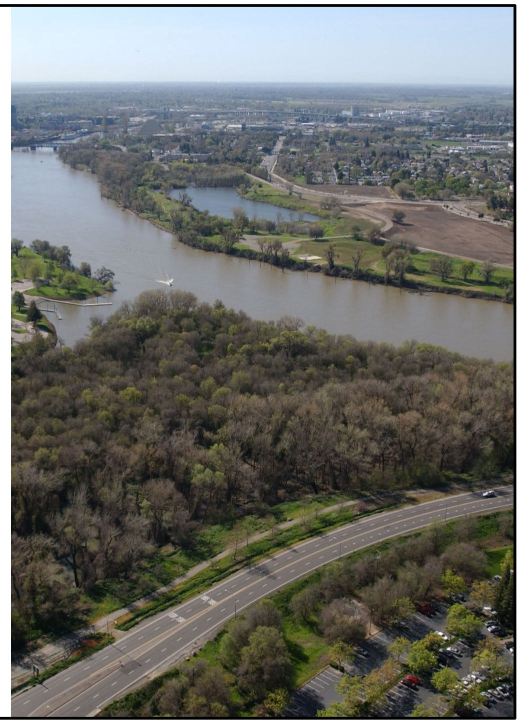
Risk Analyses in a Complex Interconnected System: Sacramento River

David Ford, PE, PhD
Nathan Pingel, PE
Steve Cowdin, CFM

January 2021

HDR



Nathan Pingel
Nathan.Pingel@hdrinc.com

Questions that I will address:

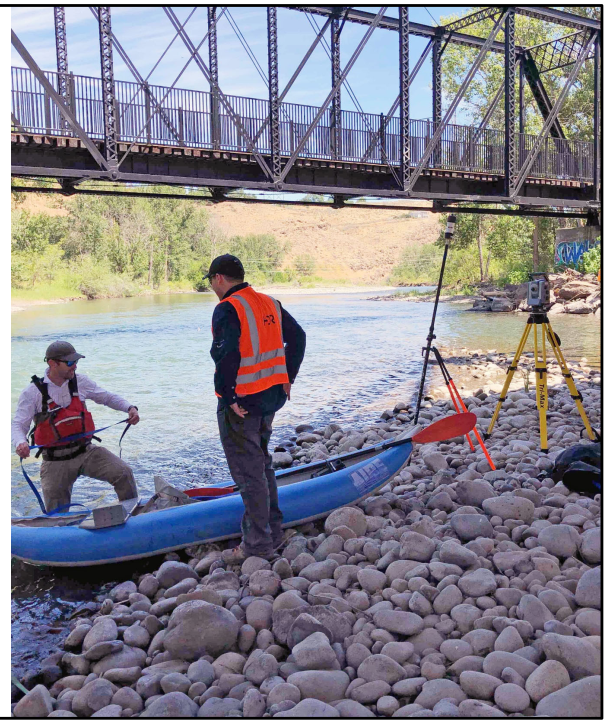
01 What's the flooding situation in the lower Sacramento River system?

02 Who has assessed risk there and why?

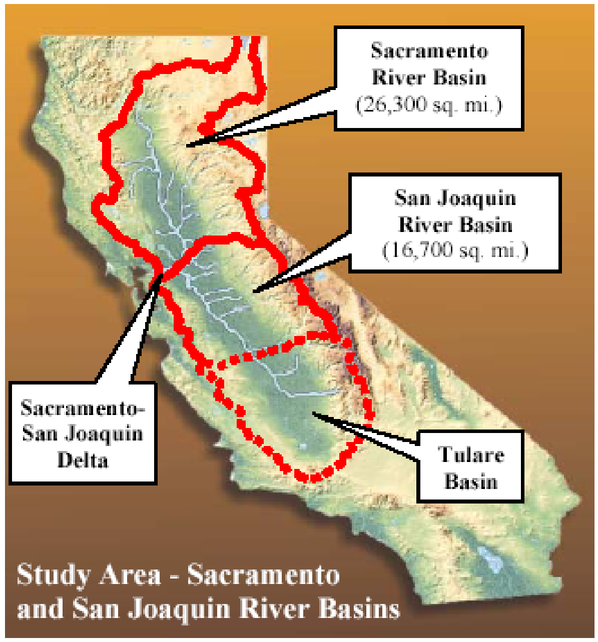
03 How was risk assessed for the system?

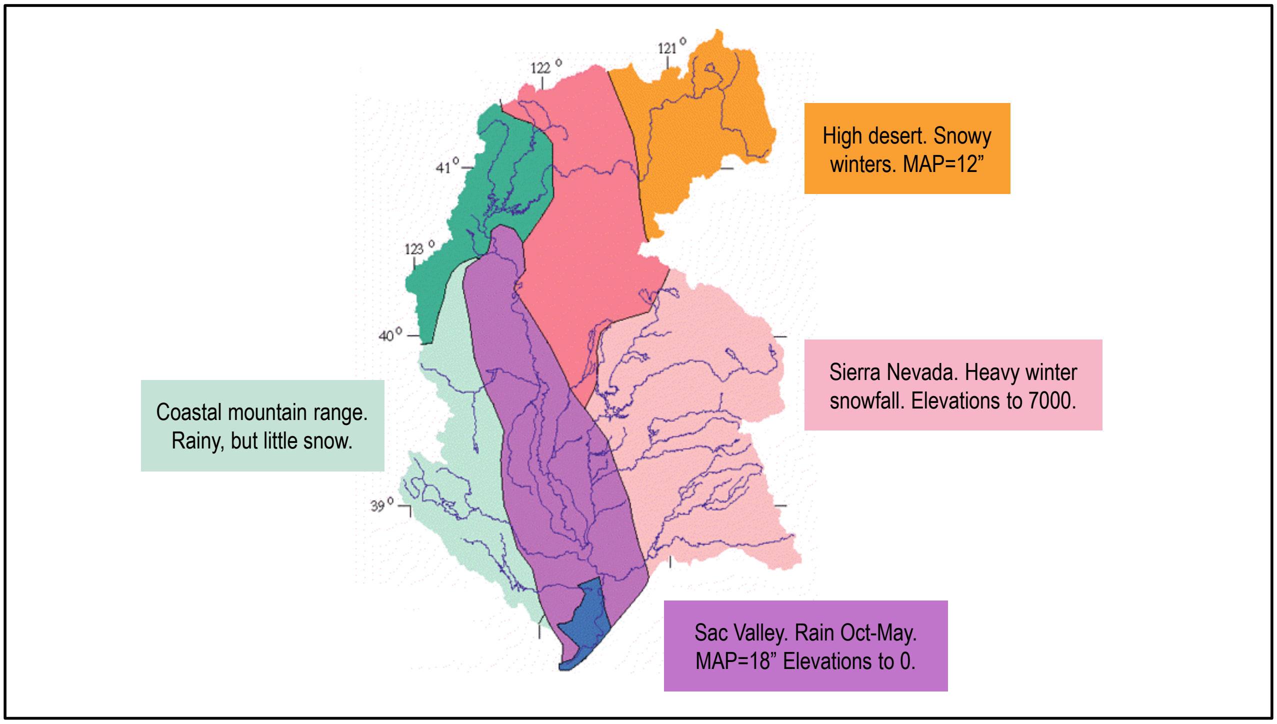
04 What makes that assessment difficult?

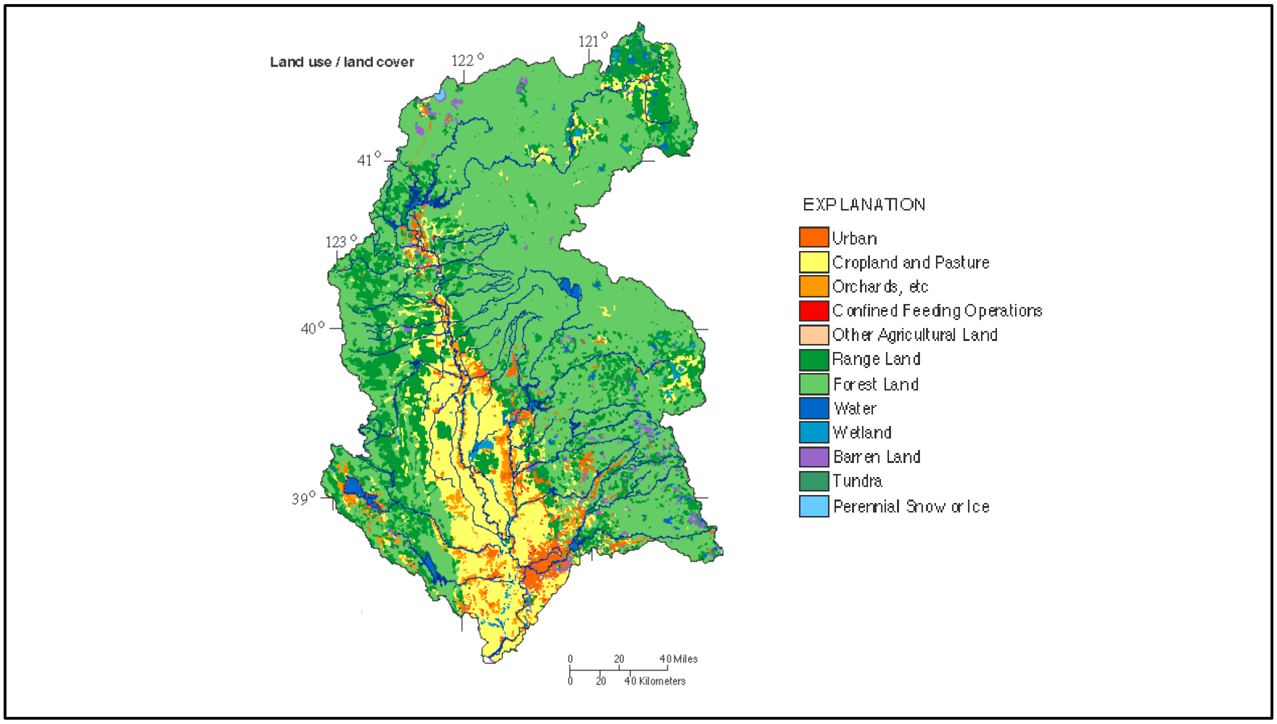
05 What can you learn from our analyses?



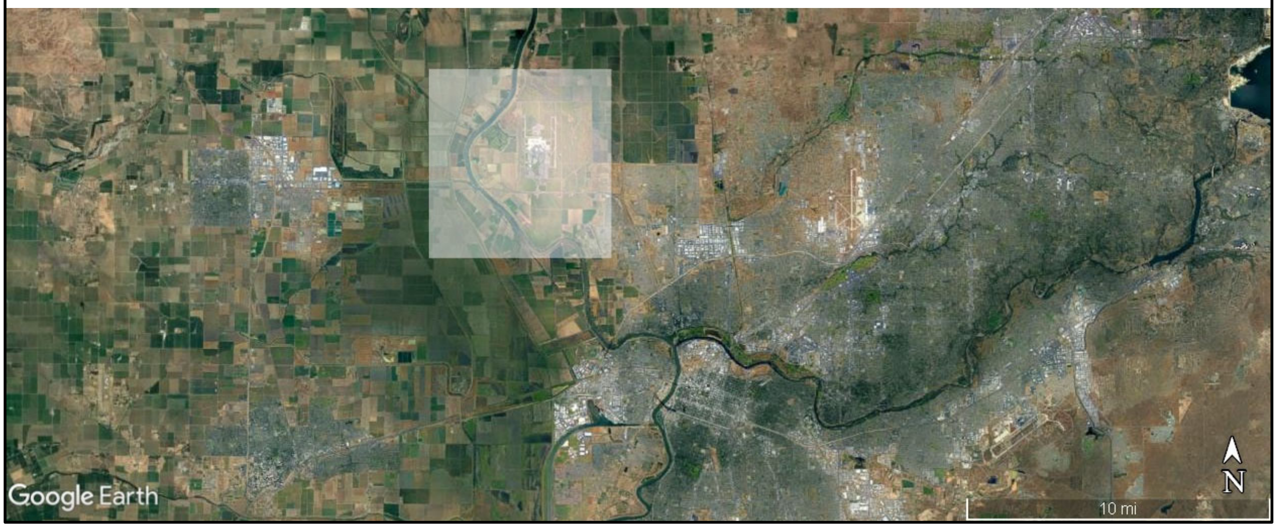
01 What's the flooding situation in the lower Sacramento River system?


Sacramento
River Basin
(26,300 sq. mi.)
San Joaquin
River Basin
(16,700 sq. mi.)
Sacramento-
San Joaquin
Delta
Tulare
Basin
Study Area - Sacramento
and San Joaquin River Basins

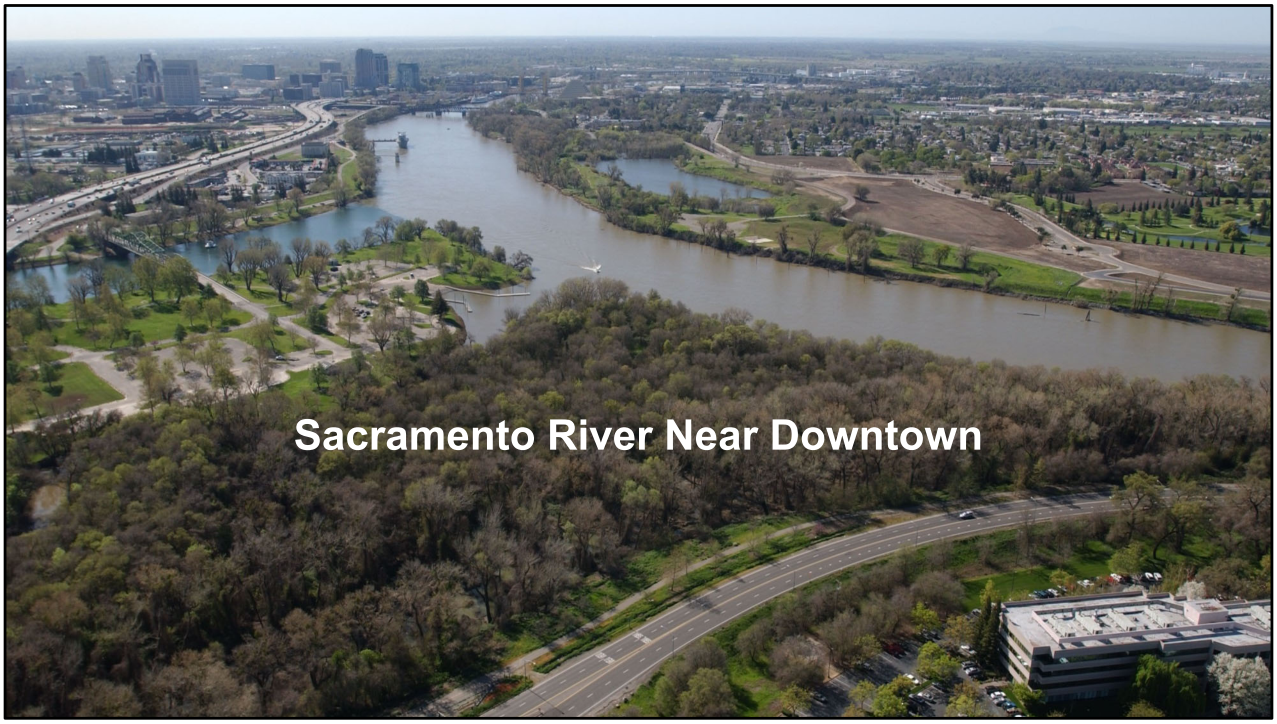

122°
121°
41°
123°
40°
39°
High desert. Snowy winters. MAP=12”
Sierra Nevada. Heavy winter snowfall. Elevations to 7000.
Coastal mountain range. Rainy, but little snow.
Sac Valley. Rain Oct-May. MAP=18” Elevations to 0.


Land use / land cover
122°
121°
41°
123°
40°
39°
EXPLANATION
Urban
Cropland and Pasture
Orchards, etc
Confined Feeding Operations
Other Agricultural Land
Range Land
Forest Land
Water
Wetland
Barren Land
Tundra
Perennial Snow or Ice
0 20 40 Miles
0 20 40 Kilometers

Sacramento River Near Airport

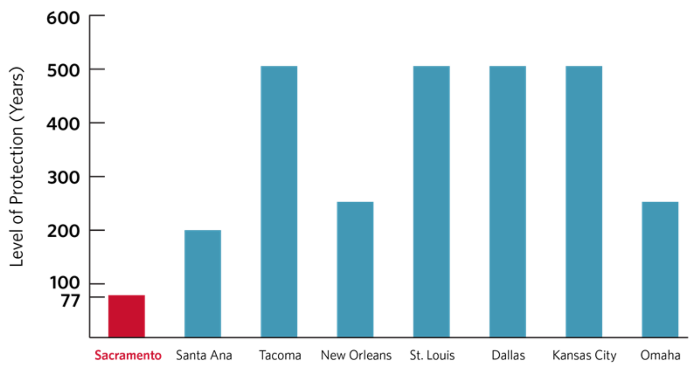


Sacramento International Airport


Sacramento River Near Downtown

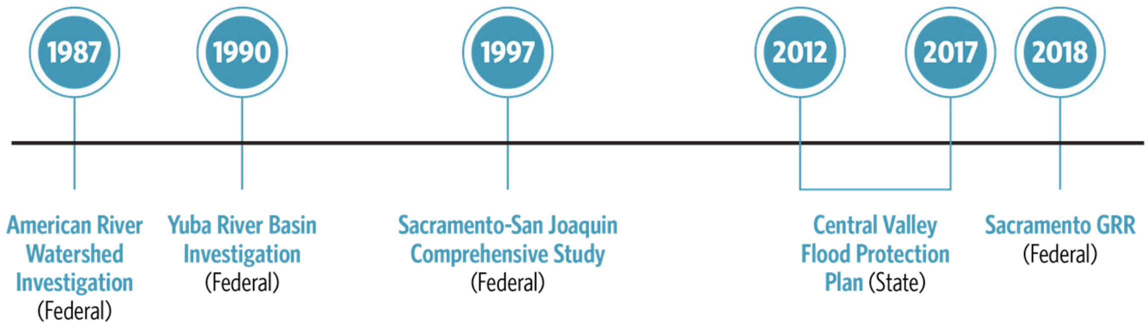
"Level of Protection" and Damage

- Low level of protection (high AEP) for city of Sacramento. (See graph below)
- Recent major floods in 1986 and 1997.
- Estimated damages = $187 million in 1986 and $524 million in 1997.



02 Who assessed the risk there and why?

Who assessed risk there and why?



1987 American River Watershed Investigation (Federal). Study flooding in Sacramento area due to Sacramento and American Rivers.
1990 Yuba River Basin Investigation (Federal). Yuba and Feather River watershed.
1997 Sacramento-San Joaquin Comprehensive (Comp) Study (Federal). "…comprehensive assessment of the Central Valley's flood management system to reduce flood damages and restore the ecosystem."
2012 and 2017 Central Valley Flood Protection Plan (State).
2018 Sacramento GRR (Federal).

Who assessed risk there and why?

Other related studies included:

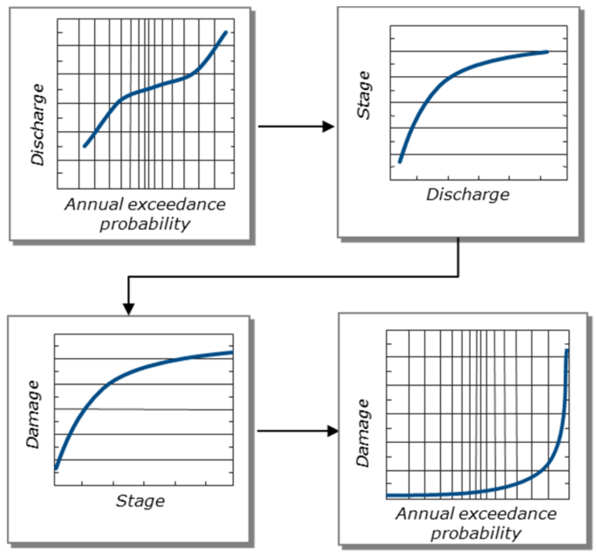
- **Risk reduction planning studies**.
  - Sacramento Area Flood Control Agency (SAFCA)
  - City of West Sacramento
  - Three Rivers Levee Improvement Authority
- **Permitting studies**. For Section 408 and State permits.

Risk reduction planning studies. By Sacramento Area Flood Control Agency (SAFCA), City of West Sacramento, Three Rivers Levee Improvement Authority. Use Corps' analysis programs. Objective to reduce risk, get reimbursement in cost sharing agreement, get permits to alter system.

Permitting studies. For Section 408 and State permits.

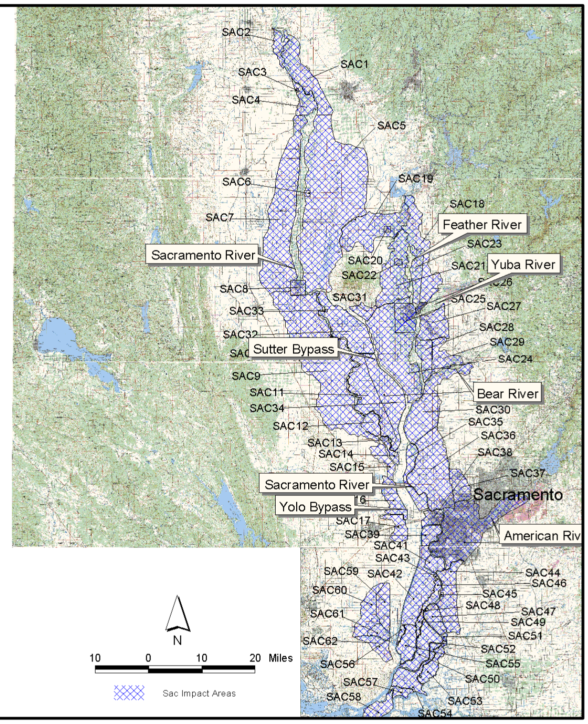
03 How was risk assessed for the system?

How We Assessed Risk

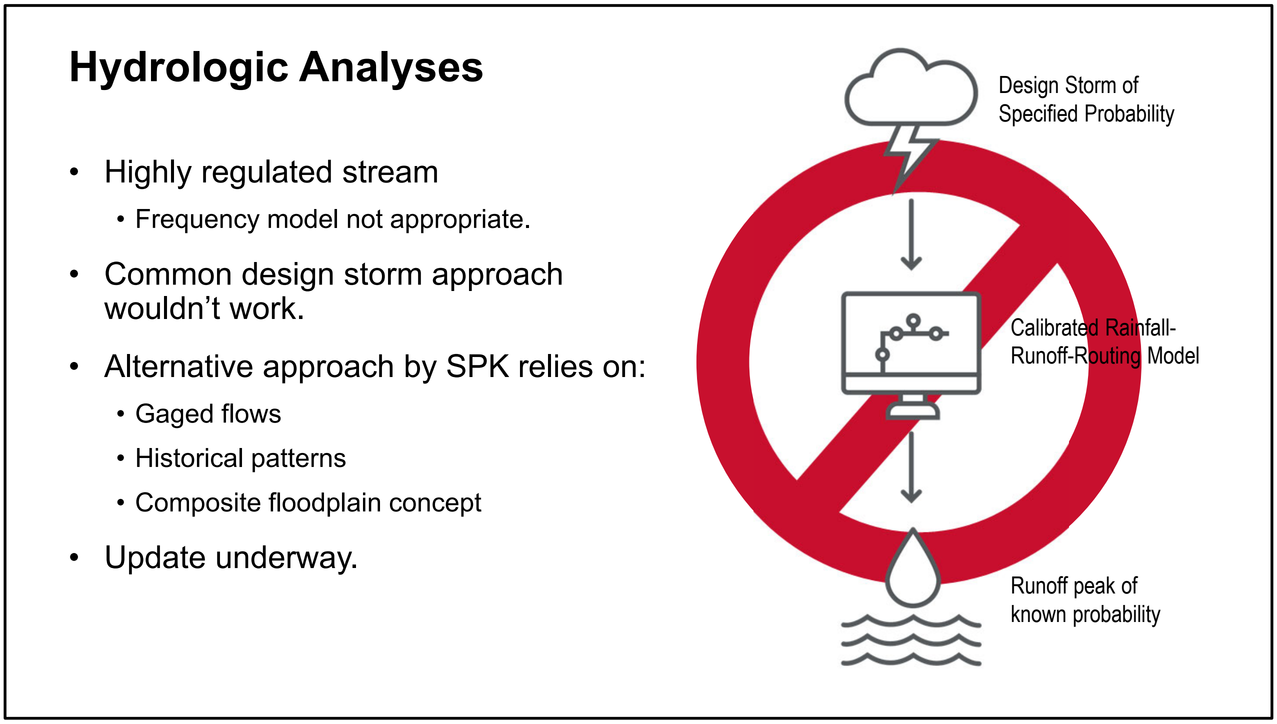


Model Configuration

- About 60 impact areas.
- Consequence related to stage on adjacent/predominate stream.
- Stage-consequence and H&H models from Comp.



- ~60 impact areas
- Consequence related to stage on adjacent/predominate stream.
  1 stream per impact area, with exceptions.
- Stage-consequence models from Comp. Study, enhanced through CVFPP.
- H&H models from Comp. Study, enhanced through CVHS and CVFED.

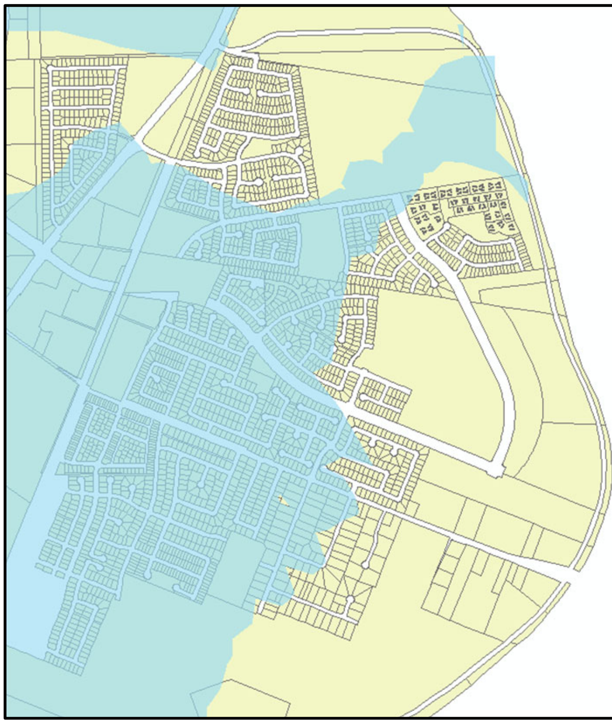


- Highly regulated stream;
  - fitting frequency model to gaged data not appropriate.
- Common design storm approach wouldn't work.
- Alternative approach by SPK relies on gaged flows, historical patterns, composite floodplain concept.
- Update underway.

Hydraulic Analyses

- Hydraulic analyses now use HEC-RAS.
- Geometric data collected.
- 100+ routing reaches and 3,000 cross sections.
- Extensive use of advanced modeling features.

- Hydraulic analyses use unsteady network model—mother of all UNET models initially, now HEC-RAS.
- Geometric data collected using digital terrain models and bathymetric surveys (2-ft contours.)
- 100+ routing reaches and 3,000 cross sections.
- Extensive use of advanced modeling features, including hydraulic storage areas, lateral weirs, flow diversions, levees, and bridges.

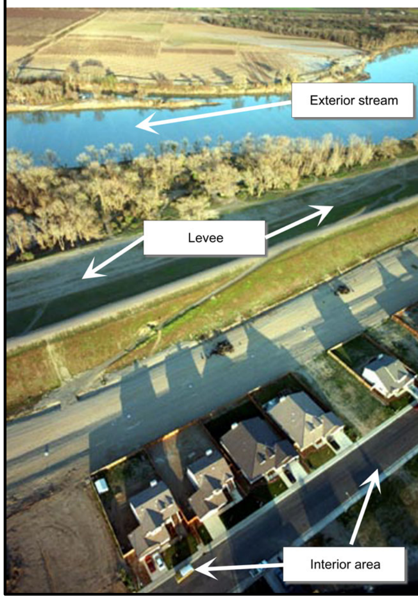


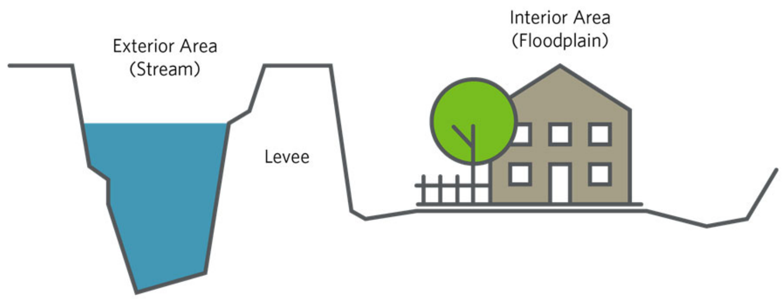
Exposure for Consequence Analysis

Parcel ID (1)	Value of Property ($1,000) (2)
046-491-005-000	165.83
046-491-004-000	150.97
046-492-008-000	217.21
046-503-001-000	239.81
046-492-002-000	192.66
046-521-005-000	219.72
046-491-002-000	195.40

04 What makes analysis difficult?

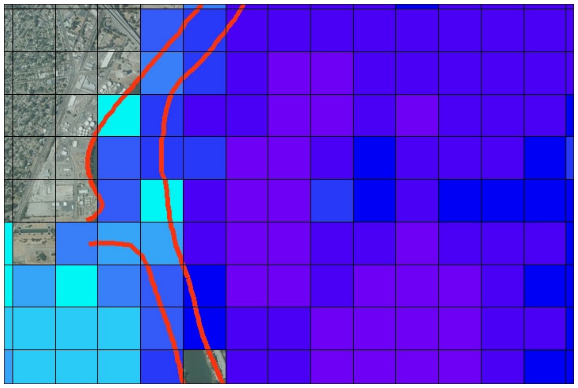
Part 1: What makes analysis difficult?

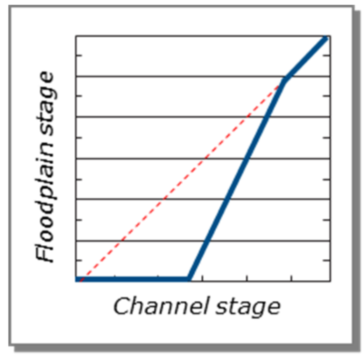


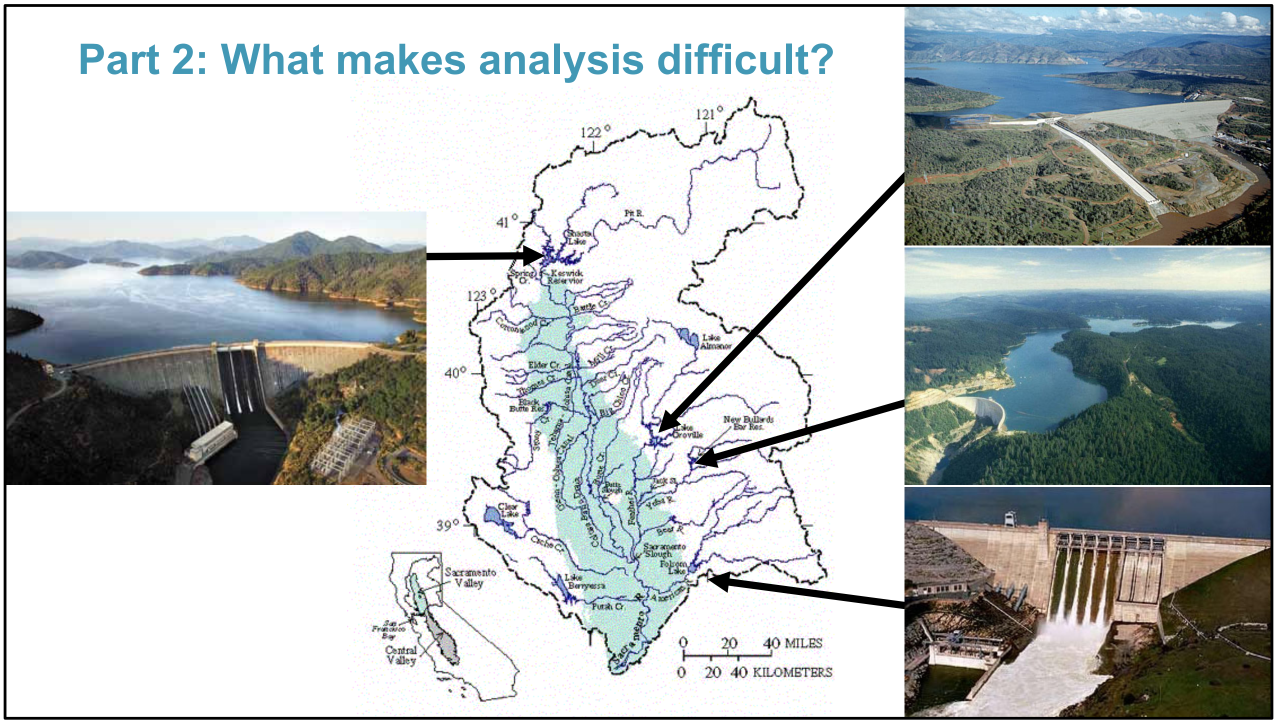


- Much of what matters to people in region protected by levees.
- Exterior stage-frequency function does not represent interior flooding, so cannot be used for risk and damage computations.

How We Deal With That

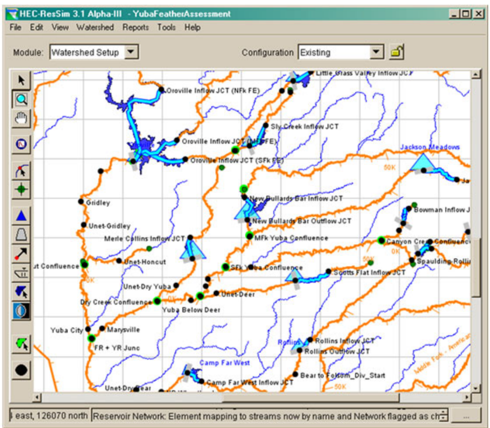


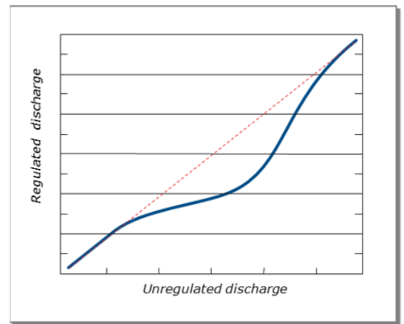




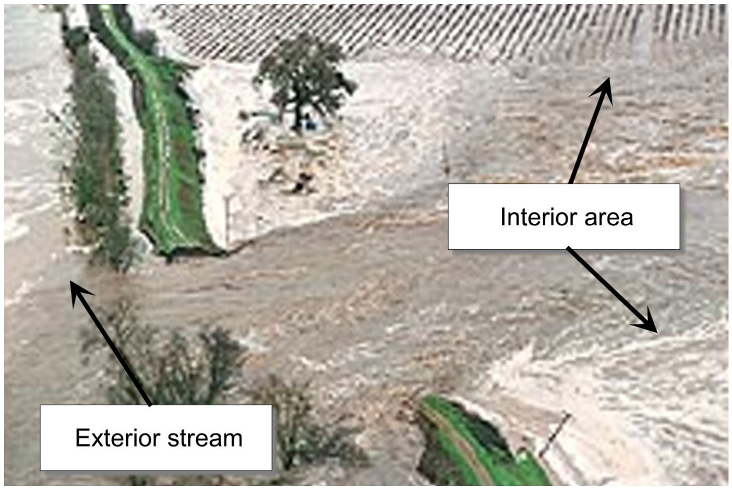
- Folsom 1M,
- NBB 2M,
- Oroville 4.5M,
- Shasta 4.5M

How We Deal With That

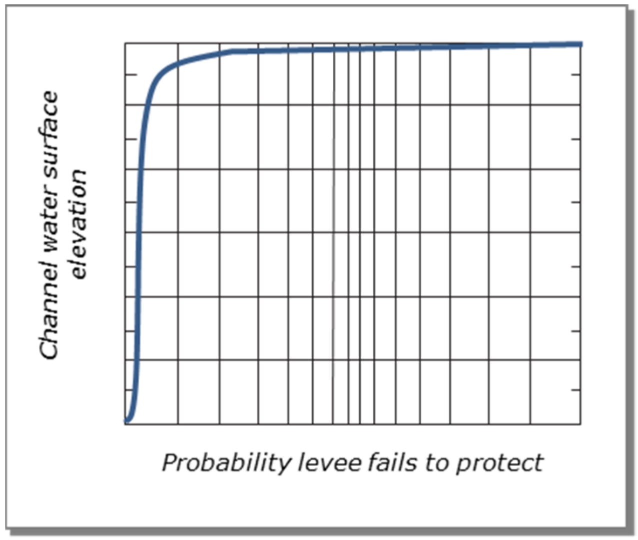




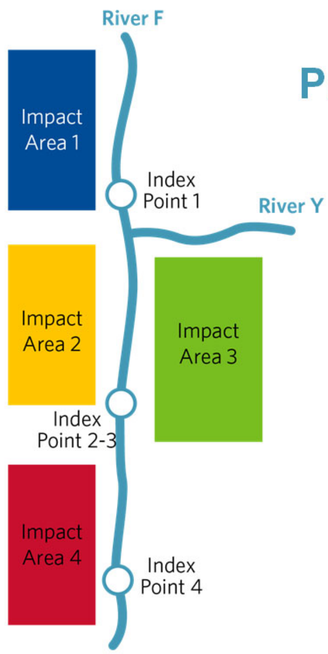
Part 3: What makes analysis difficult?



How We Deal With That



- Develop levee performance functions at index points
- Different studies had varying degrees of “rigor”.
    - For CVFPP, much exploration, drilling, etc. + expert elicitation



Part 4. What makes analysis difficult?

- What is p=0.01 stage at index point 1?
- What is p=0.01 stage at index point 4?

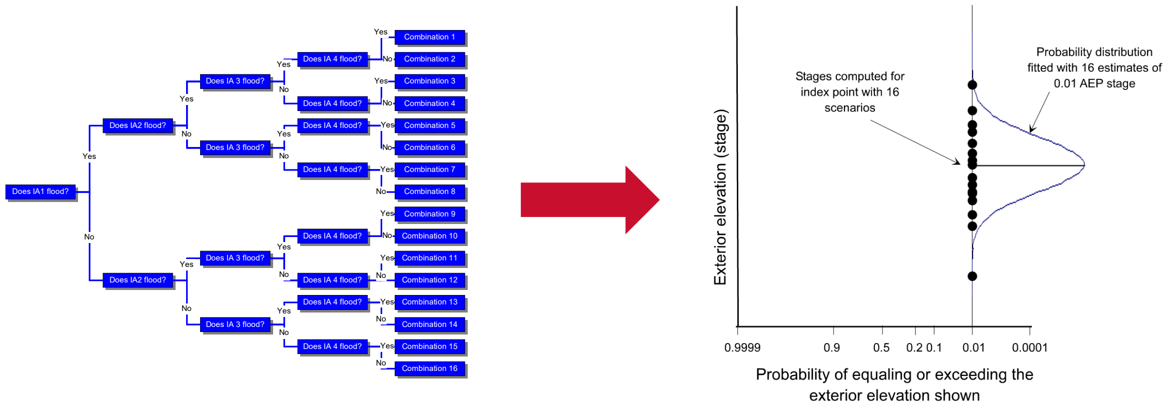
What is p=0.01 stage at index point 1?
What is p=0.01 stage at index point 4?
Q: Given set of frequency-based design storms, appropriate watershed and channel models, and descriptions of uncertainty about system behavior and performance, how can we define stage-frequency function at any index point in a leveed system?

What would you do?

Possible solutions

1. Ignore it and hope that it goes away or that no one else notices. (Good luck.)
2. Use the worst case, like FEMA does.
   (Defeats the purpose of risk analysis, doesn't it?)
3. Use frequency-based storm analysis with complete enumeration.
4. Use frequency-based storm analysis with selective enumeration.
5. Use frequency-based storm analysis with integrated sampling.
6. Use period-of-record analysis.

Frequency-Based Storm Analysis with Complete Enumeration

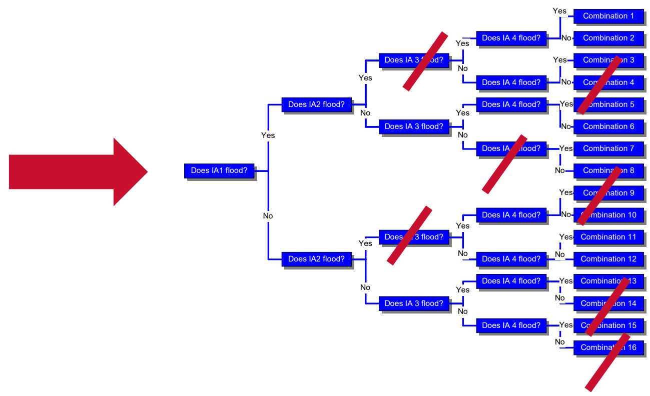


- For 20 impact areas, 8 storms, 2 centerings – 16 million runs.
- If they take 5 min – 160 yrs for analysis

Frequency-Based Storm Analysis with Selective Enumeration

Ask experts to identify more-likely failure scenarios.

Evaluate only those.

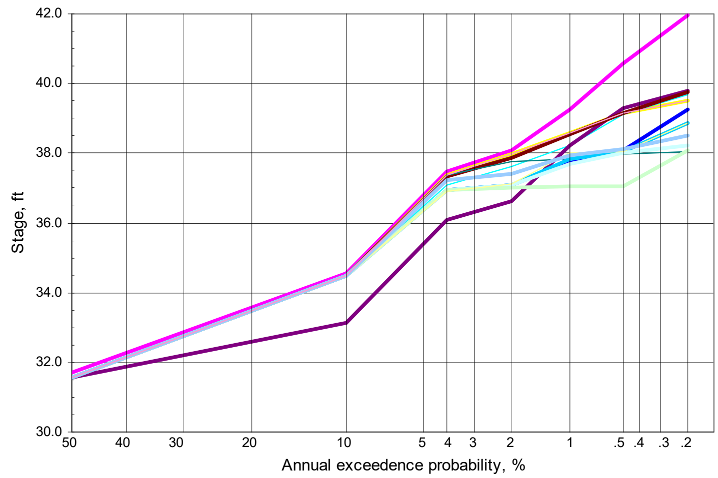


Steps in our solution

- Found experts.
- Provided information.
- Opinions on failure for p=0.50 to p=0.002 events.
- Configured and ran HEC-FDA.
- Statistically analyzed computed EAD and other measures of performance.

- Found experts who understand the system, know the history, etc.
- Provided info. such as profiles for overtopping only, infinitely-high levees, etc.
- Asked experts for opinions on failure for p=0.50 to p=0.002 events.
- Configured and ran HEC-FDA separately and independently for each expert’s stage-frequency function.
- Statistically analyzed computed EAD and other measures of performance.

Stage-Frequency Functions for Expert Scenarios for SAC36



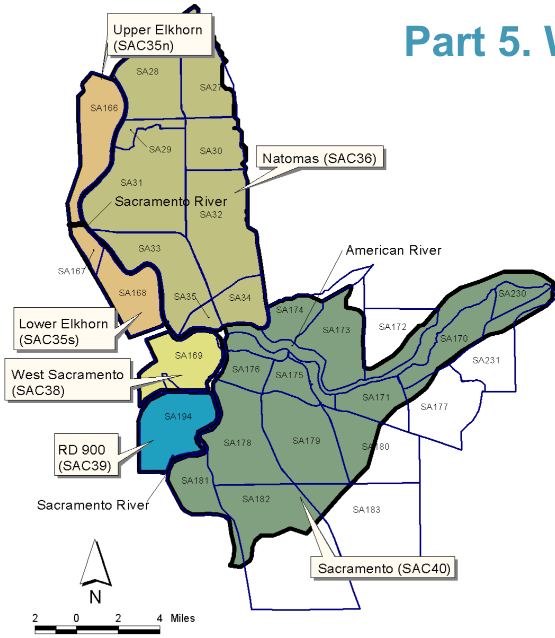
Results of Analysis for SAC36

Scenario (1)	EAD ($1000) (2)	Annual exceedence probability (3)	Conditional non-exceedence probability for 0.01 AEP flood (4)
1	14,223	0.0110	0.6425
2	8,473	0.0070	0.7981
3	6,433	0.0050	0.8778
4	3,982	0.0030	0.9854
5	9,095	0.0070	0.7979
6	3,967	0.0030	0.9210
7	7,261	0.0060	0.8056
8	6,565	0.0050	0.8064
9	6,375	0.0050	0.8077
10	3,150	0.0020	0.9680
11	6,516	0.0050	0.8069
12	3,719	0.0030	0.8911
13	8,473	0.0070	0.7981

Why it is so hard to keep your eye on the ball…

- ***Paterno v. State of California*.**
  - 3000 plaintiffs sued for damages when Linda levee collapsed in 1986.
  - State's potential liability $800M to $1.5B.
- **Most-likely future without project condition now?**
  - Maybe fix levees to design profile. But when?

- *Paterno v. State of California*. 3000 plaintiffs sued for damages when Linda levee collapsed in 1986. State assumed responsibility for levee in 1953. Plaintiffs argued that State owed for property lost in flooding.
- 3rd District Court of Appeals found State should have known fragility, had "ample opportunity" to monitor & make necessary improvements. State Supreme Court refused to hear on appeal. State's potential liability $800M to $1.5B.
- Most-likely future without project condition now?
  Maybe fix levees to design profile. But when?



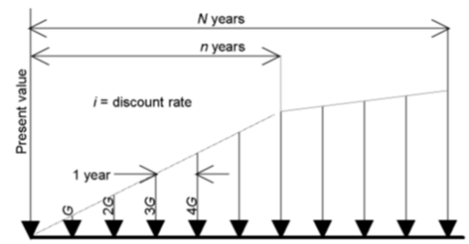
Part 5. What makes analysis difficult?

- Configured UNET.
- Created “sub-impact areas.”
- Computed EAD, AEP, CNP.
- Now, channel elevation to floodplain surfaces.

- Configured UNET w/ storage areas to account for spatial variations of stage. Water flows between.
- Created “sub-impact areas” with interior-exterior relationship for each.
- Computed EAD, AEP, CNP, for each, as before, with multiple scenarios.
- Now, channel elevation to floodplain surfaces.

Part 6. What makes analysis difficult?

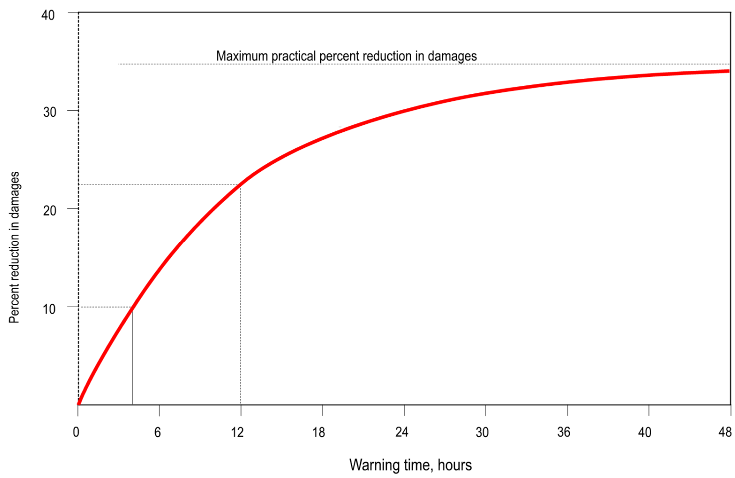
- Development continues.
- Forecasted future damage.
  - Future, without-project = conditions expected in absence of project.
  - Must consider NFIP participation.
  - Used population projections.
- Scaled or recomputed EAD.



- Development continues.
- Forecasted future damage, without & with project.
  - Future, without-project = conditions expected in absence of project. Gotta consider NFIP participation.
  - Used population projections, authorized plans, to develop growth rate.
- Scaled or recomputed EAD.

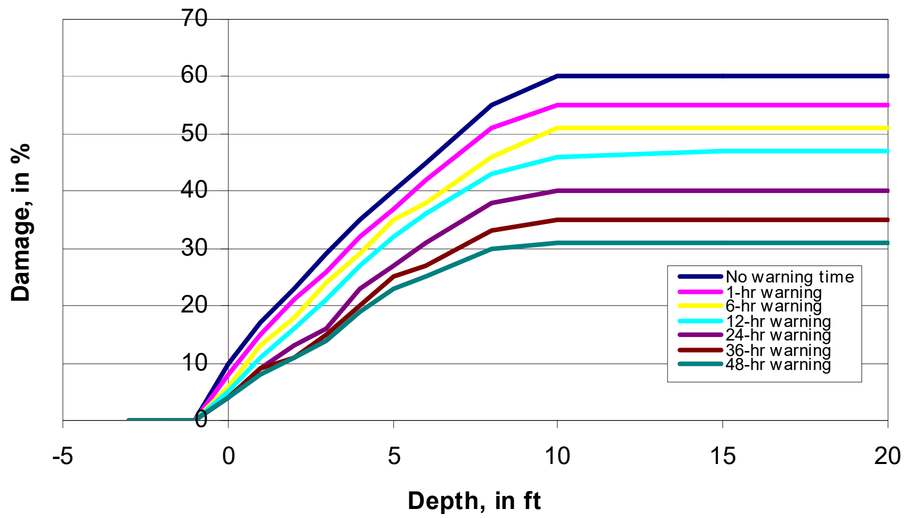
Part 7: What makes analysis difficult?

Sacramento River system has outstanding flood forecasting/ response system in place.



- Sacramento River system has outstanding flood forecasting / response system in place.
  - Advanced warning offers damage reduction.
  - Plans include enhancing that system.
  - All earlier Corps' flood warning studies use Day curve to evaluate. HQUSACE said **NO** here.

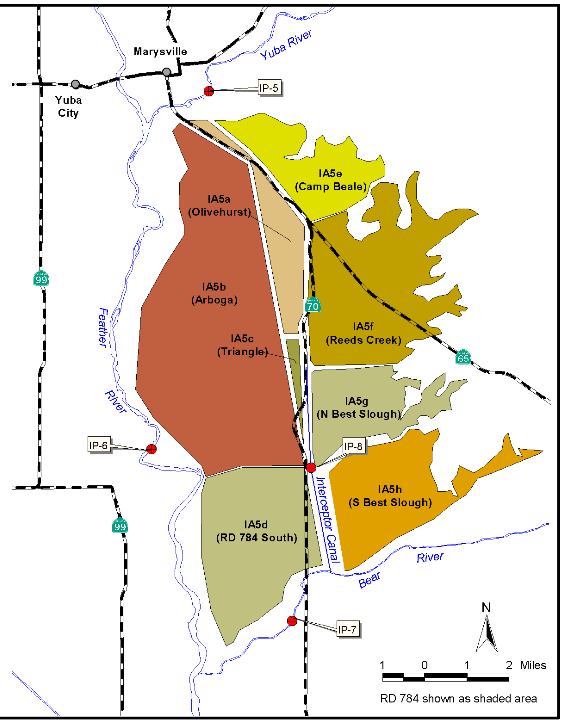
Depth-damage-warning time



- Started with Corps' depth-damage function for residential content.
- Surveyed experts for opinion re: damage reduction possible with varying mitigation time.
- Produced and used new method that accounts for lead time, system efficiency.
- Technical paper on procedure in ASCE journal. Also accepted by NWS and USGS.

Part 8: What makes analysis difficult?

- Flooding from multiple sources with levees to protect.
  - For example, RD 784 (see right).
- How do we characterize risk and potential damage in a case such as this?



- In some locations, flooding from multiple sources--with levees to protect.
  - For example, RD 784 (at right) subject to flooding from Yuba, Feather (trib to Sacramento), Bear, and WP Interceptor Canal.
- How do we characterize risk and potential damage in a case such as this?

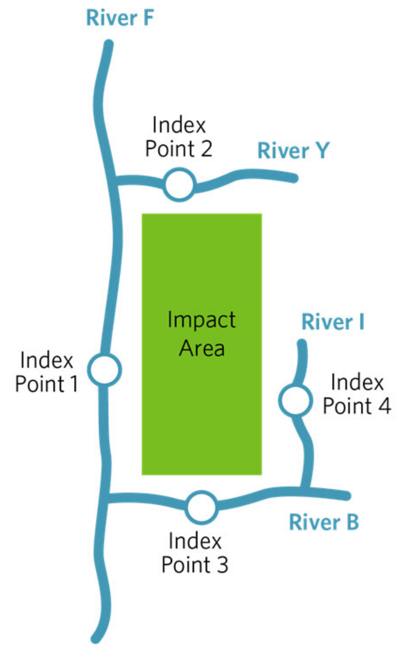
What would you do?

Our Previous Approach

- Identified index point (IP) on each stream.
- Computed weighted EAD, with weights assigned as:

$$wt_{IP} = \frac{AEP_{IP}}{\sum_{IP=1}^{n} AEP_{IP}}$$

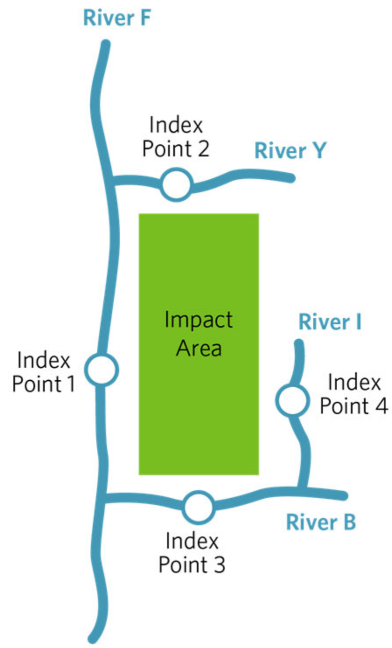
- $AEP = \min(AEP_{IP})$



- Identified index point (IP) on each stream.
  - Developed stage-freq for IP.
  - Defined interior-exterior relationship for impact area (IA) with that IP.
  - Computed AEP and EAD for IA with selected IP.
  - Repeated for each IP.
- Computed weighted EAD, with weights assigned as (equation pictured)
- $AEP = \min(AEP_{IP})$

Our Current Approach

- Assess independence of IPs
  - Assess degrees of correlations
  - Use appropriate methods based on findings.
- Compute EAD with that.
- Determine AEP with that.



Assess independence of IPs.
Assess degree of correlation between dependent IPs. (Watch consistency in correlation assumptions with hydrology and hydraulics)
Use appropriate method based on findings of correlation analysis.
Compute EAD with that.
Determine AEP with that.

Multiple Flood Source Expected Annual Damage Computations

Nathan Pingel, M.ASCE[1]; and David Watkins Jr., M.ASCE[2]

Abstract: For flood damage reduction analysis, the standard for measuring risk is expected annual damage. This index represents a long-term average annual flood damage for a given structure or area. We compute this index by integrating a probability-damage function. In practice, we develop the required function by developing a water level (stage)-probability function and an elevation-damage relationship. The analysis becomes complex when the stage-probability function is dependent upon multiple flooding sources. For example, this occurs when an area is protected by multiple leveed reaches or can be flooded from more than one stream. Here we propose alternative analysis frameworks for computing expected annual damage considering this complicating factor. An example illustrates that appropriate methods depend on the alternatives evaluated, the correlation of discharges, and the number of levee reaches.

DOI: 10.1061/(ASCE)WR.1943-5452.0000031

CE Database subject headings: Risk management; Damage; Floods; Computation.

Author keywords: Risk analysis; Expected annual damage; Index point; Flood damage reduction studies; Risk management.

Motivation

Why Are Flood-Damage Reduction Studies Undertaken?

For flood management planning, we are interested in the optimal expenditure of funds to protect lives and property. Many alternatives can reduce flood damages to a specific area, so the question becomes: what is the most efficient alternative for reducing flood damages? In this analysis, we must consider the risk reduction for a given alternative, thus the difference in risk without the project and the risk with the project. To provide information for answering this question, flood-damage reduction studies are undertaken and the flood risk is quantified for different conditions. Risk is a function of probability of occurrence and the associated consequences. To account for the random nature of flooding, we use the expected value of annual damage to measure flood risk. This considers the impact of all floods, weighting the damage caused by each flood by the likelihood of the flood occurring, and is referred to as the expected annual damage (EAD). EAD is the standard of practice index for economic evaluation of flood damage reduction projects.

Note that EAD typically does not consider other risks such as potential loss of life; rather it focuses on property damages. Since Hurricane Katrina, and the resulting lives lost and regional economic impacts, more emphasis has been placed on addressing social, economic, and ecological risk in a broader context (Interagency Performance Evaluation Task Force 2007; D. A. Moser, "Transforming the Corps into a risk managing organization." Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, Va., unpublished report, 2007). Further, flood damage reduction studies are beginning to quantify these other benefits of flood damage reduction projects (Bowles and Aboelata 2007).

EAD Computations

Computation of EAD involves the use of watershed, channel, and economic models to develop and integrate the probability-damage function. These computations are typically done to estimate the economic benefits, measured as reduction in EAD, of proposed flood-damage reduction alternatives. The EAD computations are described in Pingel and Ford (2004), NRC (2000), and USACE (1996). The current standard-of-practice method for EAD computations involves the use of the U.S. Army Corps of Engineers' computer program HEC-FDA (USACE 1998). The program includes the risk analysis methods prescribed in Corps of Engineers policy regulations ER 1105-2-100 (USACE 2000) and ER 1105-2-101 (USACE 2006), as well as the technical procedures described in EM 1110-2-1619 (USACE 1996). Specifically, the program aids in plan formulation and evaluation for flood damage reduction studies, with consideration of uncertainty in discharge-frequency, stage-discharge, and stage-damage relationships. The user defines a stage-damage function (with uncertainty) for each impact area (IA), and each IA is associated with a single index point (IP) where discharge-frequency and stage-discharge relationships (both with uncertainty) are defined. Alternatively, an IP may simply have a stage-frequency relationship.

For the computations, from an economic perspective, we must develop an elevation-damage relationship for the floodplain. From a hydrologic and hydraulic perspective, we must develop an elevation (stage)-probability function. For this latter function, to simplify the computation, we represent a reach with a single IP, which is assumed representative of the stream or reach and is used to relate the hydrologic and hydraulic relationships to the

[1]Senior Hydrologic Engineer, David Ford Consulting Engineers, Inc., P.O. Box 188529, Sacramento, CA 95818 (corresponding author). E-mail: pingel@ford-consulting.com

[2]Associate Professor, Dept. of Civil and Environmental Engineering, Michigan Tech Univ., Houghton, MI 49931. E-mail: dwatkins@mtu.edu

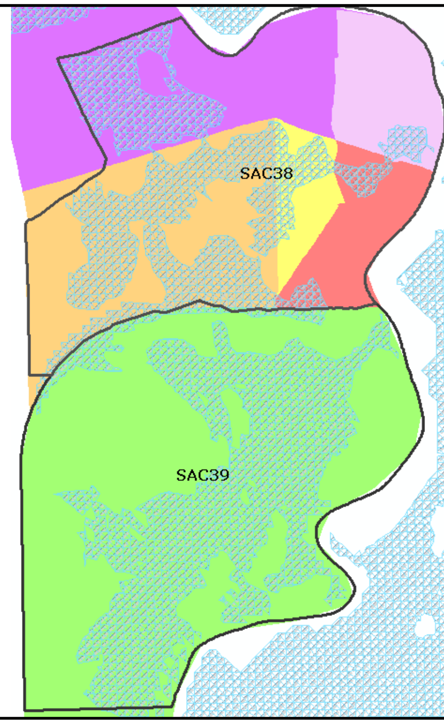
Note. This manuscript was submitted on December 19, 2008; approved on May 5, 2009; published online on May 15, 2009. Discussion period open until October 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 136, No. 3, May 1, 2010. ©ASCE, ISSN 0733-9496/2010/3-319–326/$25.00.

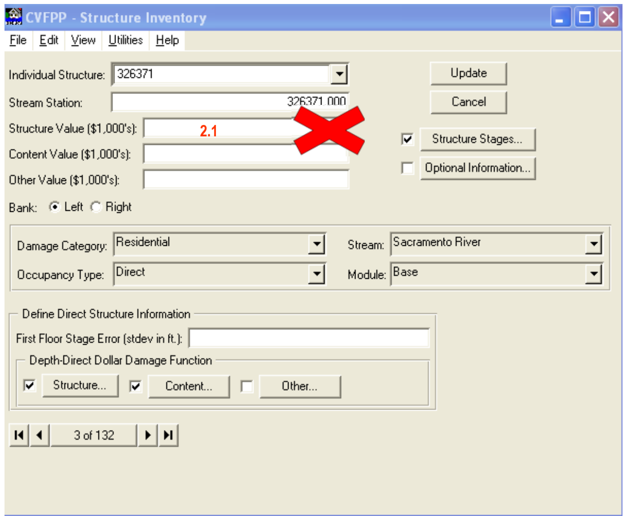
ASCE Journal of Water Resources (May/June 2010)

Part 9: What makes analysis difficult?

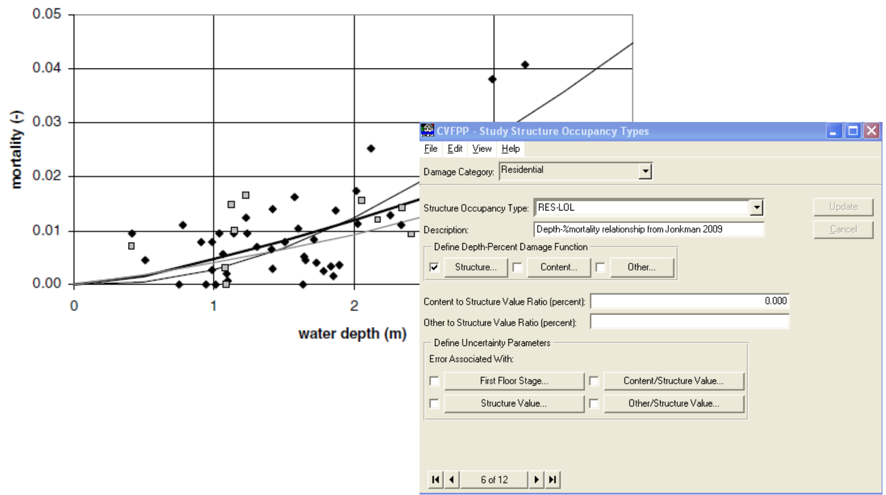
Exposure for Life Risk Analysis

Impact area (1)	Population in floodplain (2)
SAC38	91644
SAC39	789797
SAC40	7217
SJ99	12565

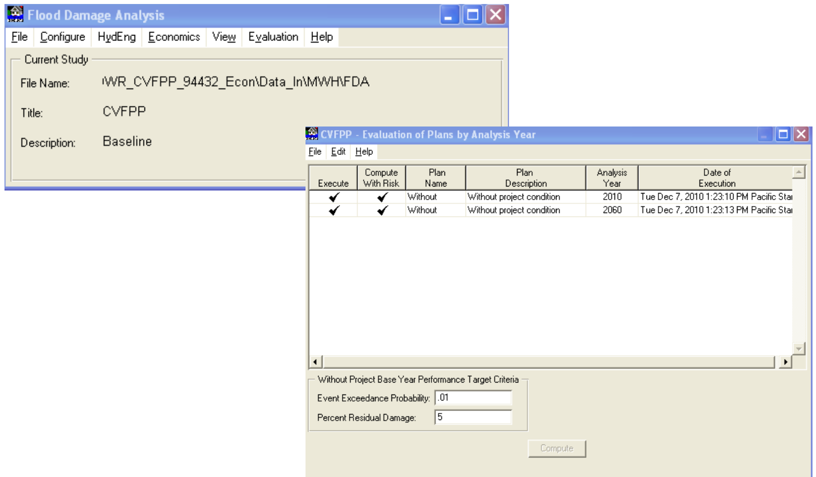



CVFPP - Structure Inventory
File Edit View Utilities Help
Individual Structure: 326371
Stream Station: 326371.000
Structure Value ($1,000's): 2.1
Content Value ($1,000's):
Other Value ($1,000's):
Update
Cancel
Structure Stages...
Optional Information...
Bank: Left Right
Damage Category: Residential
Occupancy Type: Direct
Stream: Sacramento River
Module: Base
Define Direct Structure Information
First Floor Stage Error (stdev in ft.):
Depth-Direct Dollar Damage Function
Structure...
Content...
Other...
3 of 132

Vulnerability



Consequence-Likelihood Computed with HEC-FDA



05 What can you learn from our analyses?

Maintain maximum flexibility in developing depth-damage model.

Work cooperatively with other analysts.

Account for future conditions but be sure to follow the regulations closely.

Answer the questions that are relevant.

- **Maintain maximum flexibility in developing depth-damage model.** For example, don't build in a levee-breech assumption; use the interior-exterior relationship for that.
- **Work cooperatively with other analysts.**
  - Make sure that the geotechs understand how critical performance curves are (*and how difficult it is for you to redo the risk analysis*).
  - Same with H&H analysts. You will bridge any knowledge gap.
  - Remember it's a systems analysis.
- **Account for future conditions but** be sure to follow the regulations closely.
  - ER 1105-2-100 is clear about what to do, but you need to read it a few times to see what is between the lines.
  - Potential shift in policy re: future development.
- **Answer the questions that are relevant.** For some, you won't need EAD, just AEP and CNP.

Look hard at the results.

Account for the **impacts of flood warning** in your watershed.

Don’t oversimplify cases with multiple sources of flooding.

Don’t forget life risk analysis.

- **Look hard at the results.** Make sure the risk analysis is complex, but if the results seem wrong, they probably are.
- Account for the **impacts of flood warning** in your watershed.
- **Don’t oversimplify cases with multiple sources of flooding.** Account for risk associated with each area, and remember that for any one area, only 1 value of EAD exists,1 value of the p=0.01 stage exists, etc.
- **Don’t forget life risk analysis**.