr urbanization, levees are moved in year 117 from their initial setback to a 113.6 m setback, while under the 4%/yr urbanization rate, they are moved twice, in year 97 to a setback of 87.5 m and then again in year 126, to 125.3 m. Levee height for the 2%/yr urbanization case starts at 5.4 m, remains unchanged for the first 10 years, and then increases until it reaches he height limit at year 83. The 4%/yr urbanization case follows a similar but more rapid pattern of decisions reaching the height limit of 19.8 m 23 years sooner in year 60.

[42] Figure 9 shows changing channel capacity and flooding probability over time for the HCM scenario with 2%/yr urbanization rate. When setback expands in year 117, the abrupt increase in river capacity significantly reduces flooding probability with a huge construction cost in that year. Levee height increases also reduce flooding probabilities. For this urban area and these assumed climate scenario and urbanization conditions, the model produces optimal levee designs that maintain flooding probabilities ranging from around 0.2–0.05%/yr (except for the initial condition), equivalent to events with 500- to 2000-year recurrence periods. As the value of urban land and damageable property increase over time, the long-term optimal flood protection design tends to reduce the annual probability of flooding (increase the optimal average recurrence period).

[43] These levee setback and height results have implications for long-term floodplain management. The combined effects of climate change and urbanization are more challenging than the effects from either factor alone, requiring greater and more costly adaptations. When the DP model was run with increasing real construction costs over time, levee construction activity was reduced in terms of both height and setback changes, with consequently greater flood damages. When the rate of construction cost increase exceeds the urbanization rate, levee construction becomes economical only at the beginning of the planning horizon.

6. Sensitivity Analysis of Major Economic Factors

[44] The HCM climate scenario with 4%/yr urbanization and base case parameters in Table 1 was used to explore the sensitivity of levee decisions to damageable property value, urban land value, and the discount rate. A single economic factor was changed in each run holding the other parameters at their base case levels. Results are plotted in Figure 10.

[45] Figure 10 shows that levee construction decisions are influenced significantly by economic factors. When the damageable property value was increased by 50%, levee height was increased sooner to the levee height limit of 19.8 m and levee setback was increased to a greater distance and occurred earlier compared to the reference run. Greater damageable property values lead to higher levees and greater setbacks which lower inundation probability to better protect the greater damageable property value. Changing damage property value separately from land value gives some insight into savings achievable with floodplain management actions such as flood proofing.

[46] When urban land value was increased by 50%, the north bank levee was moved three times instead of twice compared to the reference run, but increasing setbacks were smaller each time as was the final levee setback position. Greater urban land values encouraged smaller and more frequent setback changes in the face of the steeply increasing flooding risks of the HCM scenario, despite high fixed costs for moving levees and diseconomies of scale in levee construction, seeking to preserve high urban land value as long as possible. With the higher urban land value, levee height between year 10 and year 60 was slightly lower than the reference case because a lower levee occupies less urban land due to its trapezoidal shape.

[47] With a reduced discount rate of 4% (0.615 × 6.5%), levee setback changes occurred later, but the levee was always higher than the reference case until it reached the height limit. The effect of discount rate is complicated, involving tradeoffs of all the other economic factors, but generally a lower discount rate would make the future

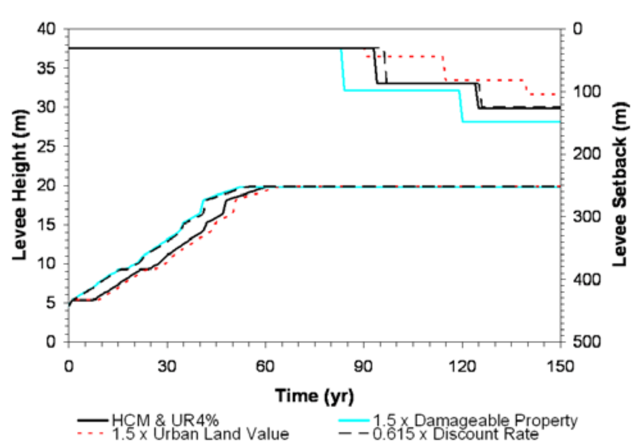

Figure 10. River capacity and flooding probability under the combined historical trend climate scenario and 2%/yr urbanization.

Table 2. Expected Present Value of Total Flood Control Costs and Damages With Economically Optimal Levee Adaptations[a]

Climate Scenario	Urbanization Rate 0%/yr	2%/yr	4%/yr
Stationary history	392	545	828
Historical trend	634	867	1269
HCM	485	677	1031

[a]Millions of dollars; 6.5% discount rate.

effects of present decisions less important, tending to accelerate some capital decisions, such as raising levee heights.

7. Costs of Flood Control Adaptations

[48] Climate change and urbanization could worsen flood control problems and significantly increase flood control costs for the lower American River. Table 2 shows total expected costs for combinations of climate scenarios and urbanization rates. Each present value cost is the accumulated discounted net cost of levee construction, expected flooding damages, and land value losses due to levee relocation over a 150-year period. Higher urbanization rates increase total flood management costs because higher damageable property and land values justify higher flood prevention expenses and raise the costs of losses when inundation occurs and levees are set back. Of the three climate scenarios, stationary history has the lowest total flood management costs, and historical trend leads to the highest costs. It may be surprising that total flood management costs for the HT scenario exceed those of the HCM scenario. However, in Figure 2, the mean and standard deviations of the changing HT flood frequency distribution exceed those of the HCM scenario for the first two decades. This increases flooding damage costs in the HT scenario in these earlier periods which are important when discounting is considered. At discount rates less than 4%/yr, the HCM scenario becomes more costly (in present value terms) than the historical trend scenario.

[49] For the HCM scenario with a 2%/yr urbanization rate, Figure 11 illustrates expected flood damages, levee construction costs, and land value losses over time. Major construction costs occur when the levee is moved or when levee heights are increased abruptly. Expected flood damage costs increase rapidly after levees reach the height limit, since increasing levee setback (the only remaining feasible action in the model) has a high fixed cost and causes economic loss of some urban land. For a time, the economic benefits (avoided costs and land losses) of deferring increases in levee setback exceed the economic risk of flooding damages. Continued urbanization and increases in damage potential eventually overcome incentive to defer floodway expansion, and the setback is abruptly increased. Land value loss (from not urbanizing the entire floodway) grows exponentially in time with the growth of urban land value and linearly with levee setback. For cases with higher urbanization rates (5+%/yr), levee setbacks change with surprising frequency late in the planning period, even with large fixed costs for levee setback changes, due to compounded effects of land value growth and inability to raise levees further.

8. Limitations and Discussion

[50] This study has several limitations. The scenario-based formulation and DP solution method assume perfect foreknowledge of climate change trends. Climate change prediction is far from perfect and there are far more uncertainties in climate and hydrological regime changes than the model can include. Actual flood control planning is bedeviled not only by imperfect short-term forecasting, but also imperfect knowledge of present and future flood climate variability. An ideal probabilistic forecast of future flood climate would have contingent future flood probabilities contingent on the mean and standard deviation of past floods at each stage. Such probabilistic contingent scenarios are not available for optimization (and would require additional state variables in the DP). Nevertheless, the current DP formulation allows exploration of the implications of potential future urbanization and climate trends. The uncertainty in future climate and uncertainty in future urbanization are interesting and potentially important, and are worthy areas for future research. While these uncertainties are interesting and important, they are not the main focus of this paper.

[51] Having uncertainty in future scenarios poses an interesting problem. For an uncertain nonstationary process, the estimates of flood frequency statistics from historical data are likely to lag their true values. This lag, by itself, would tend to delay optimal adaptation to changing climate, perhaps by a considerable time and at great economic expense. However, realizing the potential magnitude of such an economic loss might lead to accelerated response to changes in the flood record. While such exaggerated responses might be more optimal (even if they were to exceed the ideal adaptations), there would still be considerable economic regret. Knowing the true future climate scenario would always lower overall expected cost.

[52] Flood frequency may not fit a lognormal distribution when climate and hydrologic regime change. Also, hydrologic parameter changes may not follow linear trends. We are unlikely to actually know the form and rates of these trends until a long history of floods has been endured.

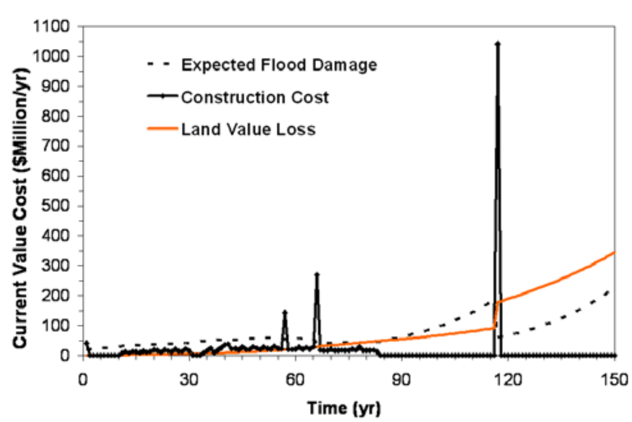

Figure 11. Costs of flood management adaptation in present values under the HCM climate scenario with 2%/yr urbanization.

Fortunately, as observed in the discussion of results in Table 2, the effects of discounting reduce the effects of distant future changes on present actions.

[53] Flood control operations for Folsom Reservoir and upstream reservoirs are crudely represented in this study. These could have important influences on the case study results, and greatly simplifies the range of upstream flood management options for this case. For example, we have neglected the effects of changing channel capacity on the unregulated versus regulated flow relationship in this illustrative case. Greater downstream flood flow capacity might encourage or discourage greater use of prereleases in reservoir operations. These are topics for further study. Since this study uses downstream flood frequency as an input, the regulated flood frequency effects of different upstream actions could form a reasonable basis for integrating upstream actions with downstream actions, costs, and damages. Nevertheless, this case study supports the main point of the paper that climate and urbanization changes can combine to affect long-term economically optimal flood management, particularly regarding levee heights and setbacks.

[54] The loss of life is always important for flood control, and flood warning and evacuation systems cannot be perfect. The neglect of human life loss in the objective function leads to underestimated inundation damage impacts and estimates in the model. If a reasonable estimate of the value of human life and number of lives lost per inundation were available and added to the objective function, it would increase the importance and size of damages from flooding, which would in this simple analysis lead to greater levee heights and accelerated onset of increases in levee setback, as observed with the sensitivity analysis.

[55] Unsteady flow routing of properly designed hydrographs might better represent stage-discharge relationships. Stochastic analysis of downstream elevations at the confluence of the Sacramento and American Rivers also might be worthwhile.

[56] The north bank levee setback is defined as a single state variable. In reality, levee relocation may be impossible in some important locations, and different setbacks for different reaches may be optimal given varying hydraulic and economic conditions. Another simplification is use of water elevation at a common index point to represent the entire levee length. However, if many state variables are used to represent multiple reaches, the DP method becomes inefficient or impossible to solve.

[57] The results presented in this paper for the lower American River are very preliminary, given these limitations in method and in parameter estimation. However, they illustrate possible trends in urbanization and climate change and their potential economic effects, point to some promising adaptation trends over long periods, and demonstrate the importance of combining economic trends and adaptations within studies of flood control with climate change.

9. Conclusions

[58] Optimal long-term flood protection for urban areas is affected by many climatic, hydraulic, economic and societal factors [*van Danzig*, 1956]. For long-term planning these interactions can be examined by optimization methods, providing some insights into this planning problem. The following conclusions are drawn from the study.

[59] 1. The DP method developed here provides a framework for long-term flood control planning and analysis of long-term climate change and urbanization scenarios. The method appears useful for exploratory analysis.

[60] 2. This study demonstrates the economically optimal interaction of flood control decisions over long periods with changing economic and climatic conditions.

[61] 3. Preliminary application of this method to the lower American River examines the effects of climatic and socioeconomic factors in this region. The results have some implications for long-term floodplain planning and management. Specifically, there might be economic value to expanding lower American River levee heights and setbacks over long periods of time, and making present-day zoning decisions to preserve such options.

[62] 4. Climate change and urbanization can have major combined effects on flood damage and optimal long-term flood management. Other factors also have influence. Climate change studies of flooding impacts and adaptations should include future changes in economic conditions and adaptive management decisions as well.

[63] Over the coming century or so, the core of metropolitan Sacramento appears destined to expand into a major floodplain of the Sacramento and American Rivers. This expanded core, with its benefits of proximity to the existing metropolitan core, will have to cope with increasing flood risk, arising largely from growth of economic activity on vulnerable lands, but also perhaps from growing flood frequencies. If flood climate and economic trends accelerate and are not otherwise mitigated, there will likely come a time when major land use dislocations are required in the North Natomas region to create a broader floodway for the American River, although the timing and extent of such dislocations remain uncertain.

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