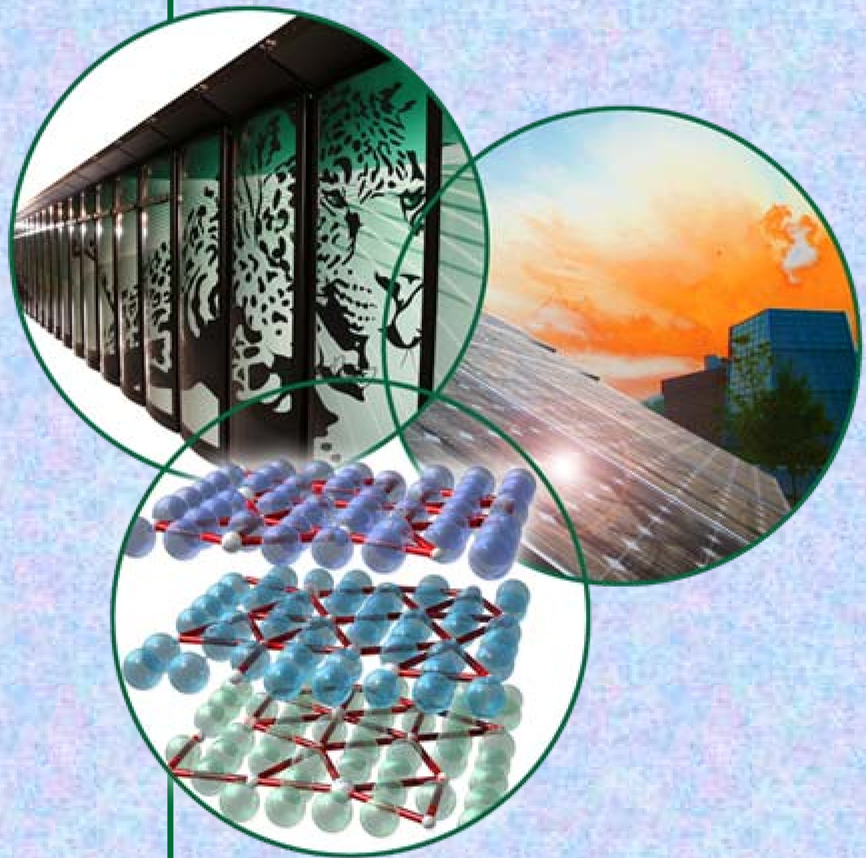
Streamflow Variability and Its Potential Impact on Energy Production

Shih-Chieh Kao, Ph.D.



U.S. DEPARTMENT OF ENERGY

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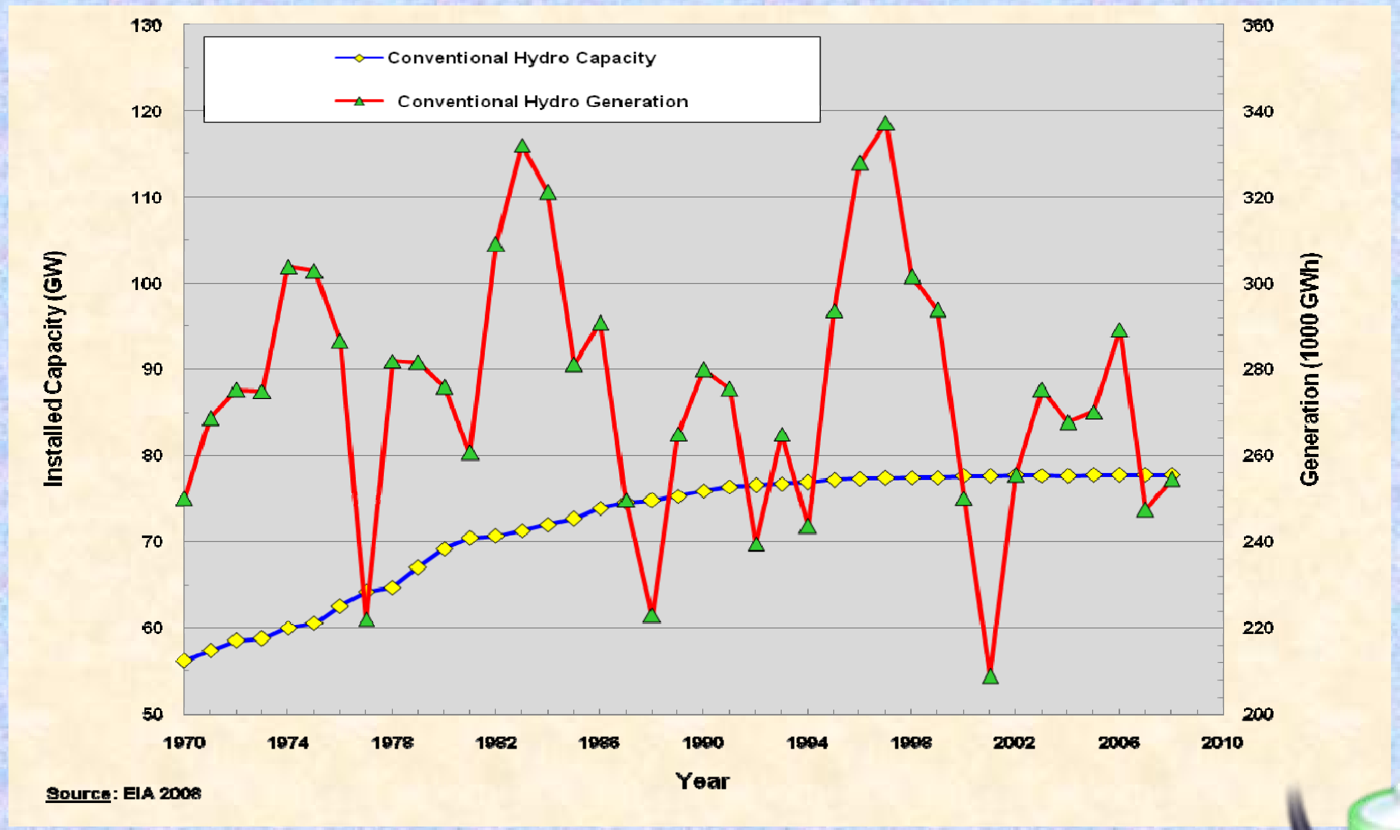
Outline

- **Background**
- **Streamflow Variability**
  - **Grand Coulee as an Example**
  - **Regional Assessment**
- **National Hydropower Asset Assessment Project**
- **Copula Applications on Hydrologic Engineering**
  - **Application I: Extreme Rainfall**
  - **Application II: Droughts**
- **Future Research**

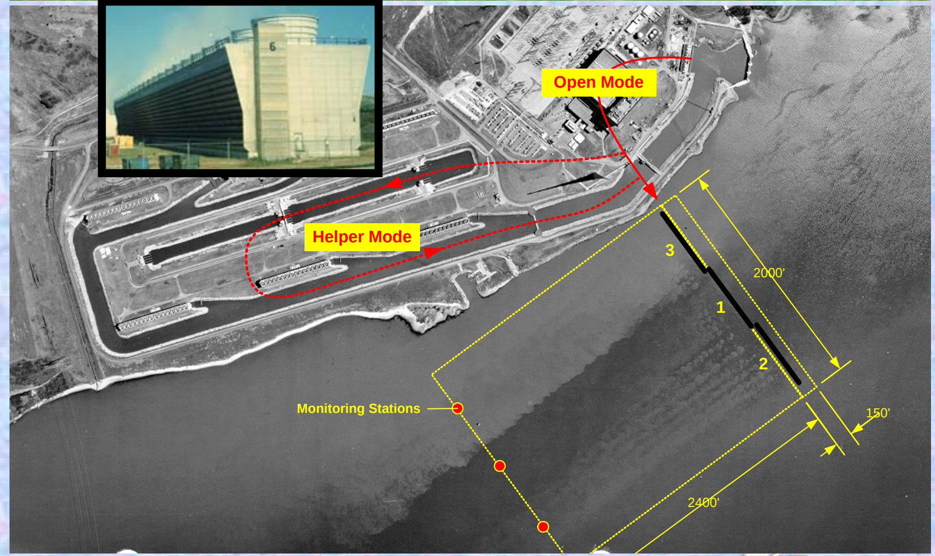
Background - Hydroelectricity



- **Power Generation**
  - **Hydro: 7% of the US & 19% of the world total**
  - **Nuclear: 19% of the US & 15% of the world total**
- **Hydropower generation is not fully proportional to capacity**

Other Impact - Nuclear Plant Cooling

- **TVA Browns Ferry Nuclear Plant**
  - **3494 MW (ORNL Jaguar 5~10 MW)**
  - **10% of the TVA total**
- **Aug 2007, TVA reactor shut down; cooling water from river too hot**
  - **"We don't believe we've ever shut down a nuclear unit because of river temperature," said John Moulton, spokesman.**
- **Aug 2010, Browns Ferry reduced to 45% due to water temperature concern**
  - **TVA spent $40 million to replace the electricity ($2 million per day)**



Picture provided by Boualem Hadjerioua

Streamflow Variability

- **Streamflow variability is often large and unpredictable**
- **Joint influence**
  - Natural variability
  - Snowmelt and groundwater recharge
  - Dam regulation / power generation
  - Domestic / industrial water usage
  - Vegetation and urbanization
  - Climate change
- **Major technical challenges**
  - Streamflow at ungauged locations
  - Watershed modeling
  - Climate projection

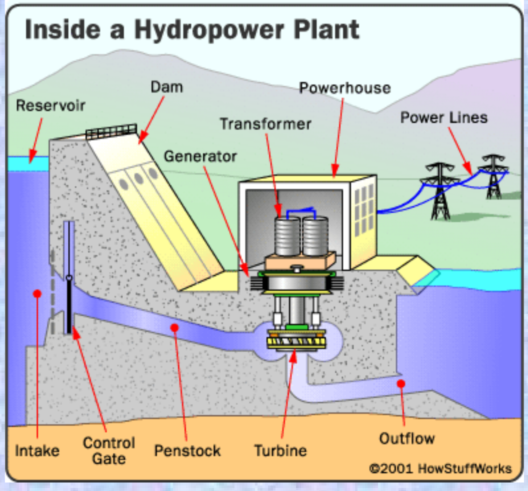
Grand Coulee

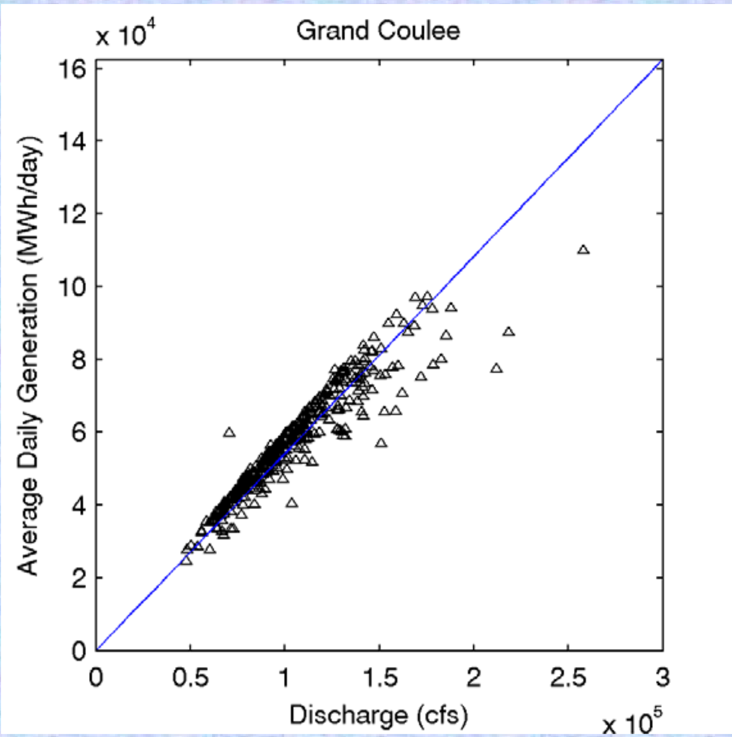
- **The largest hydropower facility in the US**
- **Capacity 6495 MW**
- **8.7% of the US Hydropower total**
- **Upper Columbia River basin**
- **Capacity factor 39.03%**

- **8 out of the 10 largest hydropower facilities from the same region**
- **Dam attributes were not found in the National Inventory of Dam**

Between Generation & Streamflow

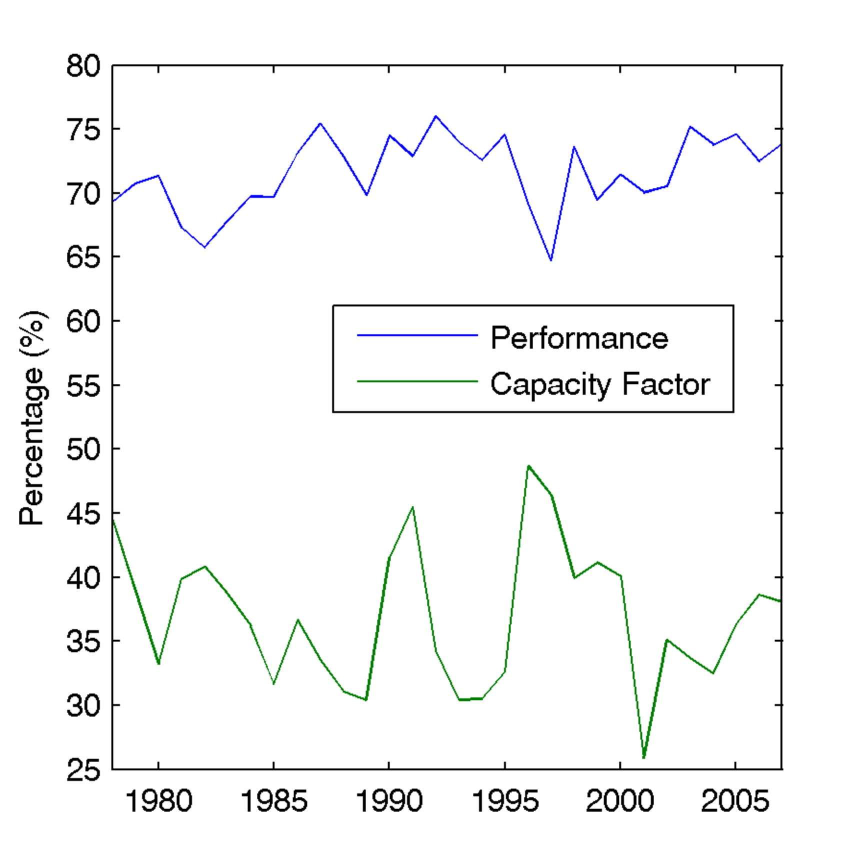
- **Data Oct. 1977 ~ Sept. 2007**
  - EIA monthly generation
  - USGS 09423000
  - Strong correlation between flow & generation (ρ = 0.93)
- **P = eγQH**
  - e, efficiency; γ, specific weight; Q, flow rate; H, head; P, power
  - *e**H = 266.78 ft
  - if *e* = 0.7, H = 381.11 ft
  - Hydraulic head: 380 ft
- **Estimate potential power generation from streamflow**



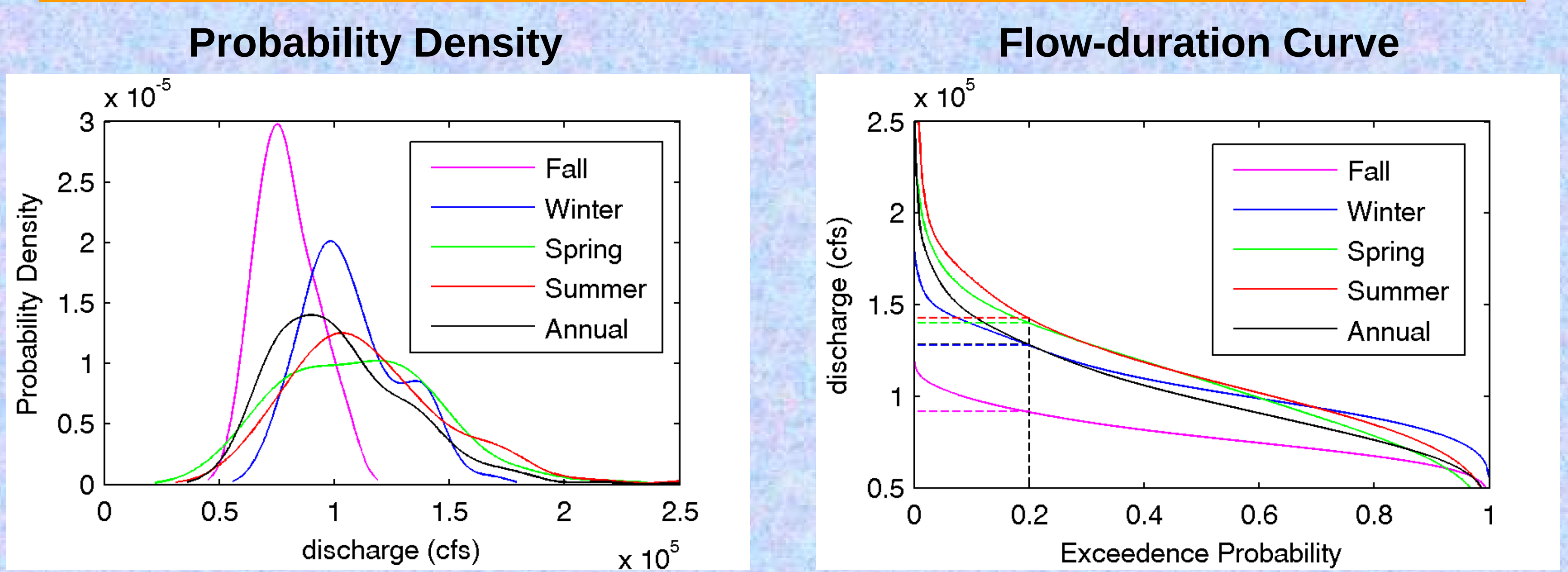


Capacity & Performance Factor

- **Capacity Factor**
  - Generation / (Capacity * 1 year)
  - Fluctuation due to streamflow availability
  - How frequent is a facility utilized?
- **Performance (efficiency)**
  - $P_{avg} / \gamma Q_{avg} H$
  - Operation and regulation
- **Both curves do not act consistently**
- **Constant head assumption to be relaxed when more detailed data are available**



Seasonal Variability



- **The upper 20% quantiles varies around 15000 cfs from fall to winter**
  - **700000 MWh difference**
- **Seasonality needs to be properly accounted for**
  - **Important feature for future site selection**
- **Streamflow has high temporal correlation**
  - **How can we utilize some new statistical methods to improve the forecasting?**

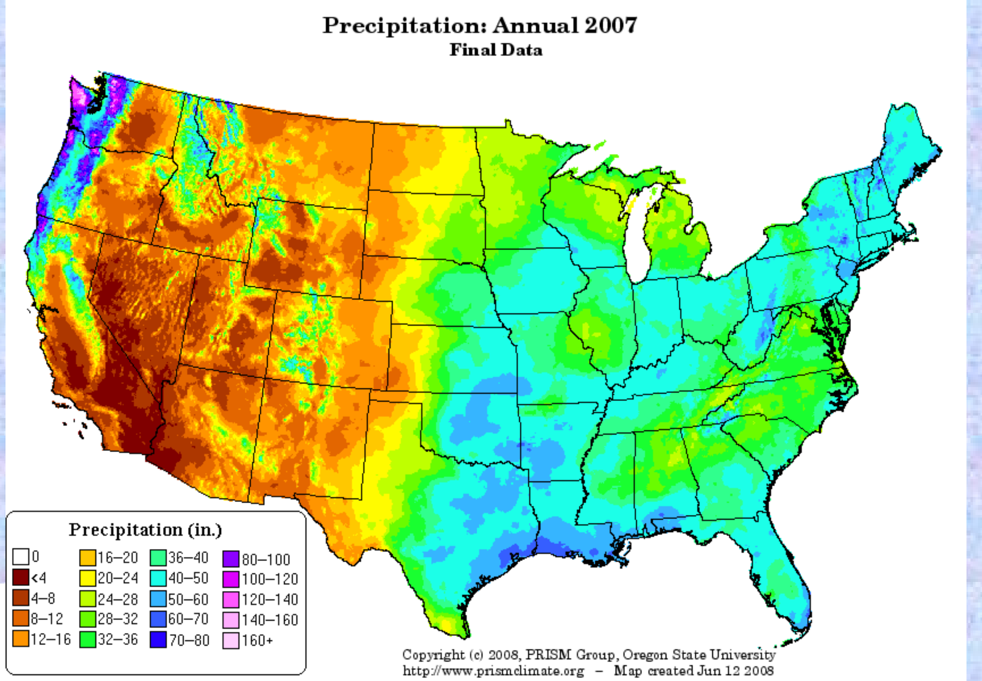
Regional Assessment

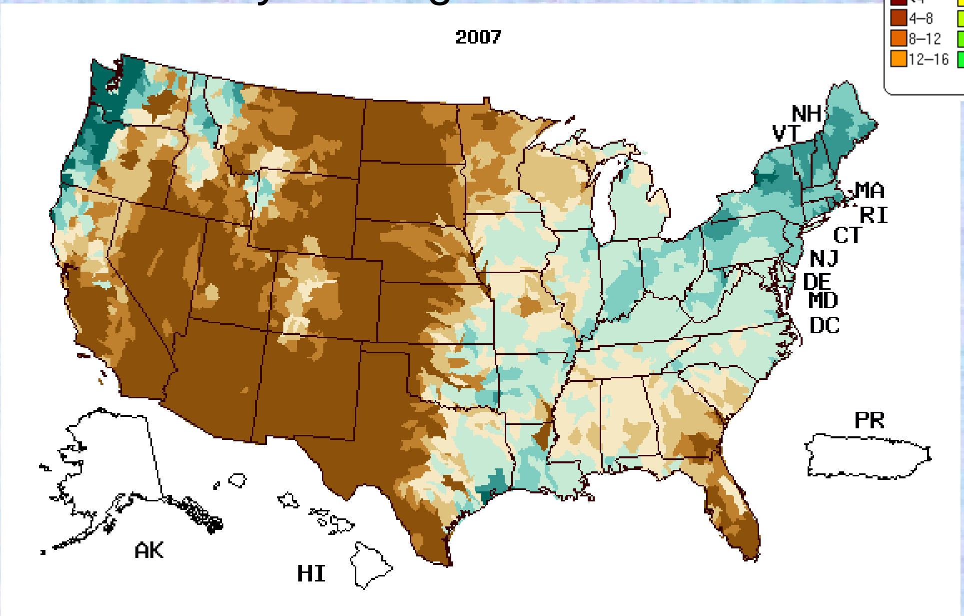
- **Analysis of historic generation, runoff, and precipitation time series**

USGS Waterwatch Runoff (mm)

- Available for each subbasin (HUC08)

- Computed from observed streamflow normalized by drainage area





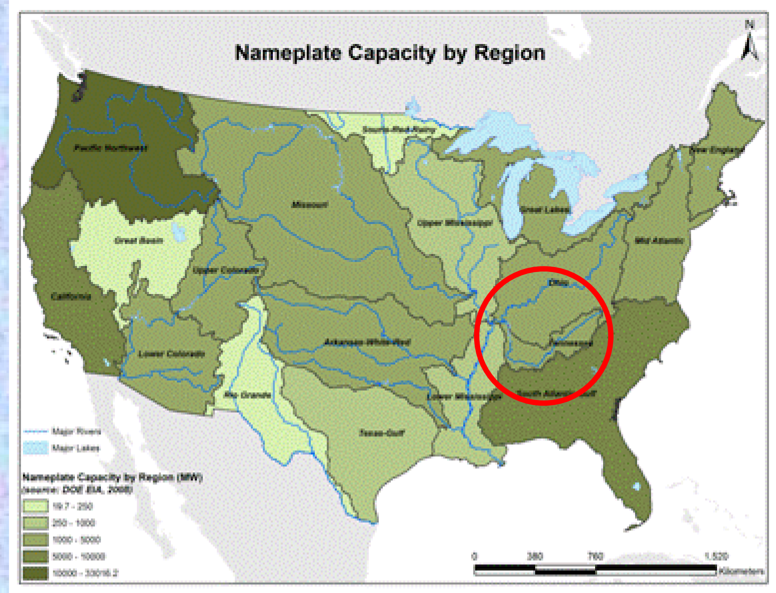
PRISM Precipitation

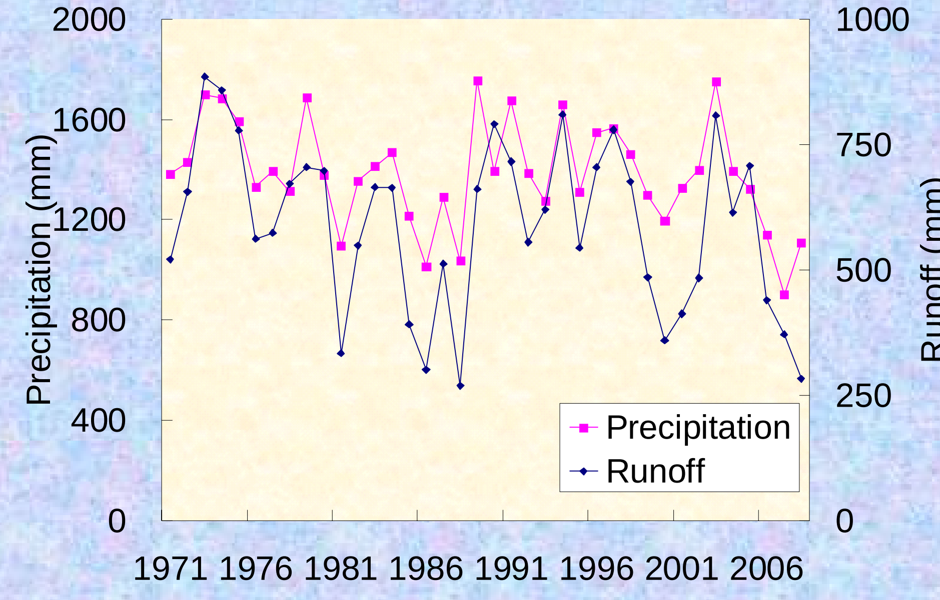
- Available for each $(4km)^2$ grid

- Observation adjusted by topographic features

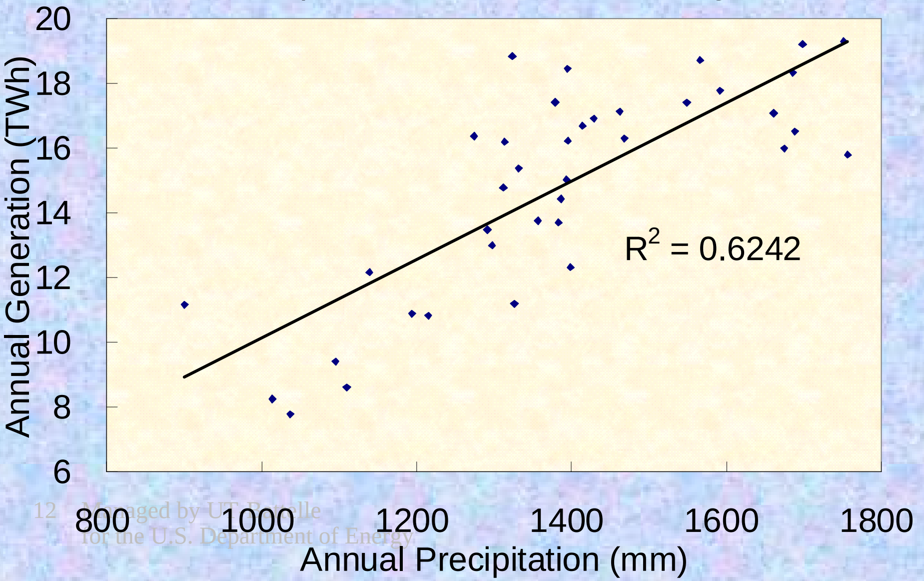
- **Region-based Assessment**

Region 06 - Tennessee

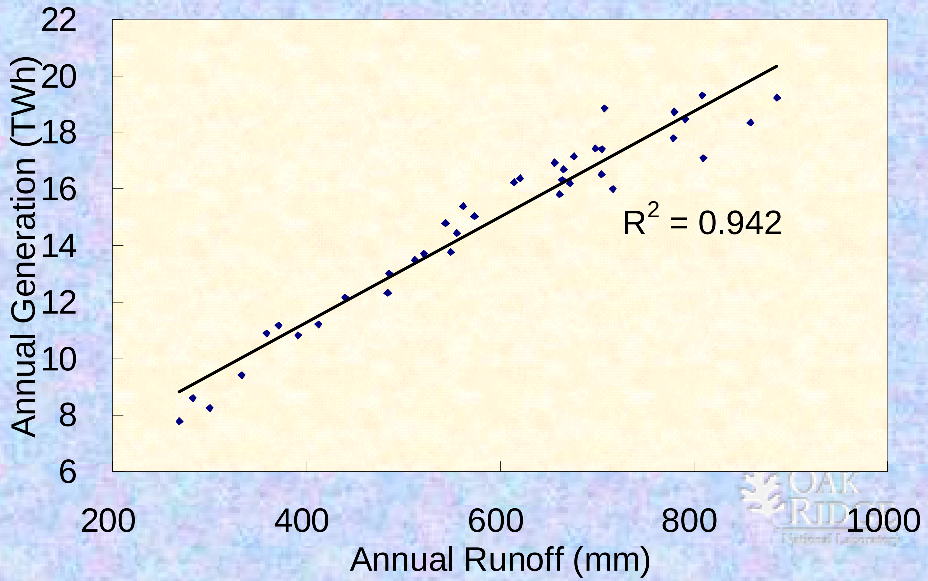




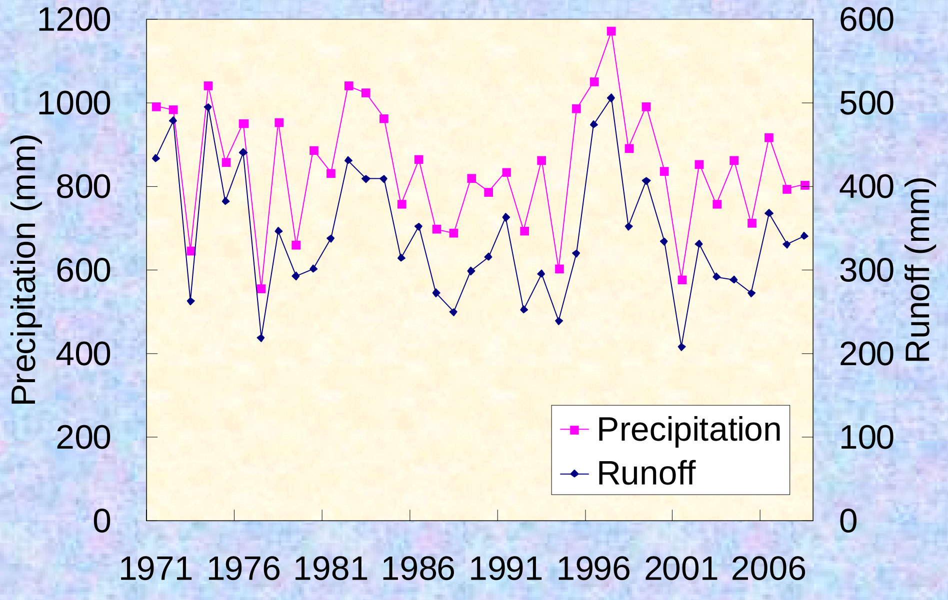
Annual Precipitation vs. Generation - Region 06

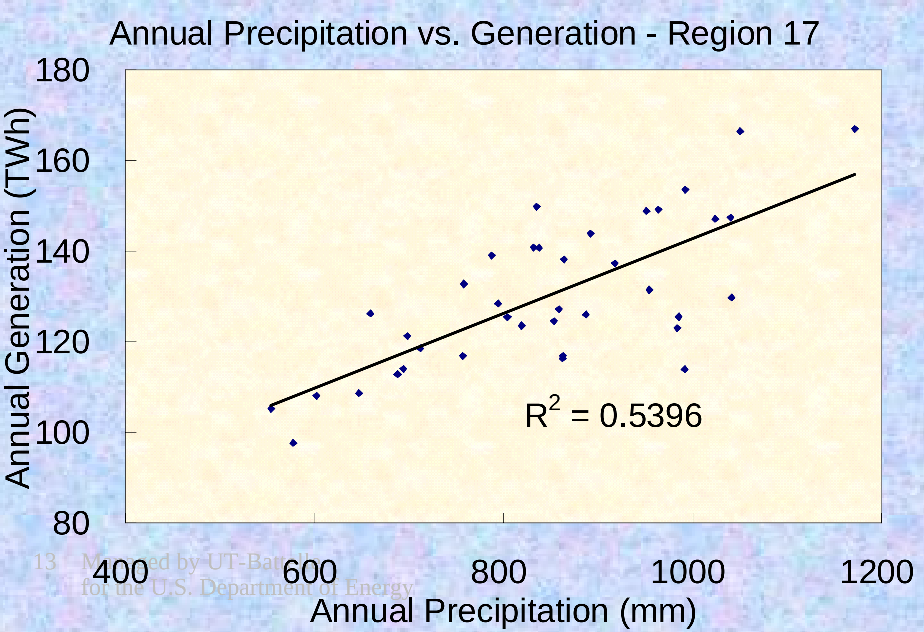


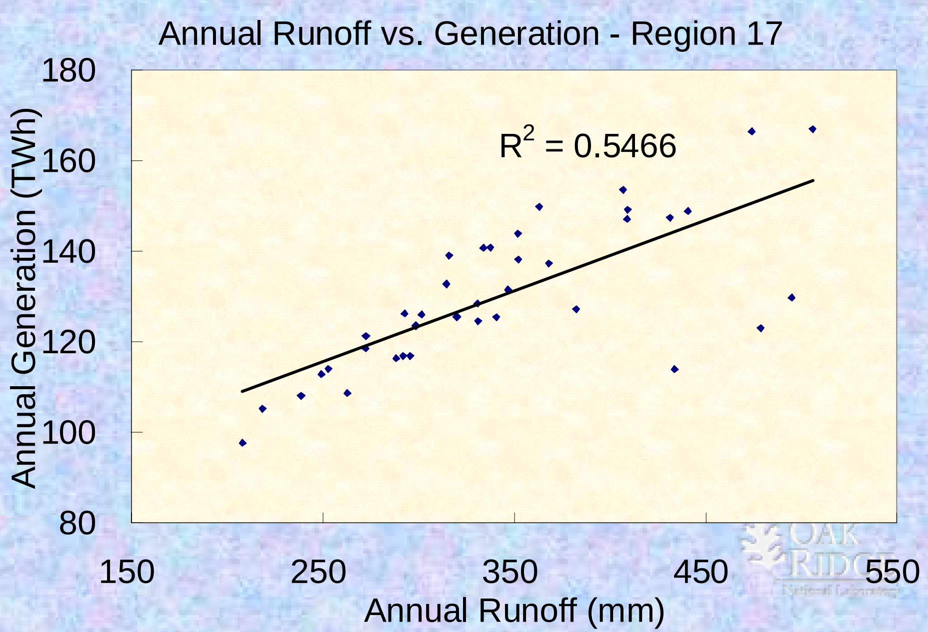
Annual Runoff vs. Generation - Region 06



Region 17 - Pacific Northwest







NHAAP (PI: Boualem Hadjerioua)

- **National Hydropower Asset Assessment Project (NHAAP)**
  - **An integrated and up-to-date national hydropower assessment**

Data Sources*

- FERC
- EIA
- NID
- NHD
- Corps
- Reclamation
- TVA
- USGS
- Gauges Stations
- Water Use

Data Processing

Data Assembly, Integration and Verification

National Water Power Assessment Tools

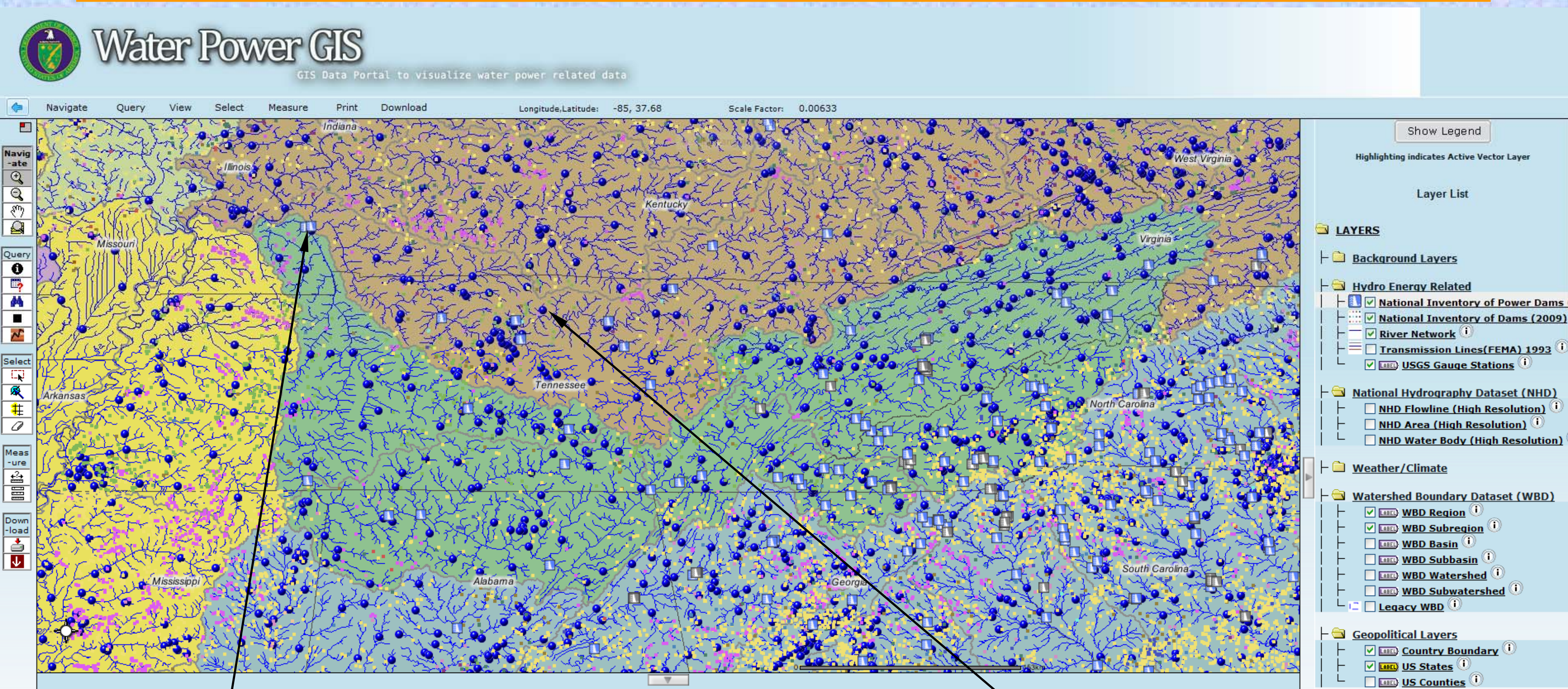
Outputs

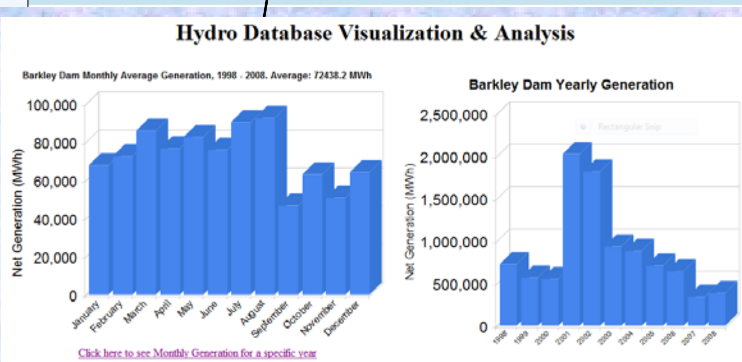
National-, Regional-, Basin-, and State-scale

- Reports:
  - Hydropower National Assessment
  - Climate Change Impacts Assessment
  - ReEDS Modeling
  - Other Information Requests
- GIS Tools to study and analyze:
  - Generation & Streamflow
  - Hydropower Opportunities
  - Hydrology
  - Climate
- Graphs, Maps, and Statistics:
  - Current Hydropower Status
  - Capacity & Generation
  - Reservoir Characteristics
  - Infrastructure status

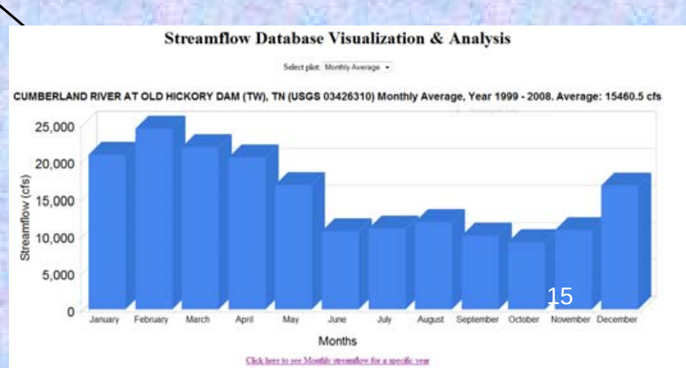
*Most of the data are covered by non-disclosure agreements

NHAAP Web-based GIS



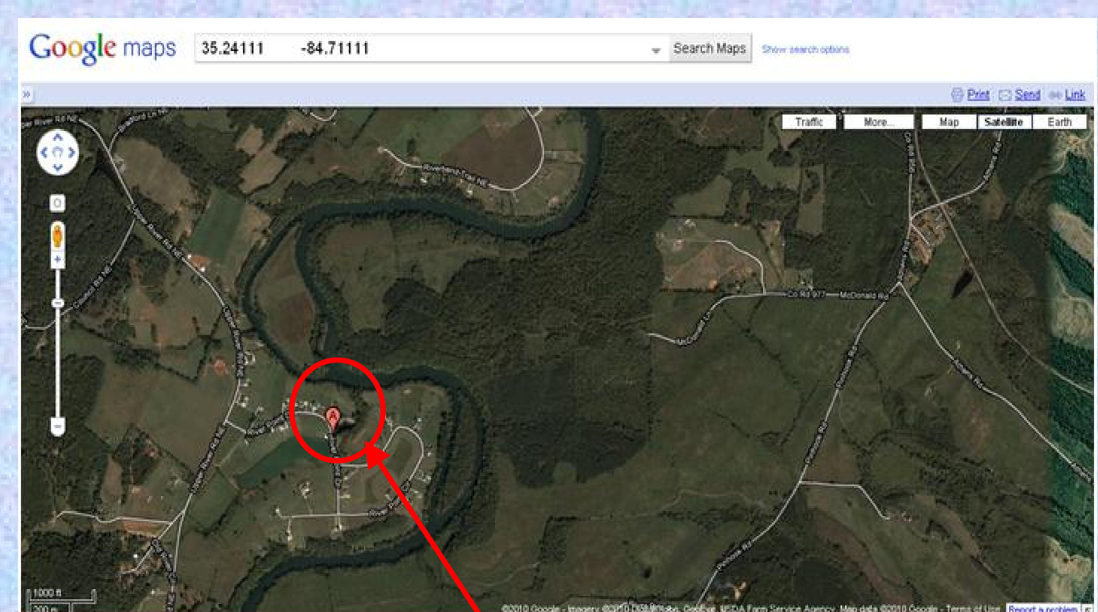


- River Network
- Water Bodies
- USGS Gauge Stations
- Hydropower Dam
- Non Power Dam
- Temperature
- Precipitation



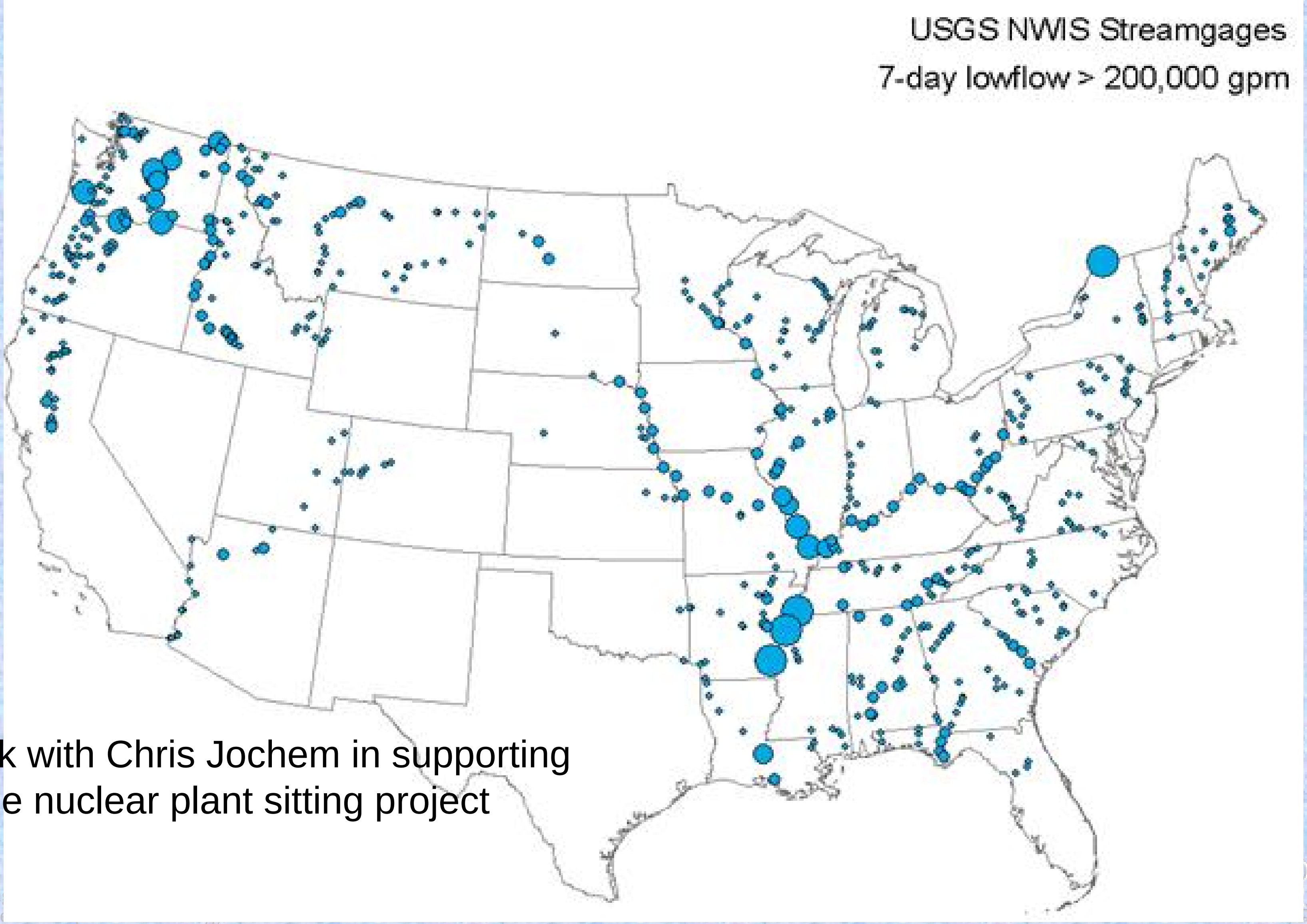
Challenge for Ungauged Locations

- **~84,000 non-power dams vs ~22,000 USGS gauges**
  - **Less than 10,000 gauges are current**
- **Regression approach: Vogel *et al.* (1999)**
  - **Regression formula for 19 HUC02 Regions**
  - **Variables: drainage area, precipitation, temperature**
  - **Annual mean flow**
- **Runoff map approach**
  - **Runoff: Streamflow normalized by drainage area**
  - **Water watch approach**
- **However, the accuracy of stream GIS layers is the dominate factor**



3 or 4200 cfs?

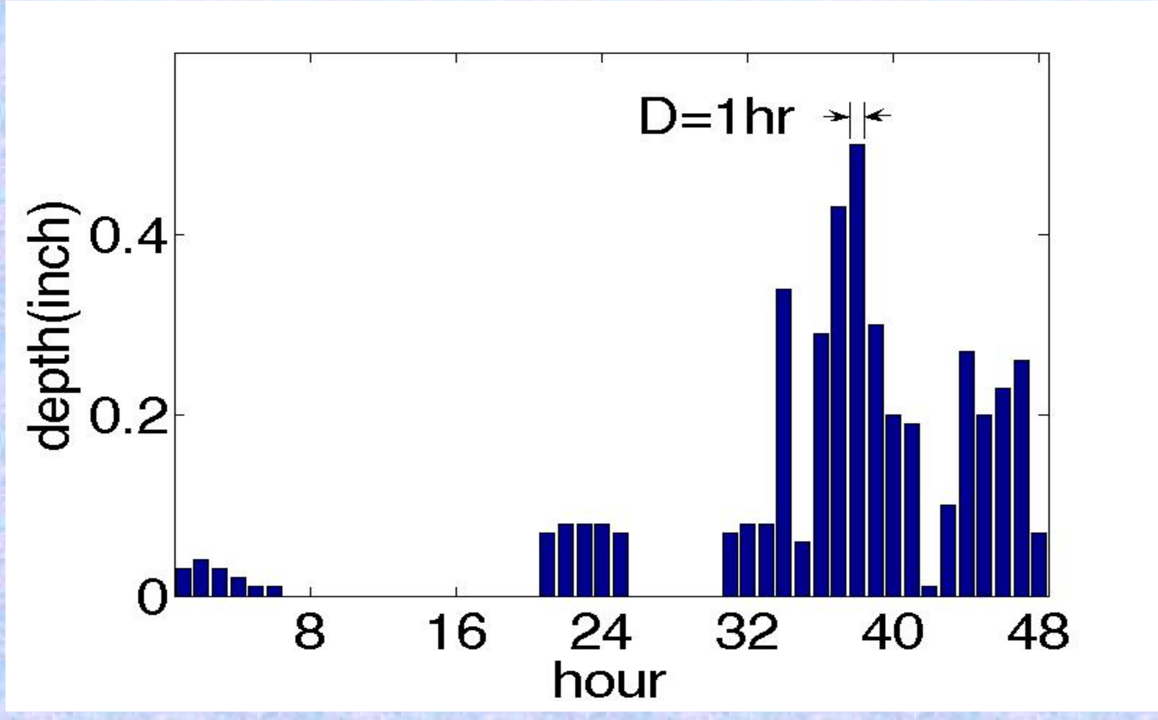
Low-flow Analysis



Work with Chris Jochem in supporting of the nuclear plant sitting project

Extreme Rainfall - Univariate Approach

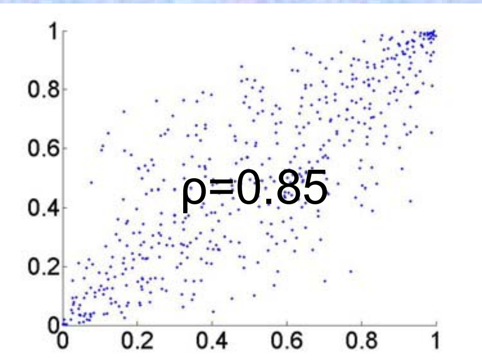
- **Selection of annual maximum precipitation**
  - ***Durations*** **are not the actual durations of rainfall events**
  - **Long-term maximum may cover multiple events**
  - **Short-term maximum encompasses only part of the extreme event**

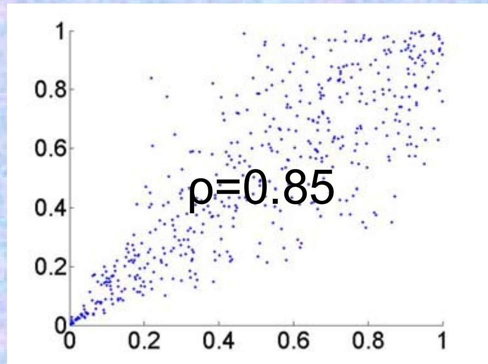


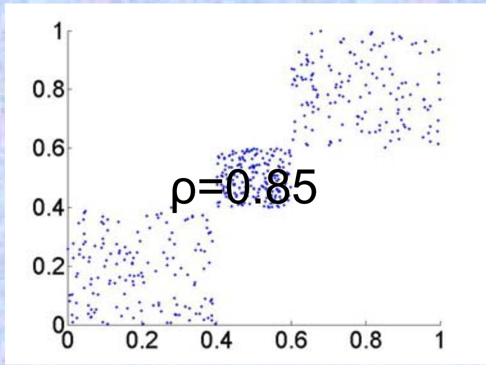
Correlation and Dependence

- **Classification**
  - **Temporal: autoregression model (AR), Markov chain**
  - **Spatial: geostatistics (Kriging method)**
  - **Inter-variable: Bayesian approach**
- **Conventionally quantified by the Pearson's linear correlation coefficient ρ**

$$\rho_{XY} = E[(X - \bar{x})(Y - \bar{y})] / Std[X]Std[Y]$$







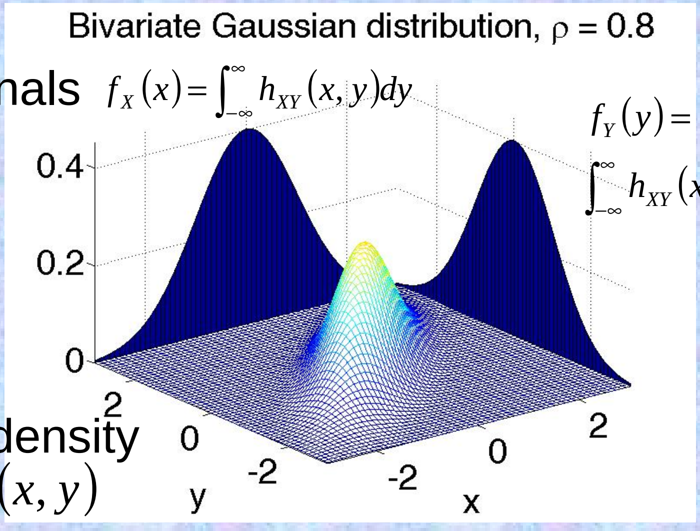
  - **Only valid for Gaussian (or elliptic) distributions**

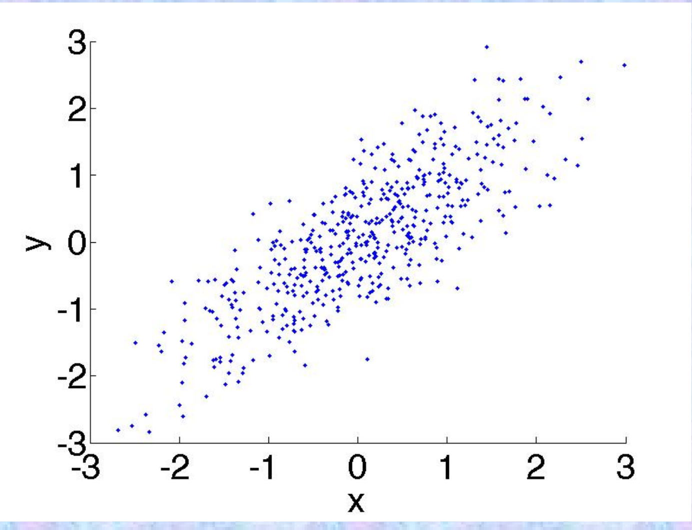
Example - Bivariate Distribution

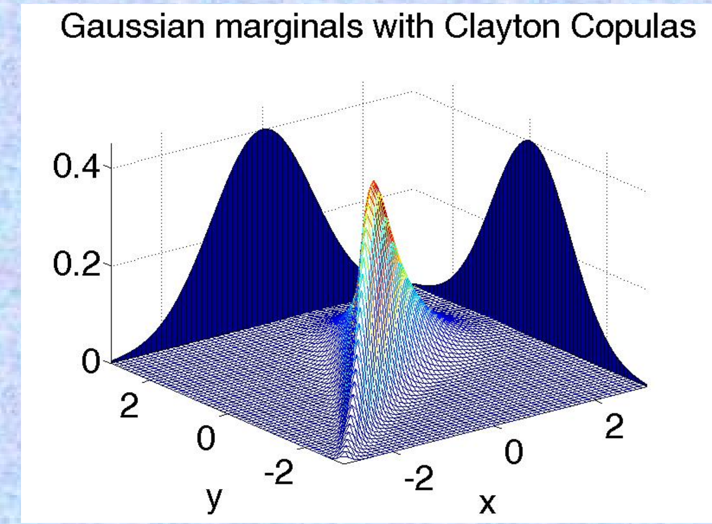
Marginals $f_X(x) = \int_{-\infty}^{\infty} h_{XY}(x,y)\,dy$

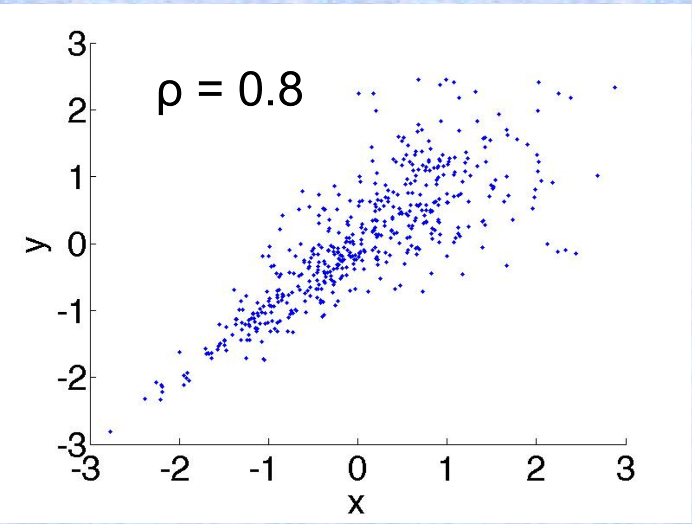
$f_Y(y) = \int_{-\infty}^{\infty} h_{XY}(x,y)\,dx$

Joint density $h_{XY}(x,y)$





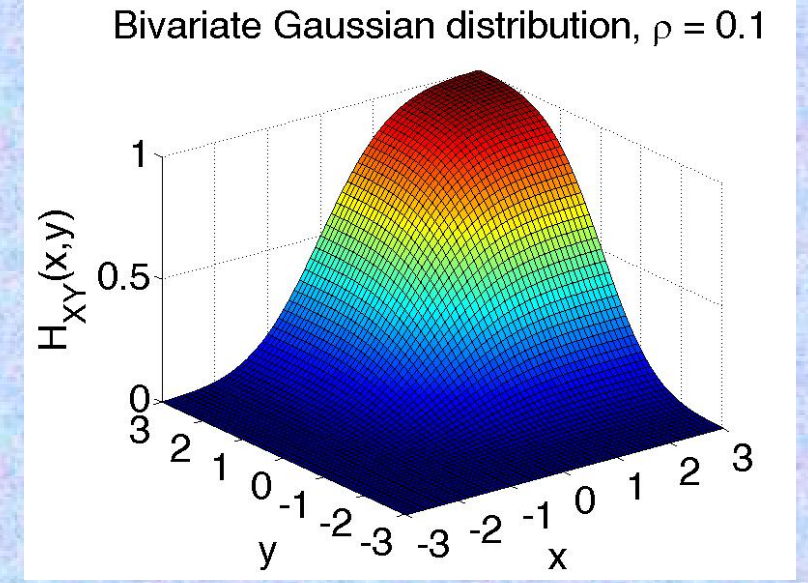


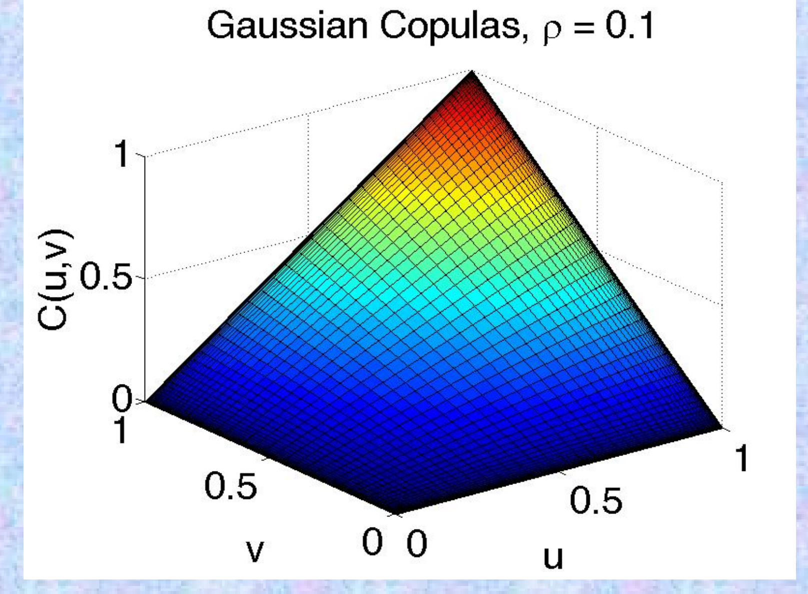


Copulas

- **Transformation of joint cumulative distribution**
  - **$H_{XY}(x,y) = C_{UV}(u,v)$**

    marginals: $u = F_X(x)$, $v = F_Y(y)$
  - **Sklar (1959) proved that the transformation is *unique* for continuous r.v.s**
- **Use copulas to construct joint distributions**
  - **Marginal distributions => selecting suitable PDFs**
  - **Dependence structure => selecting suitable copulas**
  - **Together they form the joint distribution**





Extreme Rainfall Frequency Analysis

- **Bivariate distribution H_{PD}, H_{DI}, H_{PI}**
  - **Total precipitation (P), duration (D), and peak intensity (I)**
  - **Marginal: Extreme Value Type I (EV1), Log Normal (LN)**
  - **Dependence: Frank Family**
- **Applications**
  - **Estimate of depth for known duration**

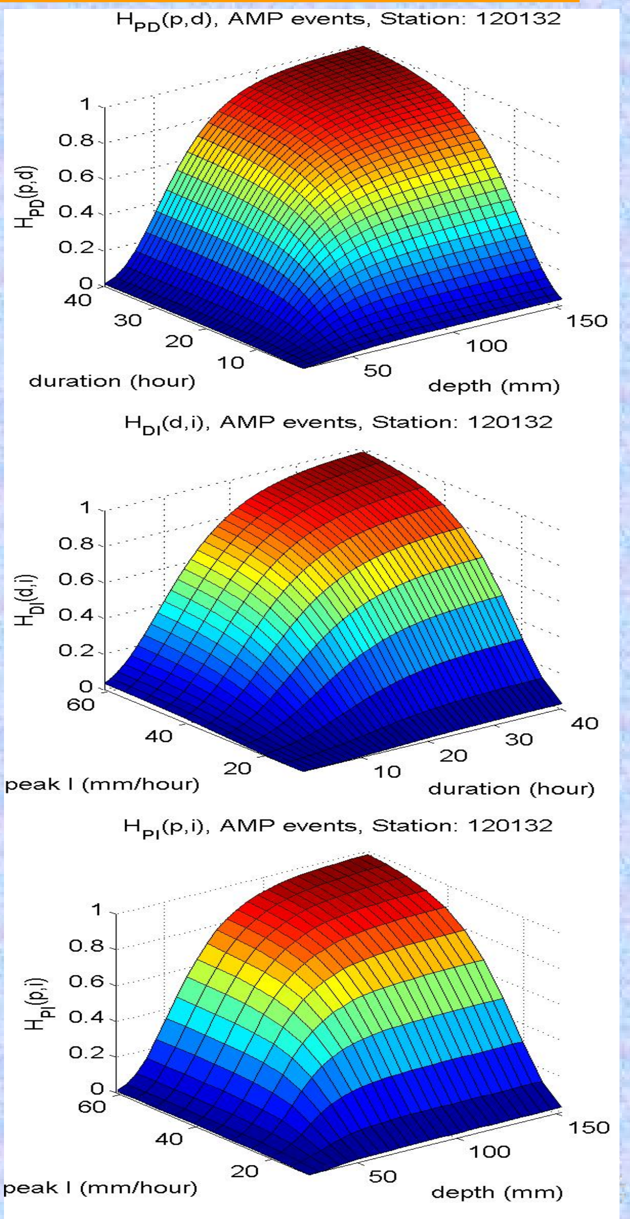
$$F_P\left(p_T \middle| d-1 < D \le d\right) = 1 - 1/T$$

  - **Estimate of peak intensity for known duration**

$$F_I\left(i_T \middle| d-1 < D \le d\right) = 1 - 1/T$$

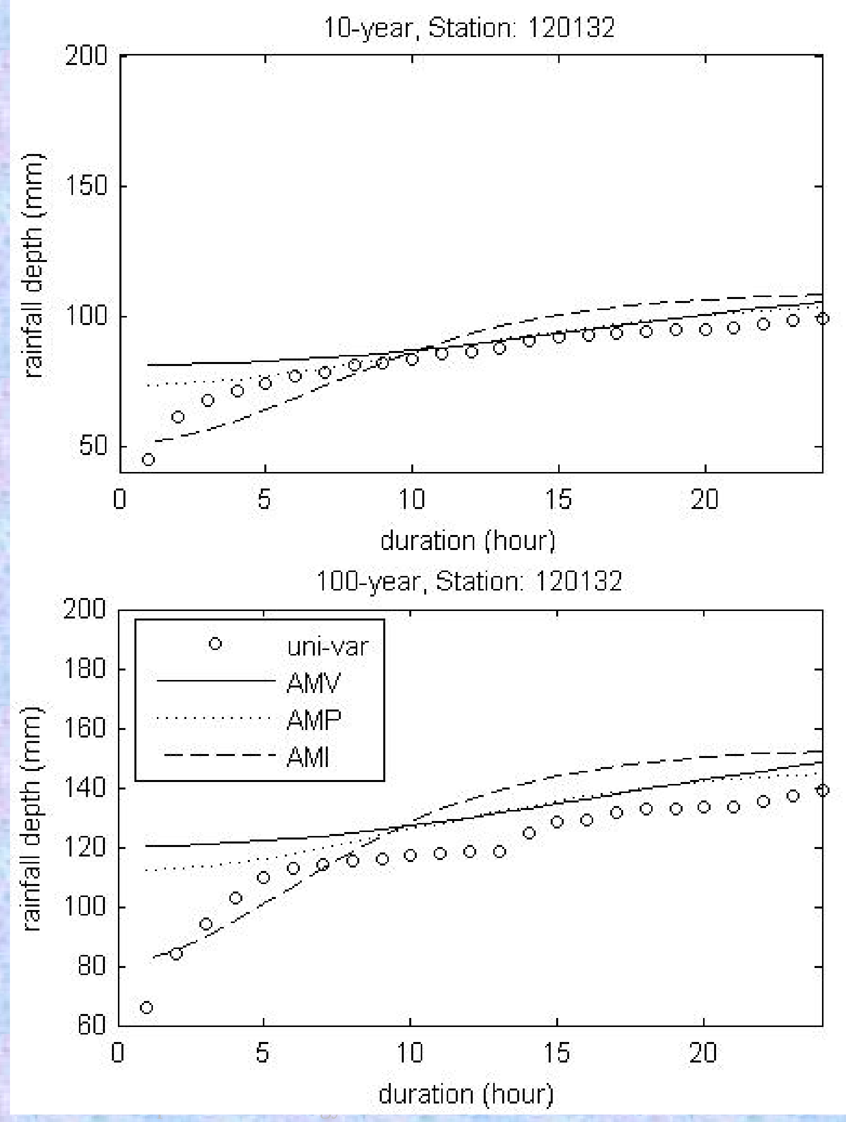
  - **Estimate of peak intensity for known depth**

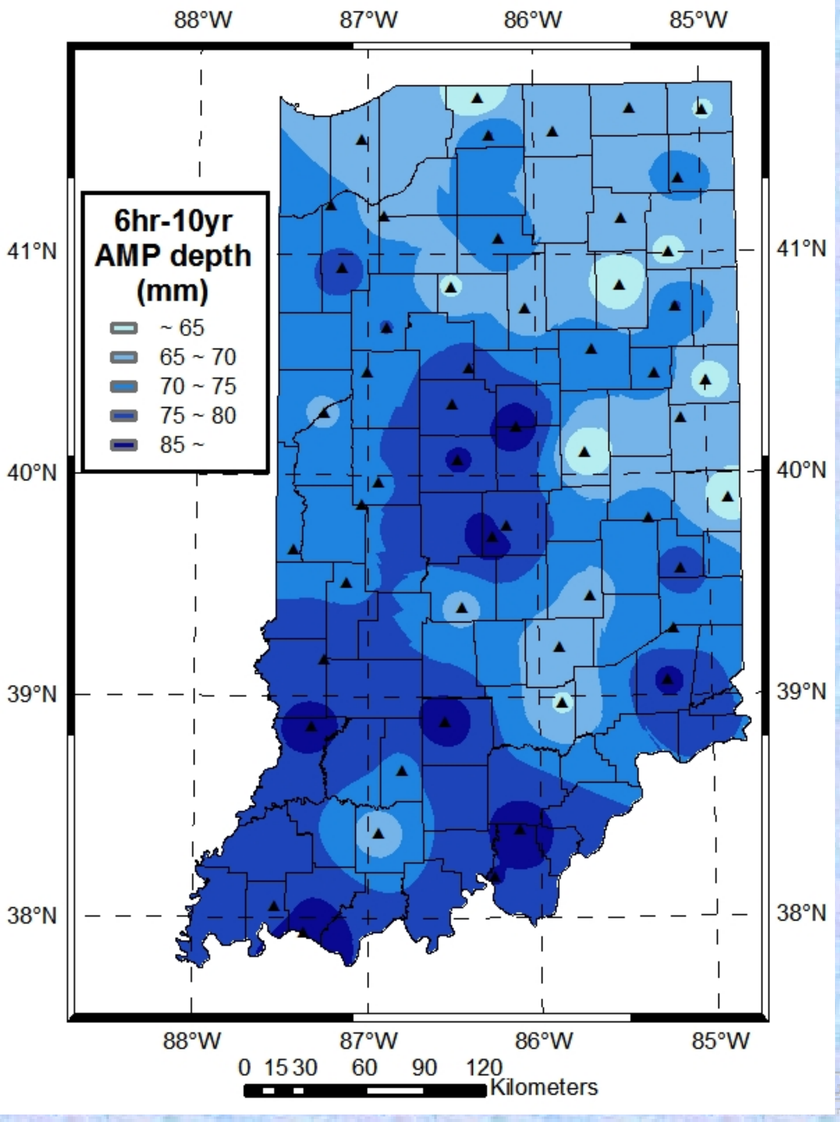
$$E\left[I \mid P > p\right]$$



Estimate of depth for known duration

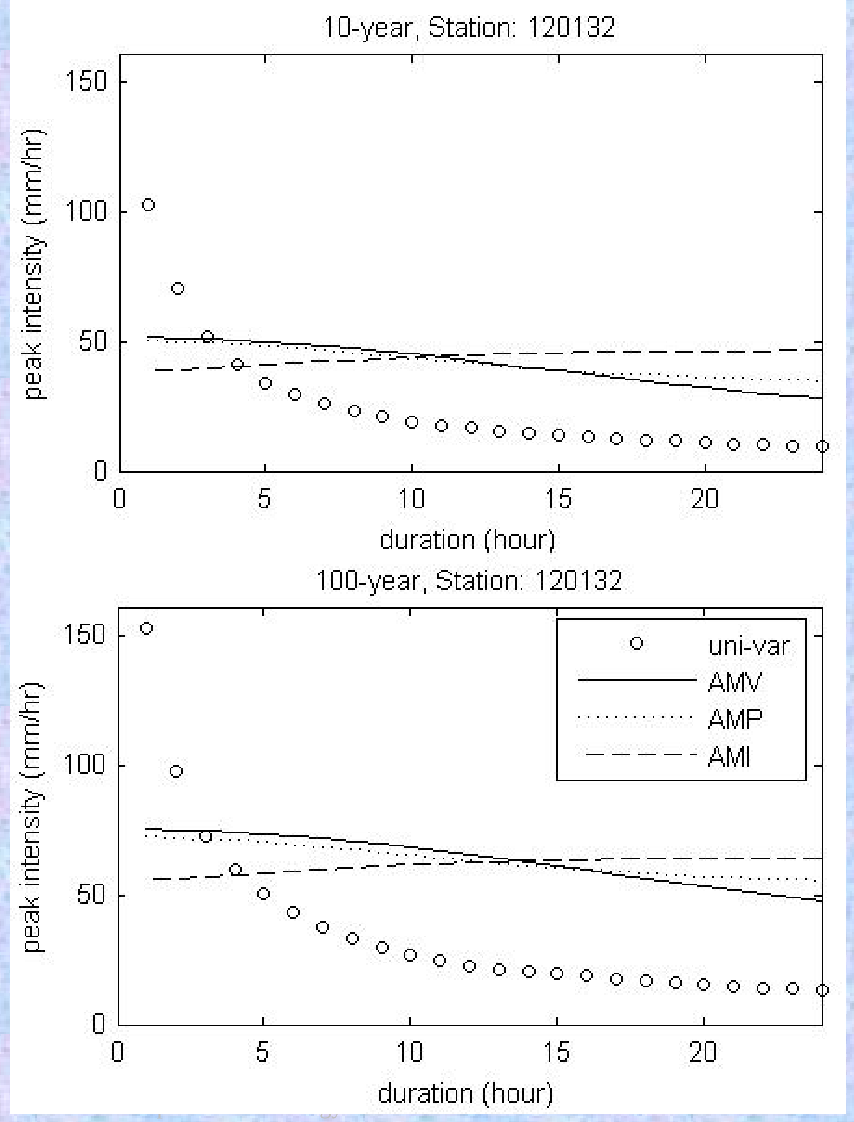
T-year depth p_T given duration d: $F_P(p_T|d-1<D<d)=1-1/T$

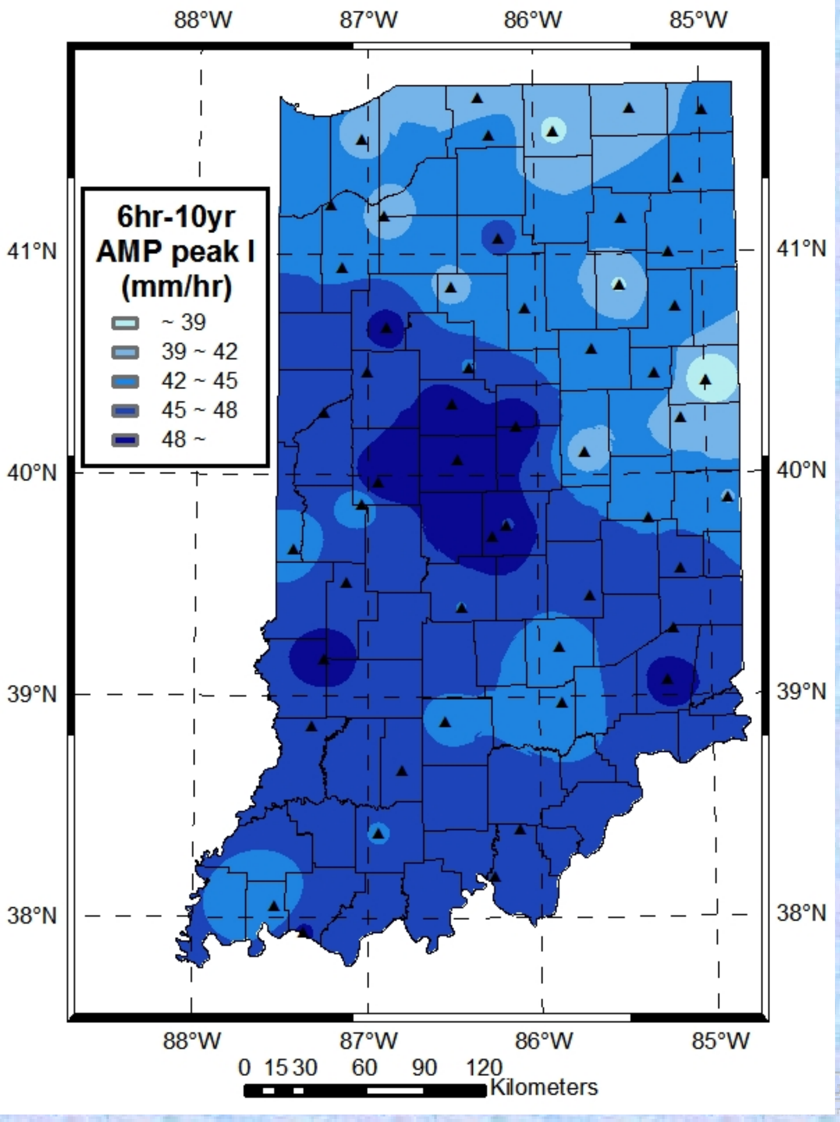




Estimate of peak intensity for known duration

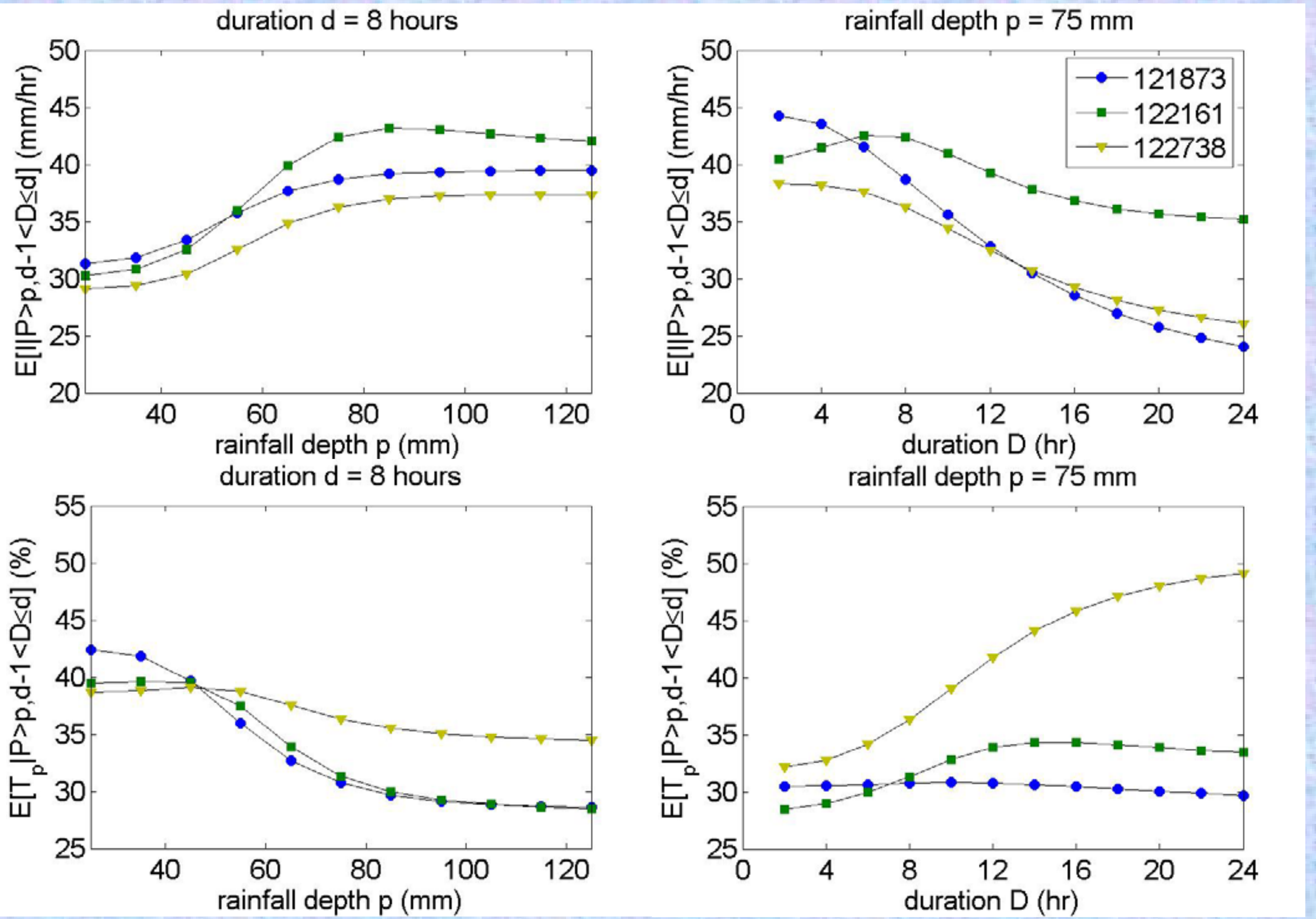
T-year peak intensity i_T given duration d: $F_I(i_T|d-1<D<d)=1-1/T$





Rainfall Peak Attributes

- **Given depth (P) and duration (D), compute the conditional expectation of peak intensity (I) and percentage time to peak (T_p)**

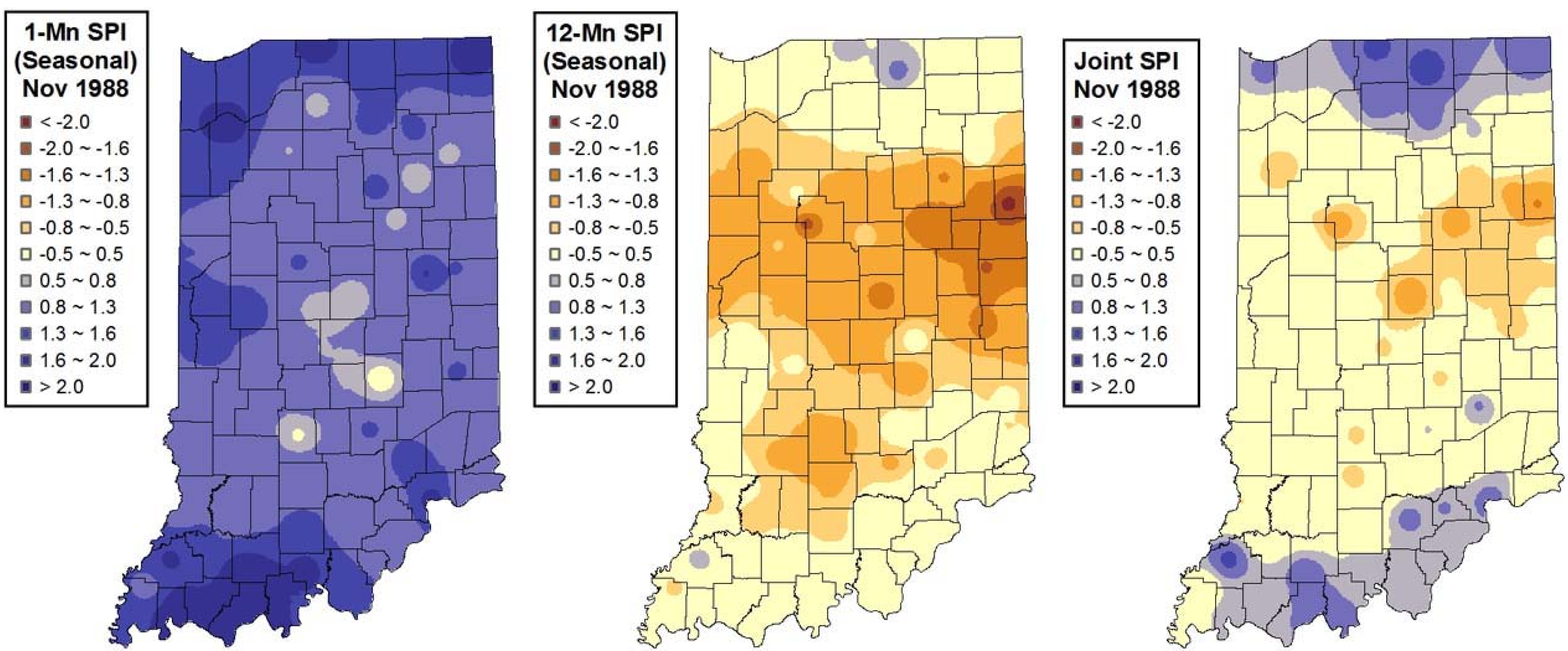


Expectation of peak intensity given P & D

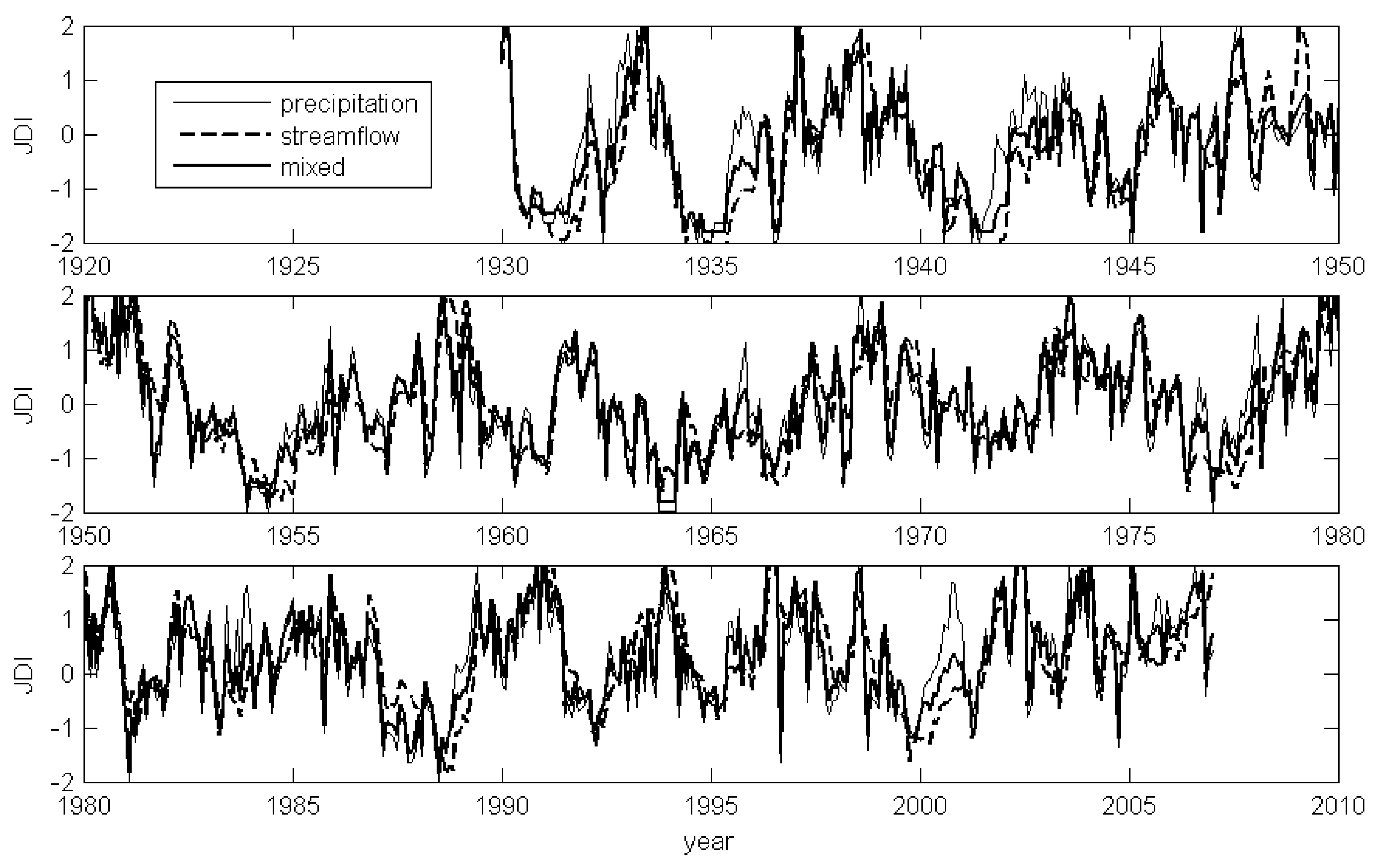
Expectation of time to peak (%) given P & D

Joint Deficit Index

- **Comparison between 1-mn SPI, 12-mn SPI, and JDI**
  - **12-mn SPI changes slowly, weak in reflecting emerging drought**
  - **1-mn SPI changes rapidly, weak in reflecting accumulative deficit**
  - **JDI reflects joint deficit**

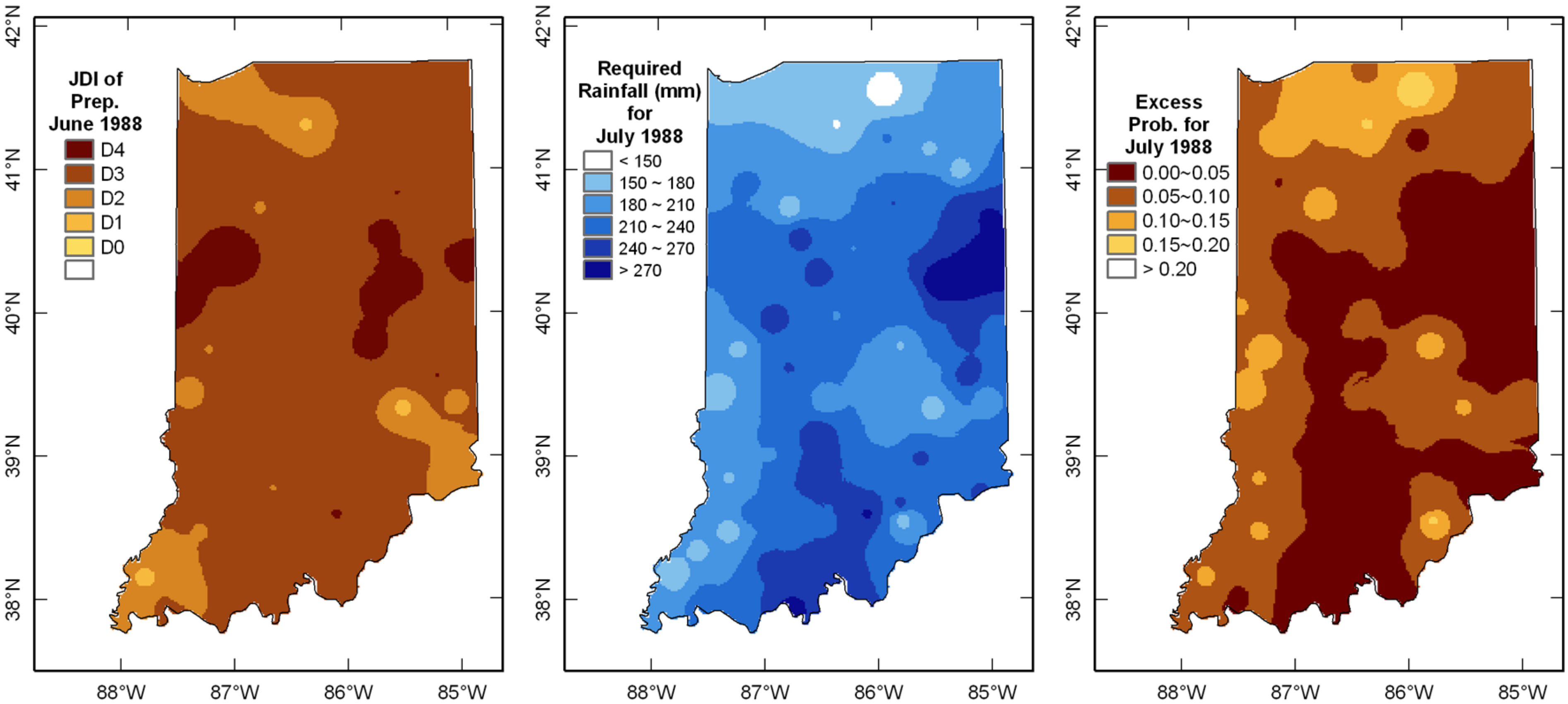


Precipitation vs. Streamflow



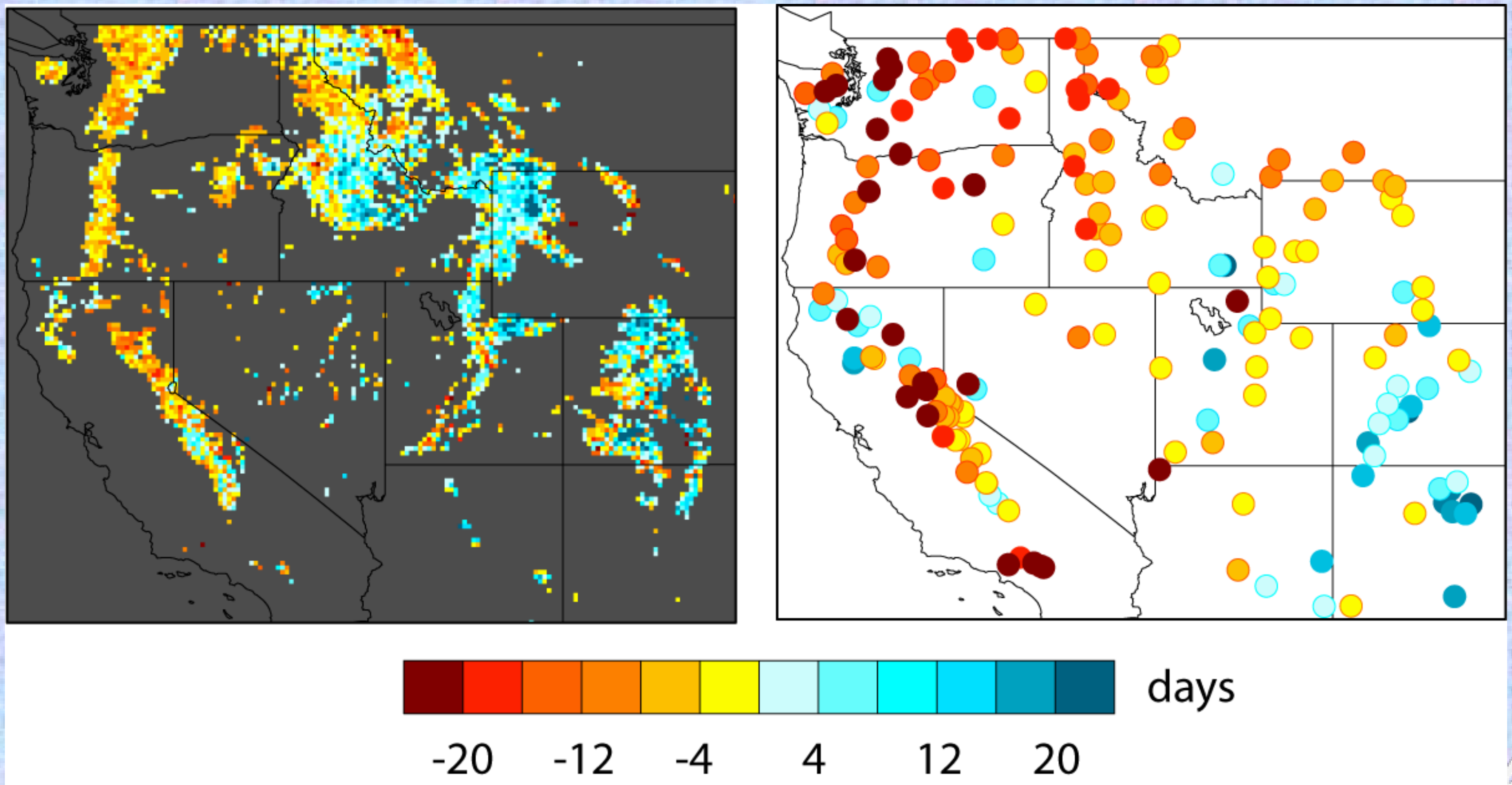
Potential of Future Droughts

- **Required precipitation for reaching joint normal status ($K_C = 0.5$) in the future**
- **Probability of drought recovery**



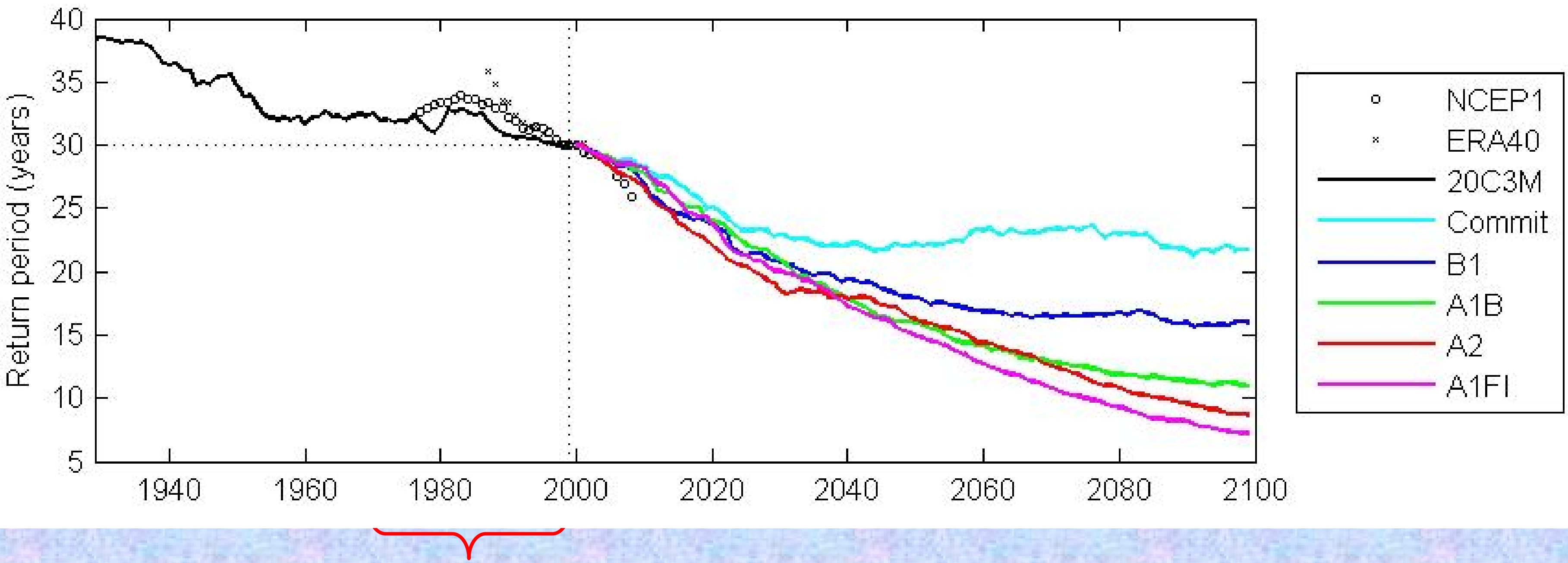
Climate Change on Snowmelt Timing

- **Investigate the trend of 1960-1999 spring onset (Cayan *et al.*, 2001)**
- **Simulation: five ensemble members of VIC model**
- **Observation: 223 unregulated and snowmelt driven USGS stations**



Joint work with Moetasim Ashfaq and the co-authors

Climate-induced non-stationary



PI: Auroop R. Ganguly

- **Annual maximum precipitation in a 6-hr interval**
- **Generalized extreme values (GEV) distribution**
- **Median of global return period corresponding to year-1999 estimates**
- **Goodness-of-fit tests at 5% significant level:**
  - **NCEP: 2.56%, ERA40: 1.24%, CCSM3: 0.02%**

National Hydrography Dataset

Thank you

Questions?

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