1. Introduction

- Levees provide partial protection against floods by earthen dam construction.
- Historically, risk analyses of levee failure only consider overtopping failure, ignoring intermediate failure modes.
- The minimum federal standards are defined in PL 84-99 for agricultural levees [Table 1].
- Design flood is increased to 1:200 years for urban levees.
- Two decision variables:
  - **Levee height**, \( H \), determines type of failure, overtopping or intermediate.
  - **Levee crown width**, \( Bc \), affects the likelihood of intermediate failure, specified by levee fragility curves.
- Risk based optimization model for levee design or evaluation of existing levees is developed by minimizing the total costs.

Table 1. Minimum levee standards to qualify for flood damage federal aid

<table>
<thead>
<tr>
<th>Standards Source</th>
<th>Crown width (ft.)</th>
<th>Land-side slope</th>
<th>Water-side slope</th>
<th>Design Flood (yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL 84-99</td>
<td>16</td>
<td>3:1 – 5:1</td>
<td>2:1</td>
<td>1:100</td>
</tr>
</tbody>
</table>

2. Methods

Model description:
- Symmetrical river cross section
- Dimensions meet minimum levee standards to qualify for federal aid under PL 84-99

![Figure 1. Idealized cross-section of a symmetrical two levee river channel system](image)

Levee Fragility Curves

Levee fragility curves graphically illustrate the levee failure probability for intermediate modes based on conceptual curves.

![Figure 2. Levee fragility curves for levees in good, fair, and poor condition](image)

3. Optimization

Objective Function: minimize total cost

\[
\text{Min } TC = EAD + ACC
\]

Where:

- \( TC \) = total expected annual cost
- \( EAD \) = expected annual damage cost
- \( ACC \) = annualized construction cost

\[
EAD = D \int Q_c(Q) f_c(Q)dQ + D [1 - F_c(Q_c)]
\]

\[
D = \text{damage per flood in } S
\]

\[
Q_c = \text{flow capacity of the levee system in ft}^3/\text{sec}
\]

\[
f_c(Q) = \text{probability distribution function of the flow}
\]

\[
f_c(Q_c) = \text{probability of levee failure for the given flow}
\]

\[
ACC = \pi \times V + c + \left( \frac{c \times (\alpha + 0.5)}{1 + \sqrt{\alpha}} \right) + LC
\]

- \( \pi \) = cost multiplier (1.3)
- \( V \) = volume of the levee along the reach in \( \text{yd}^3 \)
- \( c \) = soil compaction cost per area (\$10/\text{yd}^2)
- \( \alpha \) = interest rate (5%)
- \( n \) = number of years the levee will be repaired over (50 yrs.)
- \( LC \) = land cost of the levee in \$.

\[
LC = UC \times A \times 1
\]

- \( UC \) = unit cost of the land in \$/ft
- \( A \) = area of land the base of the levee occupies in \( \text{ft}^2 \)

4. Results

Small Levee System: Cosumnes River

- Agricultural/rural levee
- Mean annual peak flow = 930 cfs

![Figure 4. Results of total costs for various levee geometries for the Cosumnes River levees](image)

Optimum Results:
- \( H = 4.4 \) ft.
- \( Bc = 31 \) ft.
- Return Period = 144 yrs.
- Probability of overtopping failure = 0.7%
- Probability of intermediate failure = 2.5%
- Required freeboard = 1.5 ft.

Large Levee System: Sacramento River

- Urban levee
- Mean annual peak flow = 60,000 cfs

![Figure 5. Results of total costs for various levee geometries for the Sacramento River levees](image)

Optimum Results:
- \( H = 24.3 \) ft.
- \( Bc = 61 \) ft.
- Return Period = 150 yrs.
- Probability of overtopping failure = 0.7%
- Probability of intermediate failure = 2.1%
- Required freeboard = 3 ft.

After the addition of a 3 ft. freeboard, the return period increases to above the 200 year minimum.

5. Conclusions

- For minimum total costs, increasing crown widths will decrease optimal levee height.
- Probability of intermediate failure can exceed overtopping, and so should not be ignored.
- Increasing crown width mitigates seepage and decreases intermediate failure.
- For urban levees, space limitations may restrict levee crown width to less than optimum levels, in this case slurry walls may be considered to decrease seepage and intermediate failures.
- Future Work: nonsymmetrical levees to provide flood protection preference to urban land over rural land to reduce damage related costs and provide increased protection to the urban development.

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