Streamflow Variability and Its Potential Impact on Energy Production

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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

  - EIA monthly generation
  - USGS 09423000
  - Strong correlation between flow & generation ($\rho = 0.93$)

- $P = e\gamma QH$
  - $e$, efficiency; $\gamma$, specific weight; $Q$, flow rate; $H$, head; $P$, power
  - $eH = 266.78$ 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

Annual Generation (TWh) vs. Precipitation (mm)

Annual Generation (TWh) vs. Runoff (mm)

R² = 0.6242

R² = 0.942
Region 17 - Pacific Northwest

Annual Precipitation vs. Generation - Region 17

Annual Runoff vs. Generation - Region 17

R² = 0.5466

R² = 0.5396
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

![Histogram of rainfall depth over hours](chart.png)
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 $\rho$

\[
\rho_{xy} = \frac{E[(X - \bar{x})(Y - \bar{y})]}{\text{Std}[X]\text{Std}[Y]}
\]

- Only valid for Gaussian (or elliptic) distributions
Example - Bivariate Distribution

Bivariate Gaussian distribution, $\rho = 0.8$

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

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

Gaussian marginals with Clayton Copulas

$$\rho = 0.8$$
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
    \[ F_P(p_T | d - 1 < D \leq d) = 1 - 1/T \]
  - Estimate of peak intensity for known duration
    \[ F_I(i_T | d - 1 < D \leq d) = 1 - 1/T \]
  - Estimate of peak intensity for known depth
    \[ E[I | P > p] \]
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 ($T_p$).
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

- 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%

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We are here!
Thank you
Questions?

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