Practical Needs and Approaches for Water Resources Adaptation to Climate Uncertainty

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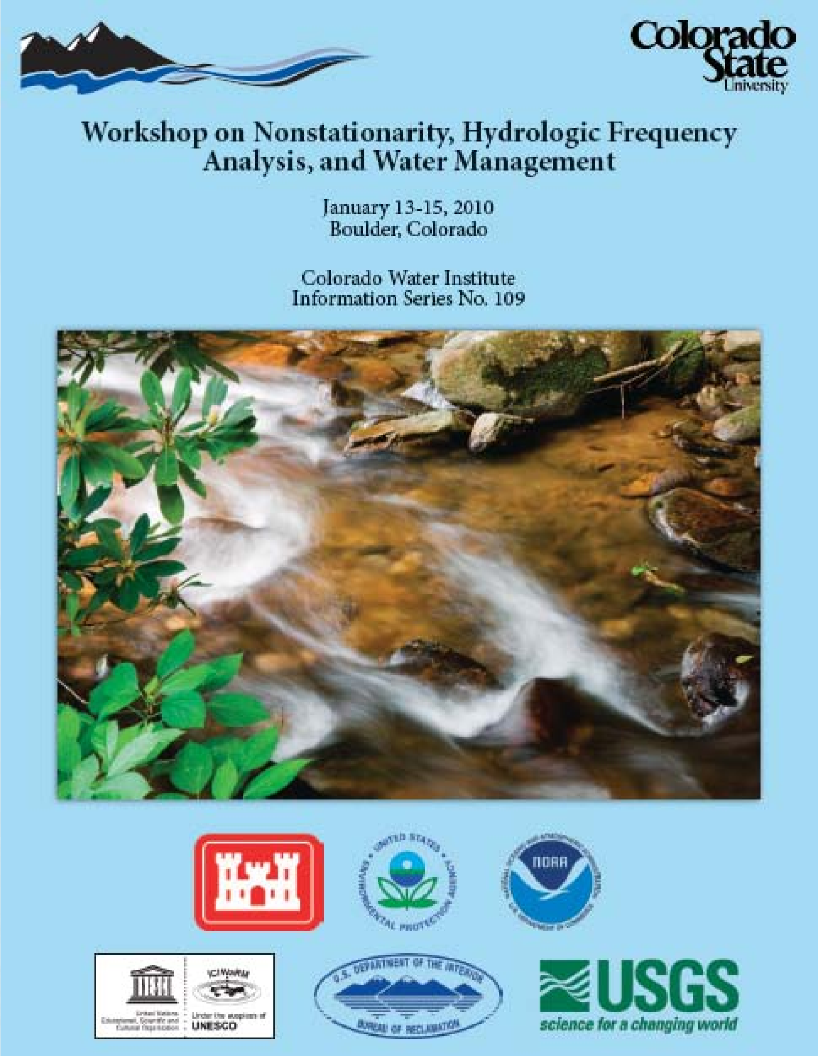

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Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management

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“We are interested in making better decisions, not in better predictions.”

Outline

- Water resources agency decision making
- Flood risk management and climate change and decadal variability
- Seasonal climate forecasts: reservoir management and emergency flood management
- Making decisions with an uncertain climate

Foundations of Water Resources Policy

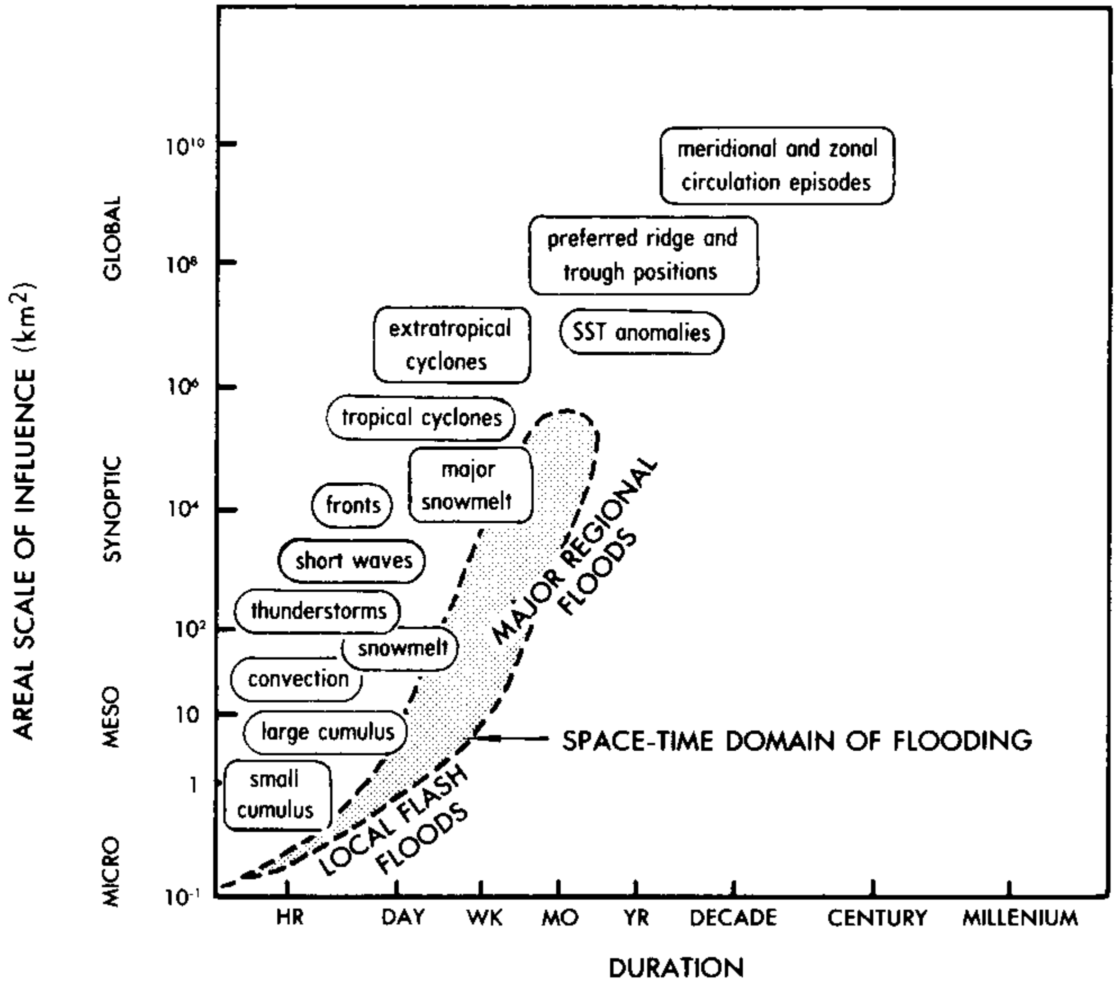
Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (1983)

“Federal objective of water and related land resources project planning is to contribute to <u>national economic development</u> consistent with <u>protecting the Nation’s environment</u>, pursuant to national environmental statutes, applicable executive orders, and other Federal planning requirements.”

Climate Variability and Water Resources

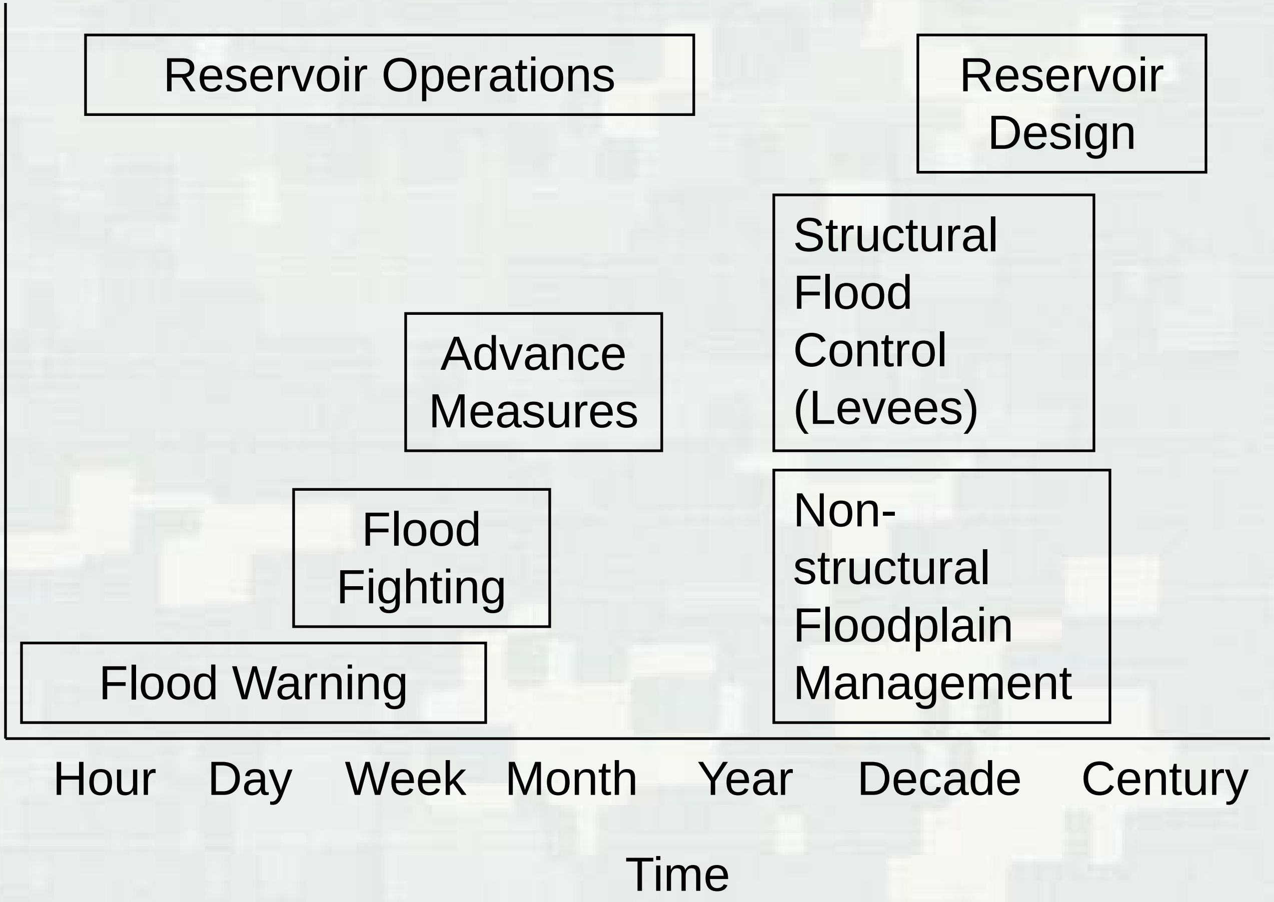
- Water resources agencies deal with climate variability on multiple time scales
    - One of the primary missions is to manage hydrologic extremes: reducing damages during floods and providing water supply during droughts
- Operating rules are generally based on historical record
- Time scale of years to decades
    - Floodplain Management
- Time scale of several weeks to several months (lead times of climate forecasts):
    - Reservoir Management
    - Emergency Management

Spatial and Temporal Scales



Spatial and temporal scales of atmospheric and hydrologic conditions related to flooding

Temporal Scale of Responses



Reservoir Operations

Reservoir Design

Structural Flood Control (Levees)

Advance Measures

Flood Fighting

Non-structural Floodplain Management

Flood Warning

Hour Day Week Month Year Decade Century

Time

Flood Risk Management and Climate Change and Decadal Climate Variability

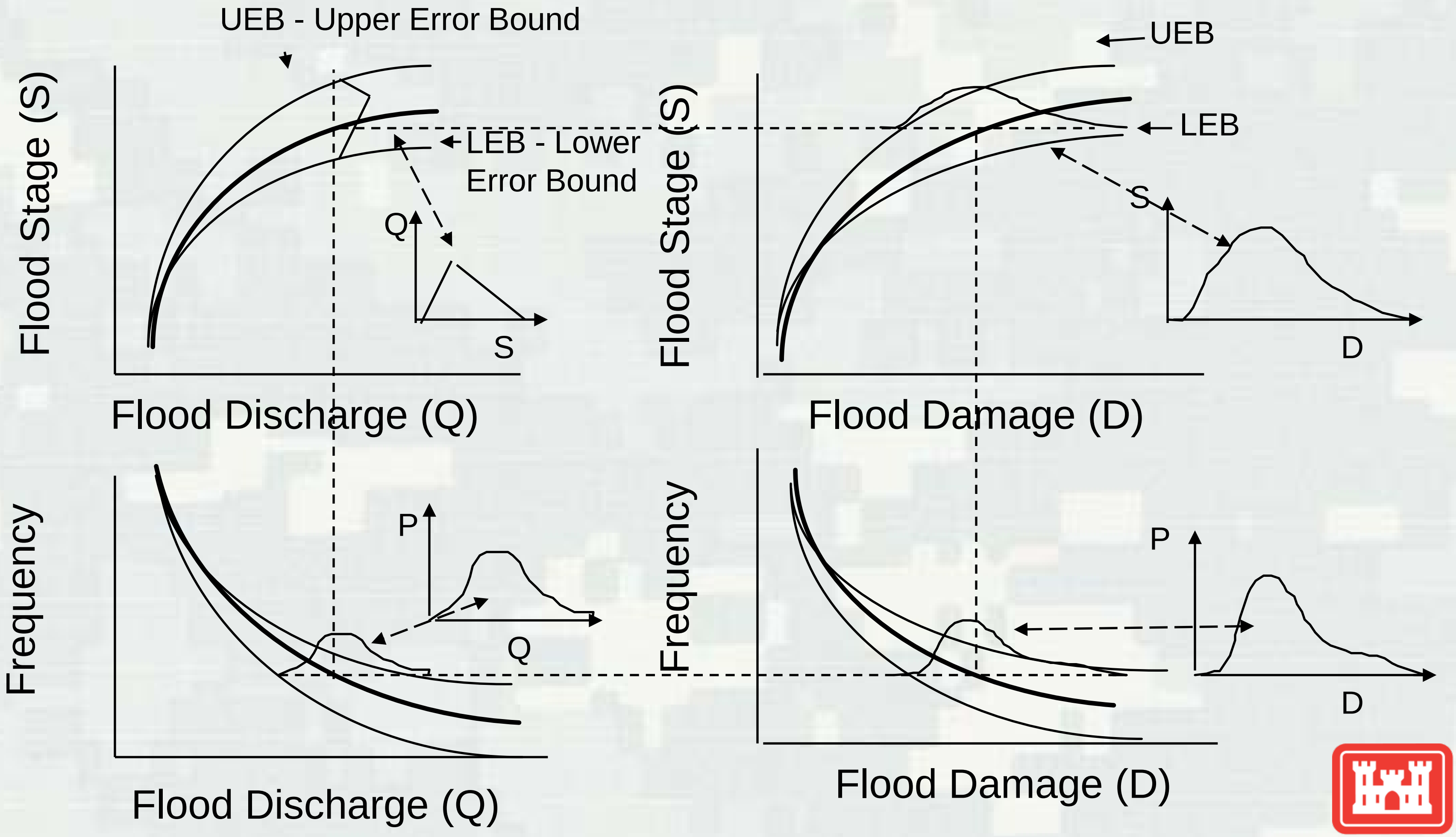
Strategies for Floodplain Management

- Structural floodplain measures (Modify flood).
  - ► reservoirs to store flood waters
  - ► levees to keep floods from a particular area
  - ► channel modifications to increase capacity
  - ► high flow diversions
- Keep people and development out of floodplain or flood proof structures already in the floodplain (Reduce susceptibility to flooding).
- Insurance and post-flood assistance (Reduce financial and social impact of flooding).
- Flood warning and response.

Floodplain Management

- National Flood Insurance Program: risk identification, hazard mitigation, and insurance.
  - Special Flood Hazard Area (SFHA) is defined as area of land inundated by flood having 1% chance of occurring in any given year.
  - Local community must regulate floodplain development as condition for participation in NFIP.
- State and local governments have major responsibility for floodplain management.
  - Development restrictions
  - Zoning laws

Flood Damage Reduction Benefits Estimation



Flood Frequency Analysis: Purposes

- Flood frequency analysis needed to support sound flood plain management.
- Regulatory floodplain defined as area with 1% chance of flood in any year (NFIP).
- Economic justification of flood reduction alternatives require calculation of expected annual damages given alternative plans.
- Flood frequency is basis of engineering design criteria for levees, dams, etc.

What is stationarity?

- The assumption behind traditional hydrologic frequency analysis is that climate is stationary.
- Stationarity means that the statistical properties of hydrologic variables in future time periods will be similar to past time periods.

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds U.S.$500 billion (*1*).

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-cover and land-use change. Two other (sometimes indistinguishable) challenges to stationarity have been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced by the slow dynamics of the oceans and ice sheets (*2*, *3*). Planners have tools to adjust their analyses for known human disturbances within river basins, and justifiably or not, they generally have considered natural change and variability to be sufficiently small to allow stationarity-based design.

An uncertain future challenges water planners.

In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming augments atmospheric humidity and water transport. This increases precipitation, and possibly flood risk, where prevailing atmospheric water-vapor fluxes converge (*6*). Rising sea level induces gradually heightened risk of contamination of coastal freshwater supplies. Glacial meltwater temporarily enhances water availability, but glacier and snow-pack losses diminish natural seasonal and interannual storage (*7*).

Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone (*8*), thereby reducing runoff in some regions. Together, circulatory and thermodynamic responses largely explain the picture of regional gainers and losers of sustainable freshwater availability that has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing (*15*). Paleohydrologic studies suggest that small changes in mean climate might produce large changes in extremes (*16*), although attempts to detect a recent change in global flood frequency have been equivocal (*17*, *18*). Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the range of historical behaviors (*19*). Some regions have little infrastructure to buffer the impacts of change.

Stationarity cannot be revived. Even with aggressive mitigation, continued warming is very likely, given the residence time of atmospheric CO_2 and the thermal inertia of the Earth system (*4*, *20*).

A successor. We need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting. Patterns of change are complex; uncertainties are large; and the knowledge base changes rapidly.

Under the rational planning framework advanced by the Harvard Water Program (*21*, *22*), the assumption of stationarity was

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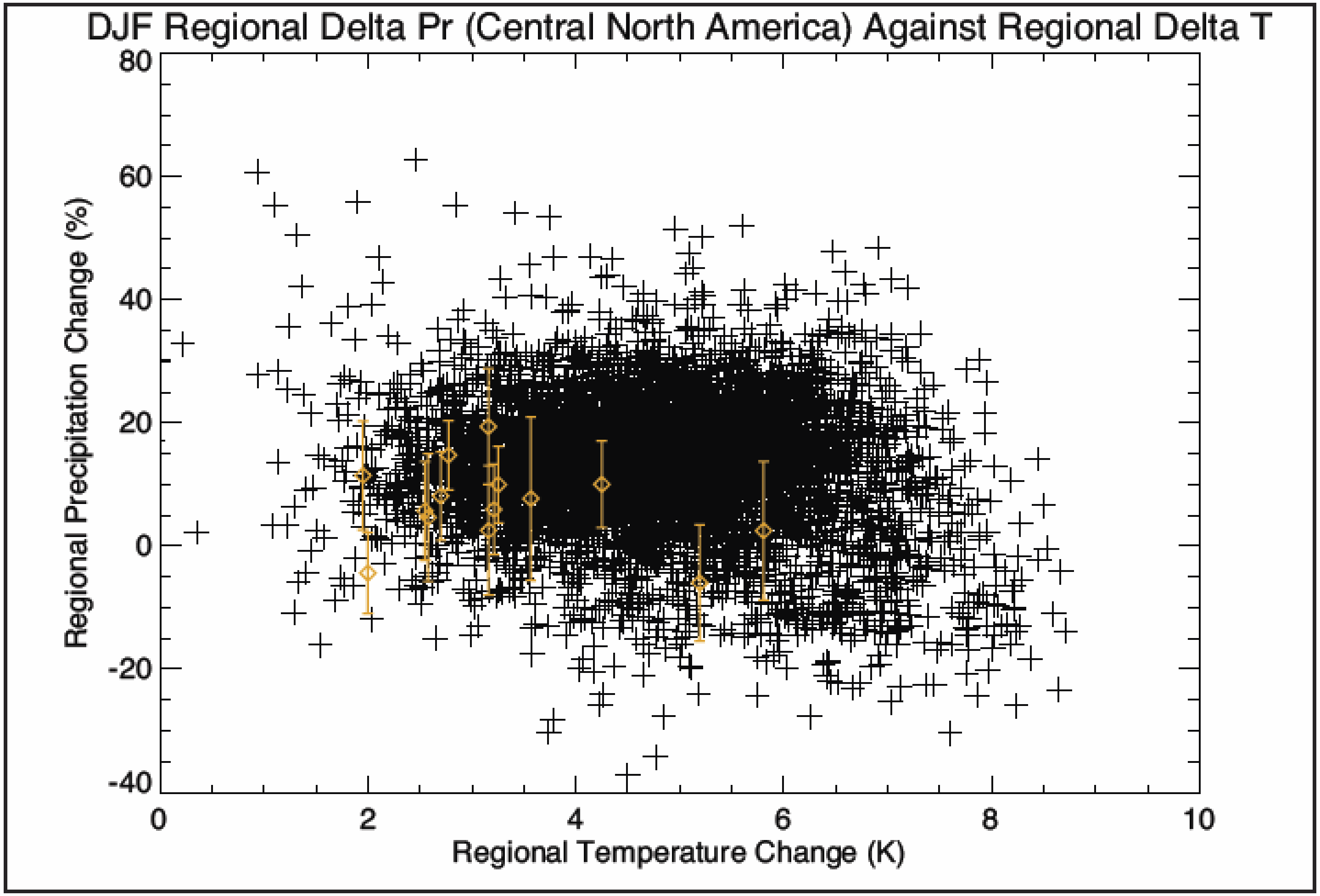
Statistics and Nonstationarity

- Statistical significance of trends may be ambiguous.
- It is difficult to assess whether an observed trend is truly a long term monotonic trend or part of an episodic pattern, of which we see only the upward or downward arm.
- Natural climate variability and long term persistence can cause episodic patterns in long term hydroclimatic records.
- Will the trend persist into the future?

Climate Model Uncertainty

- Forcing uncertainty - uncertainty with future greenhouse gas emissions (i.e. human behavior) and other natural factors.
- Initial condition uncertainty - not having precise estimates on distributed earth system conditions at the beginning of climate simulations.
- Climate modeling uncertainties - knowledge limitations about the climate system physics and limited ability to approximate those physics at space and time scales that are computationally feasible.

Climate Model Uncertainty



Current Flood Flow Frequency Activities

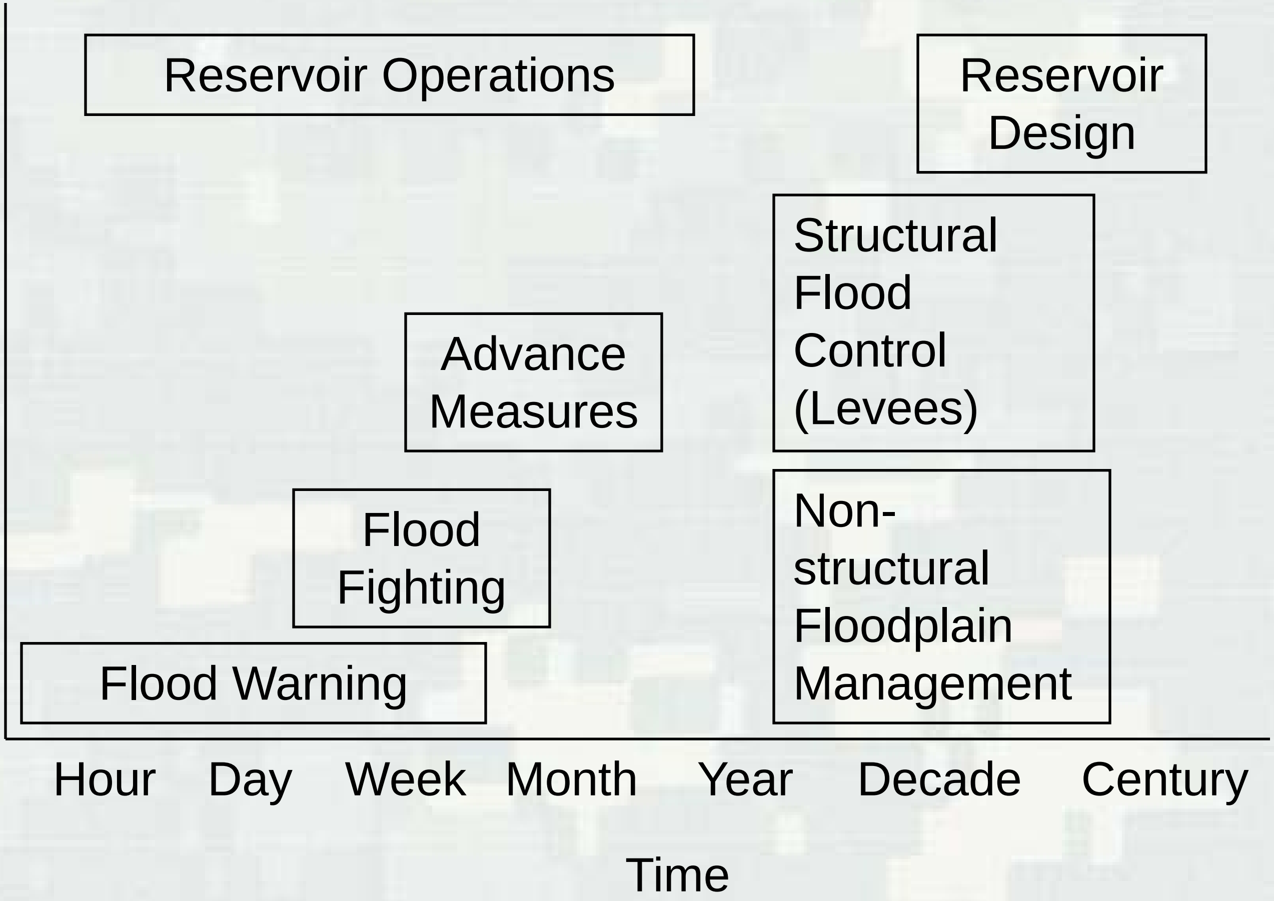
- Revision of Bulletin 17B, *Guidelines for Determining Flood Flow Frequency* will likely change current section on “Climate Trends” and may say that major changes in climate may be occurring over decades.
- May permit time-varying parameters or other techniques where changes in climate and flood risk over time can be quantified.
- In parallel with revision of Bulletin 17B, USACE, USGS, FEMA, Reclamation, and FHWA are evaluating possible approaches to and issues regarding nonstationarity, climate change, and flood risk.

Climate Change and Flood Frequency Analysis

- Adoption of alternative statistical models for flood risk estimates poses policy difficulties for floodplain management.
- Many stakeholders have financial and other interests in using the current method.
  - Flood insurance requirements
  - Levee certification

Seasonal Climate Forecasts: Reservoir Management and Emergency Flood Management

Temporal Scale of Responses



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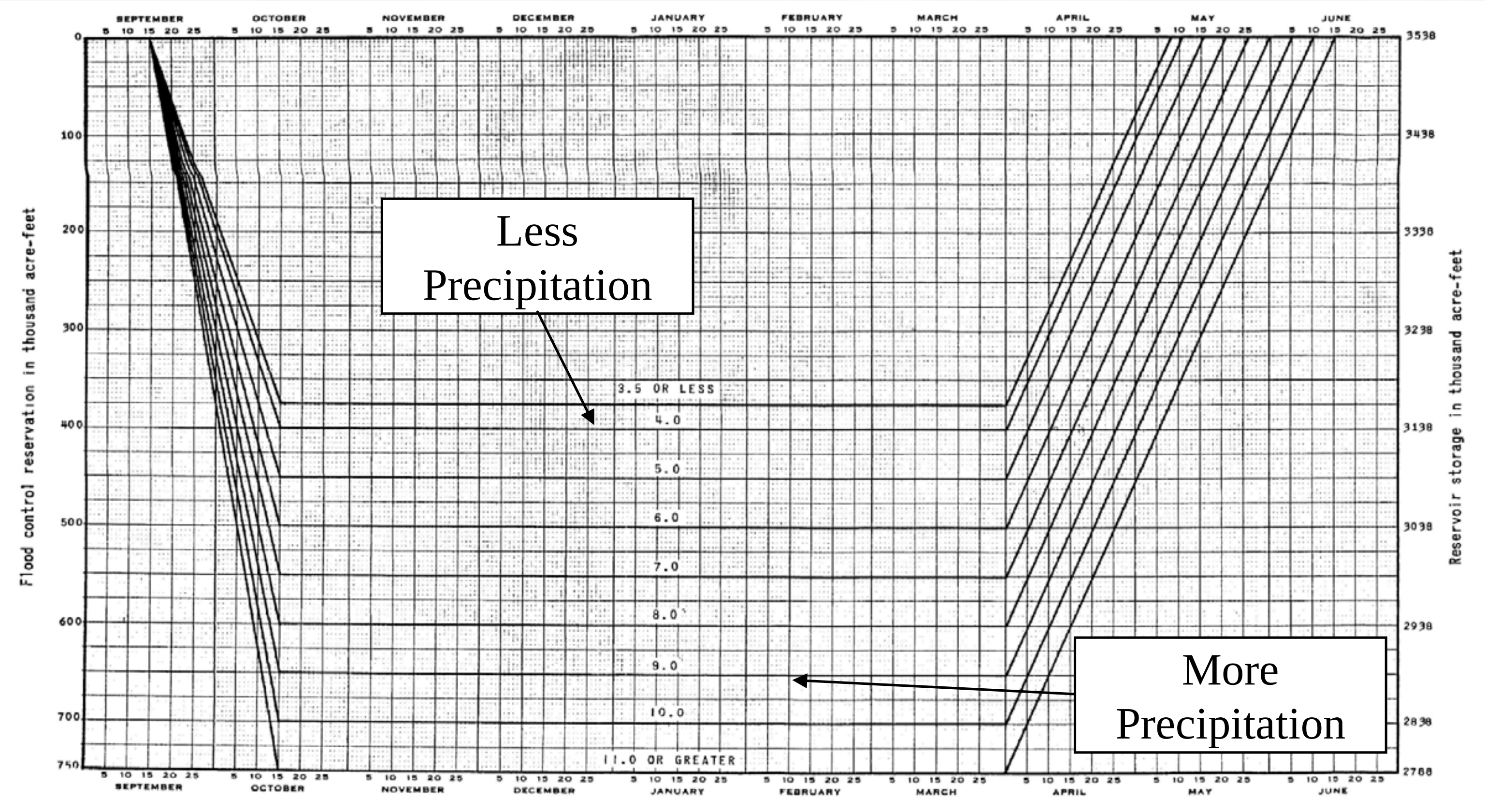
Multi-Purpose Reservoirs

- Flood Control: store runoff during peak flood season
- Hydropower: demand throughout year but peak in winter heating system or summer cooling season
- Fisheries/ Endangered Species (such as salmon, steelhead, sturgeon): naturalized flows (high flows in flood season)
- Irrigation: demand for water in growing season (late spring and summer)
- Water Quality, Recreation, Navigation

Reservoir Rule Curves



Rule curve for Oroville Reservoir, California

Reservoir Management Institutional Context

- Reservoir management is governed by complex set of laws, institutions, and regulations.
  - Congressional authorizations, international treaties, other laws and agreements, environmental regulations and water rights.
- Changes to operating procedures difficult.
  - Changes require long, complex study
  - Public involvement in approval process is required
    - Interest groups support different competing uses for water
    - Changes may cause some interests to be winners while others are losers
- Use of forecasts in reservoir operations must be evaluated in this context.

Other Impediments to Forecast Use

- Accuracy and reliability of forecasts need to be verified over long period.
- Benefits of forecasts have not been adequately assessed over long period.
- Additional uncertainties are present that are not included in forecast probabilities.
- Forecasts should have higher geographic and temporal specificity and skill.
- Variables that are forecast do not match variables needed for decision-making.

Emergency Operations

- Emergency Operations (Flood Fighting)
- Rehabilitation and Inspection of Levees
  - NRC study: Long-term forecasts of regional flooding may allow “improved prioritization of federal levee repair investments.”
  - Rehabilitation of levees in California before 1998 El Niño floods
- Technical Assistance to States and Communities
- Advance Measures

Advance Measures Program

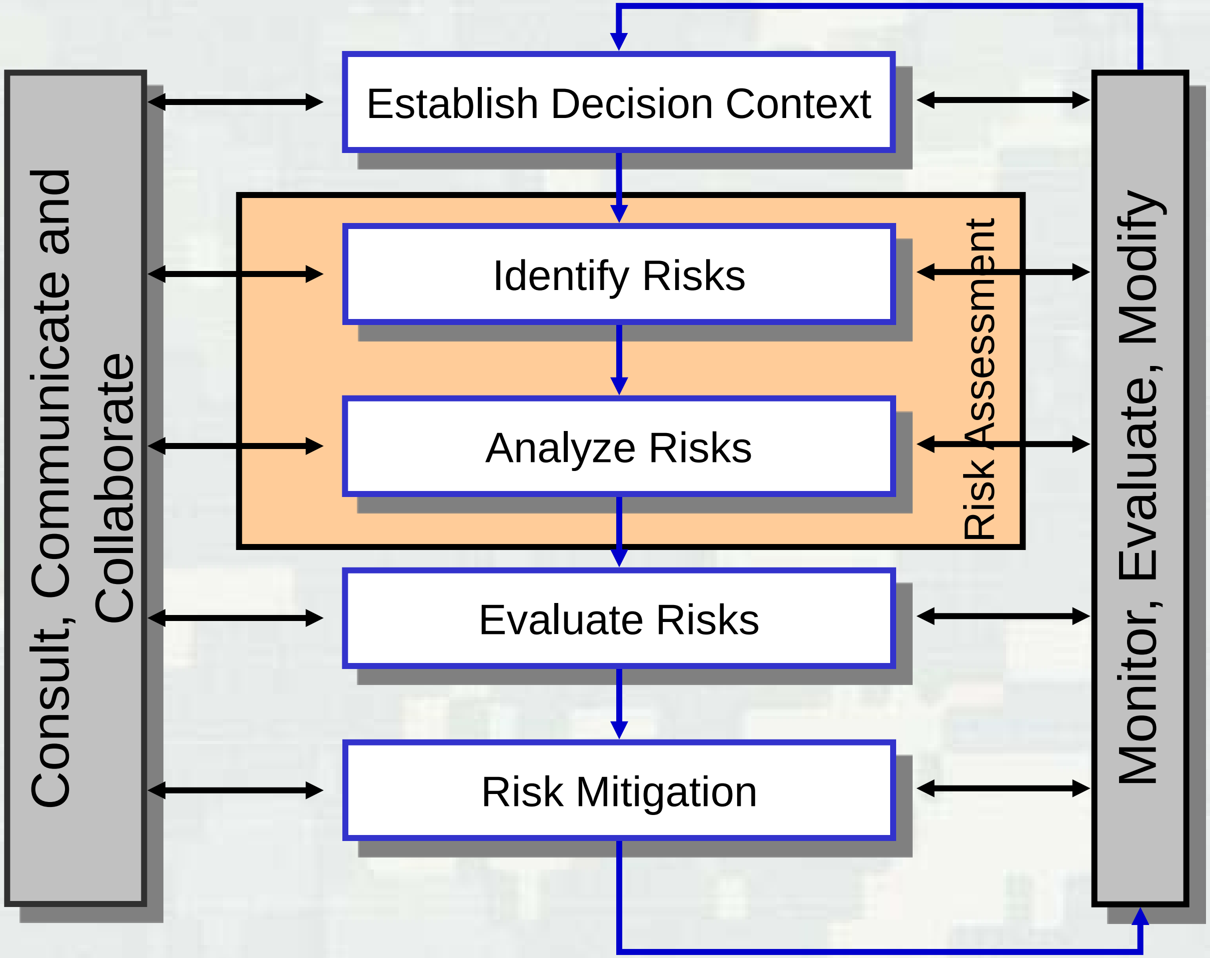
- Protect urban areas from loss of life or significant damages “due to an *imminent threat* of *unusual flooding*” *prior to flooding* or flood fighting activities
- Measures are usually temporary
- Benefit-to-cost ratio of project must be greater than one
- Originally implemented for snowmelt floods

Climate Outlooks and Advance Measures Criteria

- Imminent Threat: high probability of catastrophic damages
- Unusual Flooding: 50-year event or higher or flood of record
- Calculation of expected benefits requires estimate of the probability of flood damages
- Estimation of flood reduction benefits is problematic for flood forecasts based on El Niño/ La Niña outlooks

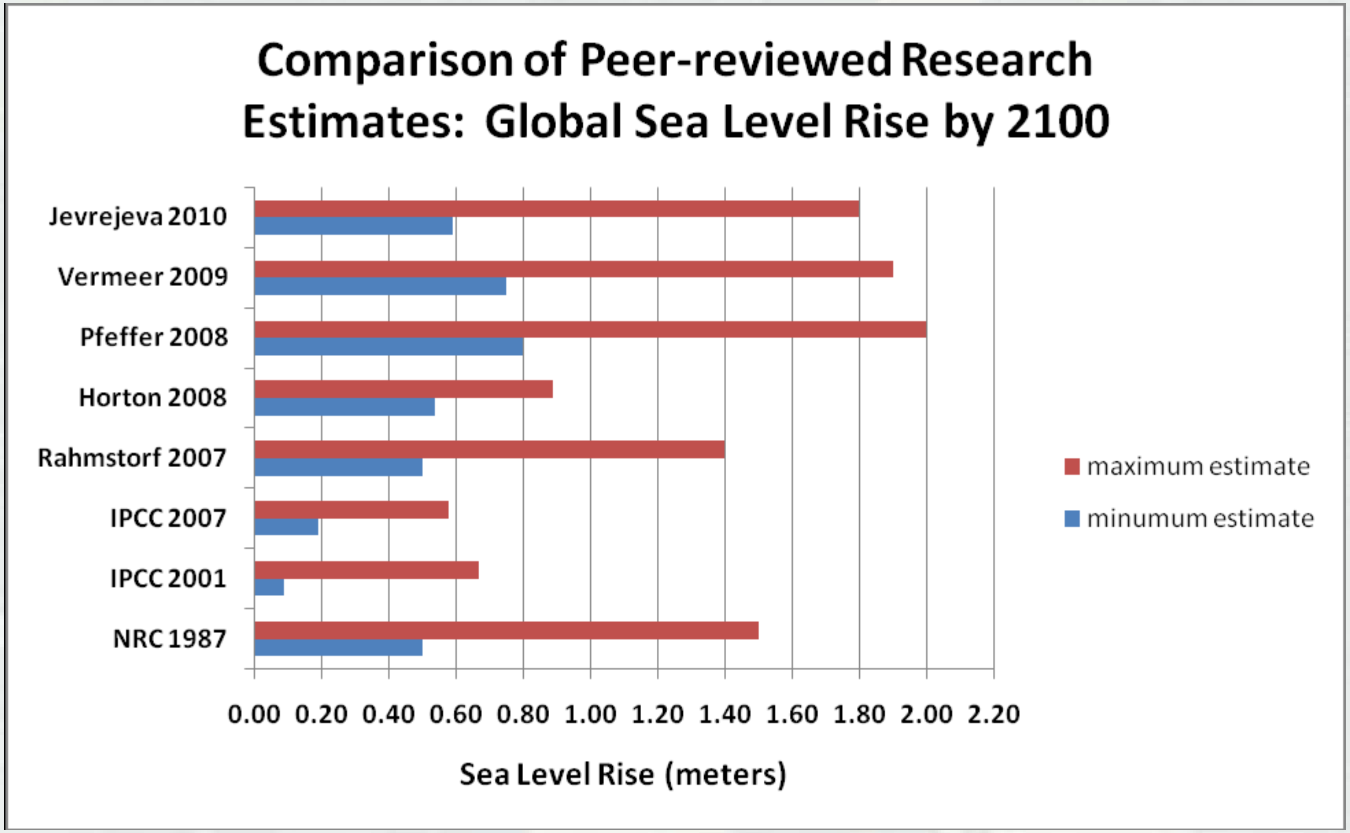
Making Decisions with an Uncertain Climate

Risk-Informed Decision Making



Adapted from ISO 31000- Risk Management—Principles and Guidelines

Science of Sea Level Rise

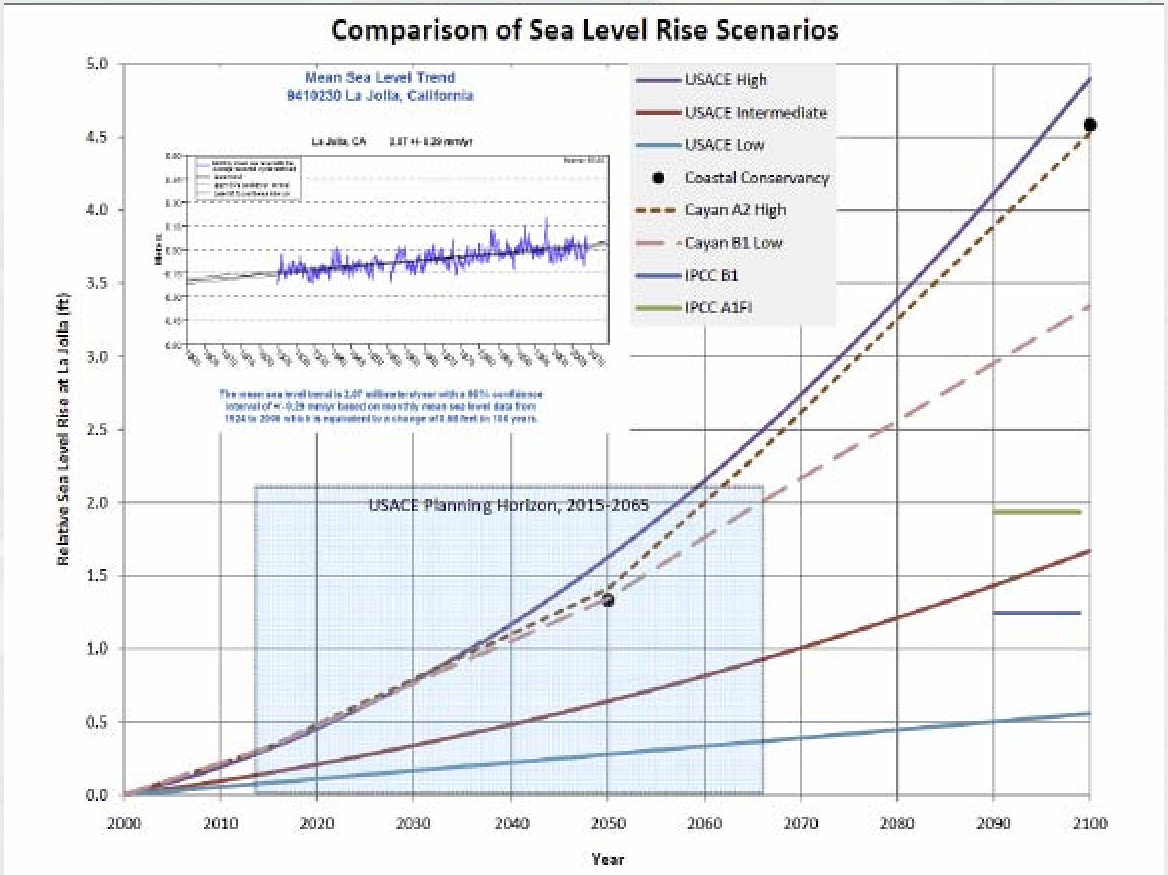


A comparison of projected sea level rise by 2100 (Steve Gill, NOAA-National Ocean Service)
National Research Council (1987) *Responding to Changes in Sea Level: Engineering Implications*

Sea Level Change Guidance

- A multiple scenario approach can account for a range of possible future conditions
- Three estimates of future sea level change must be calculated for all Civil Works Projects within the extent of estimated tidal influence
    - ► Extrapolated trend - Use historic rate of sea-level change as “low” rate.
    - ► Estimate “intermediate” rate using modified NRC Curve I [0.5 meters by 2100]. Consider most recent IPCC projections.
    - ► Estimate “high” rate using modified NRC Curve III. Modified NRC Curve III [1.5 meters by 2100].

Sea Level Rise Scenarios



BUILDING STRONG®

Formulating Risk Management Alternatives

- Formulate plans for a wider range of possible future conditions.
- Potential reversibility of decisions should be one consideration.
- Adaptive management strategy – planners can identify transition points that if crossed would lead to implementation of alternative actions.

Choosing Alternative Plans

- Robustness – find alternatives that perform well under all scenarios
  - Compare with cost-benefit analysis and maximization of National Economic Development
- Evaluation of alternatives
  - Residual Risks – what's the management plan?
  - Does the alternative preclude future decisions? Avoid this if possible. Maintain flexibility.

Managing Residual Risk

- Uncertain information about the likelihood of future flooding implies uncertain residual risk.
- We should better manage residual risk.
    - ►Require evacuation plans
    - ►Implement zoning and limit development despite structural measures that remove community from regulatory floodplain
    - ►Require flood insurance despite no longer being in a regulatory floodplain

Conclusion

- Uncertainty will remain in projections of future flood frequency and magnitudes.
- There are inherent uncertainties in climate science and we need to recognize and plan around the uncertainty.
- We should shift to a more robust “hedge-and-adjust” approach to uncertainty rather than the traditional “predict and optimize” approach.
- **We are interested in making better decisions, not in better predictions.**