MANAGEMENT OF WATER RESOURCES UNDER UNCERTAINTY IN A CHANGING CLIMATE

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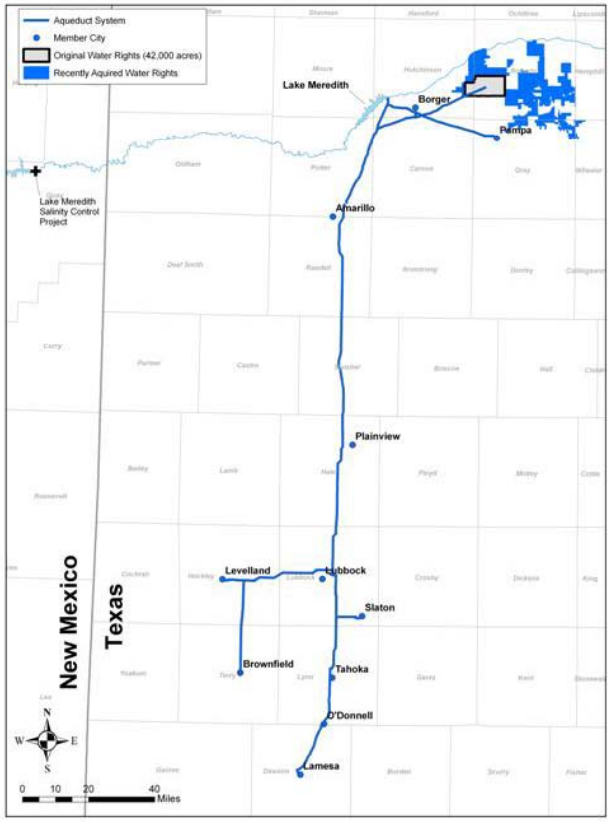
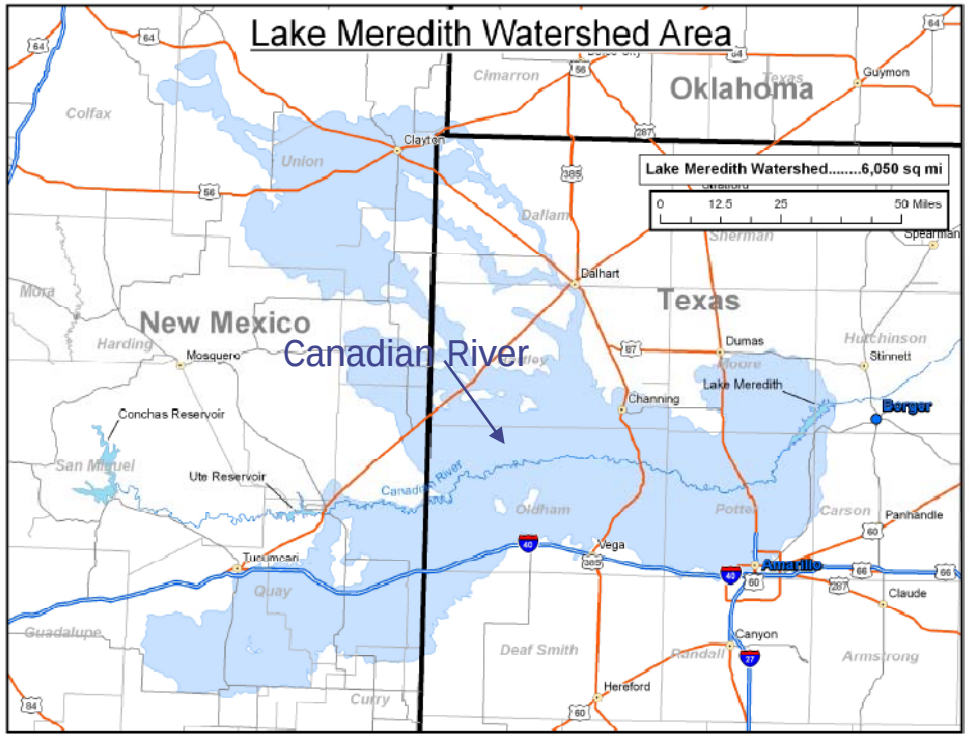
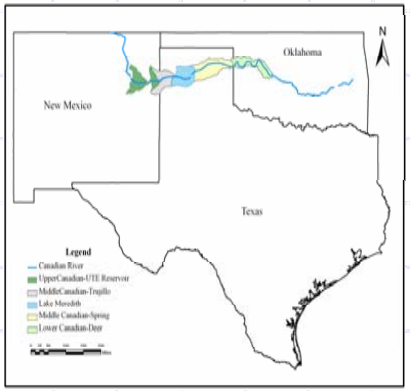
Introduction

- Management of Water Resources in High Plains Region of Texas is Crucial
  - Population growth
  - High irrigated agriculture and cattle operations
- Region has historically relied on groundwater
  - Ogallala Aquifer which is a trans-boundary aquifer
  - Undergoing significant depletion
- Cities are looking for alternative sources of Water
  - Surface water from Canadian River is used by 11 cities in the region
    - Amarillo, Lubbock,

Canadian River Wateshed and Aqueduct

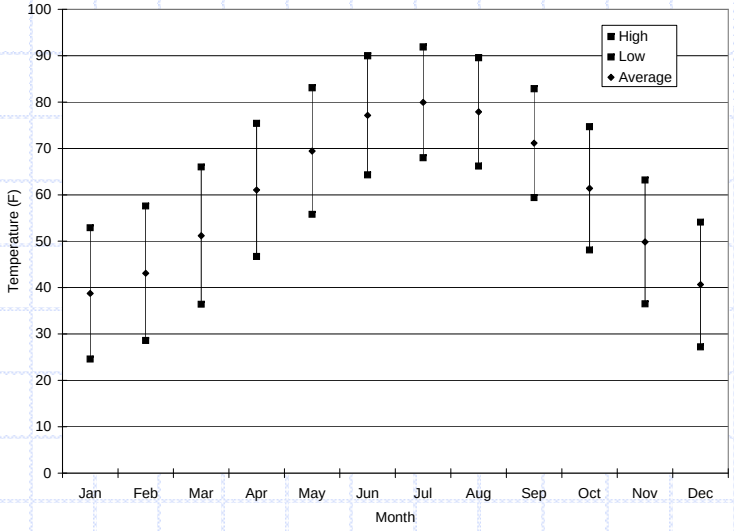


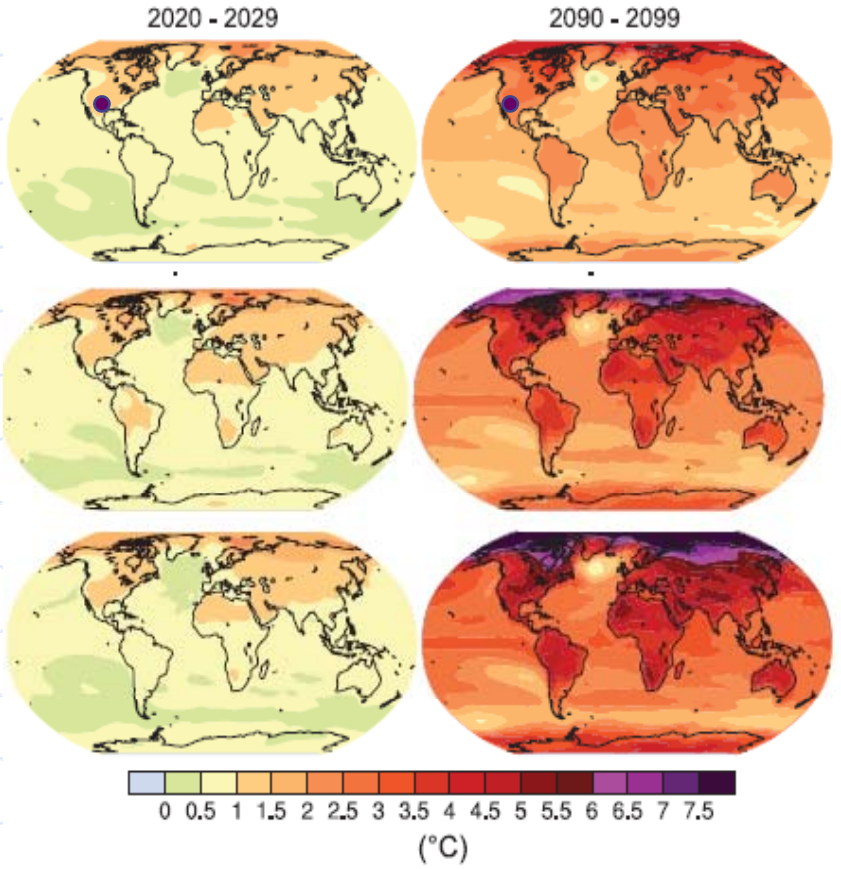




Introduction – Climate Change - Temperature

- Climate is characterized by hot summers and cool winters
  - Semi-arid Climate
  - PET >> Annual Precipitation
- Temperatures projected to increase by 4 – 6 degrees Celsius

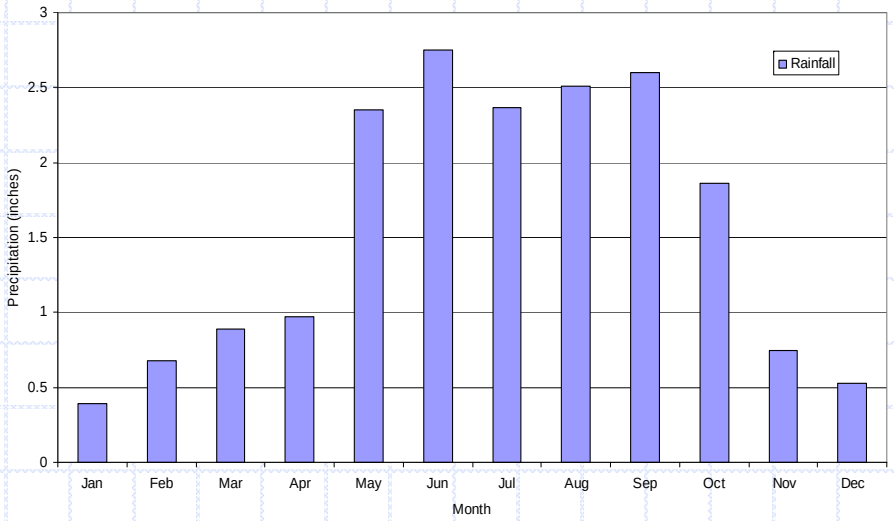


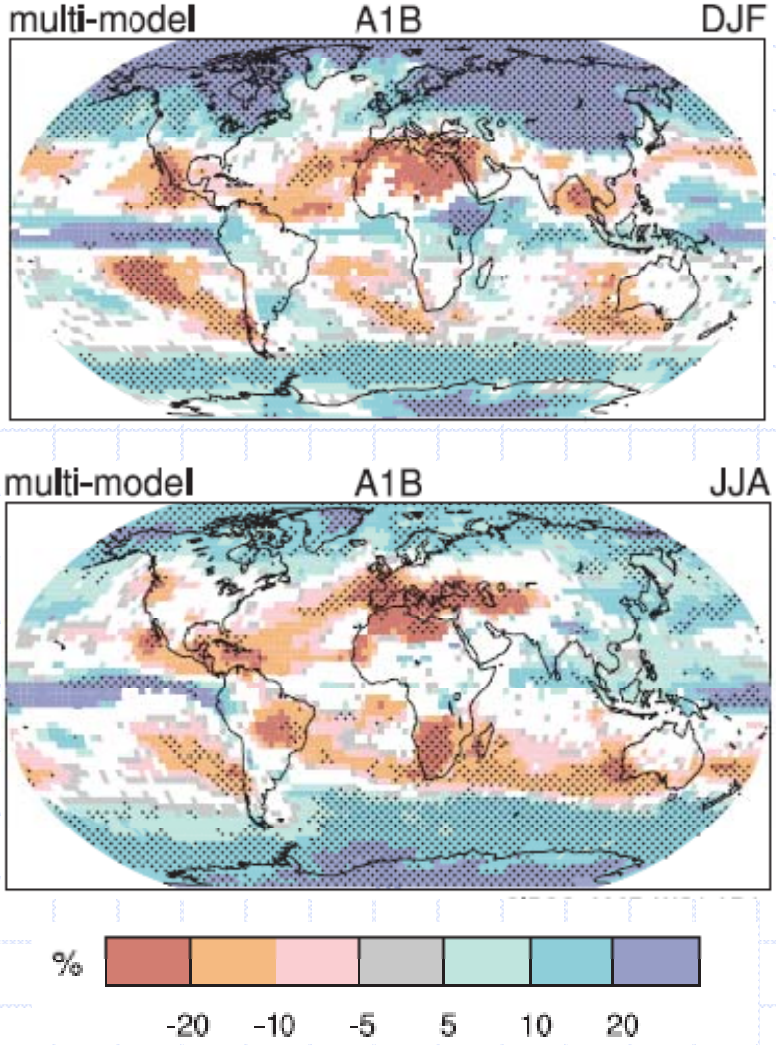


From IPCC 2007

Introduction – Climate Change - Precipitation

- Annual rainfall
  - ~ 18 - 19 “
  - ~ 8” drought of record
- High intra-annual variability
  - Fall thunderstorms
- GCMs predict decrease in winter precipitation
- Increased intensity of summer thunderstorm activity

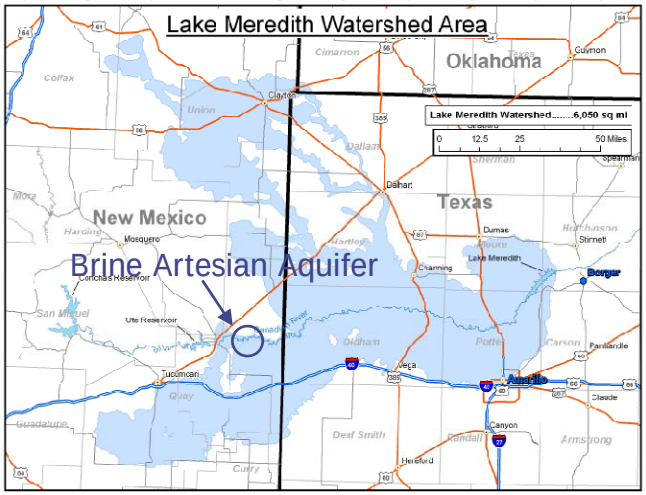


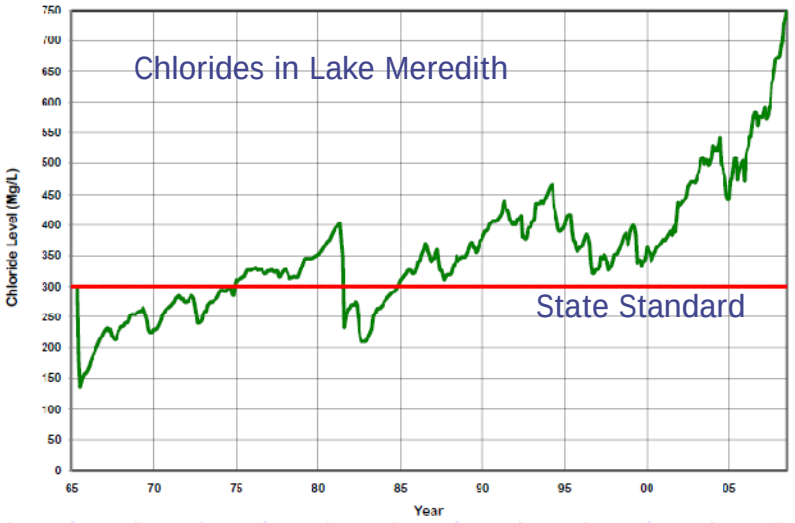


From IPCC 2007

Water Availability and Water Quality

- The availability of water in the region is also affected by water quality
  - Chlorides are seen to increase in Lake Meredith
  - More pronounced during droughts
- Canadian river water quality affected by brine outflows from artesian springs
  - Single source near Logan New Mexico has been identified as cause for 70% salinity in the river



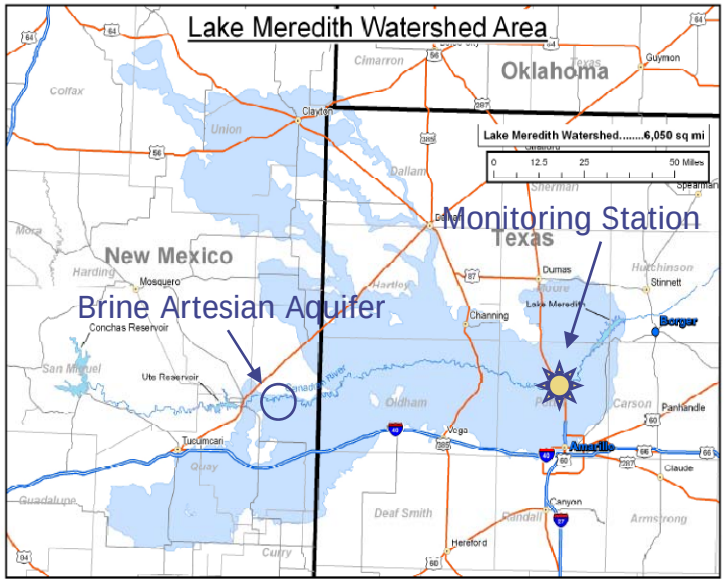


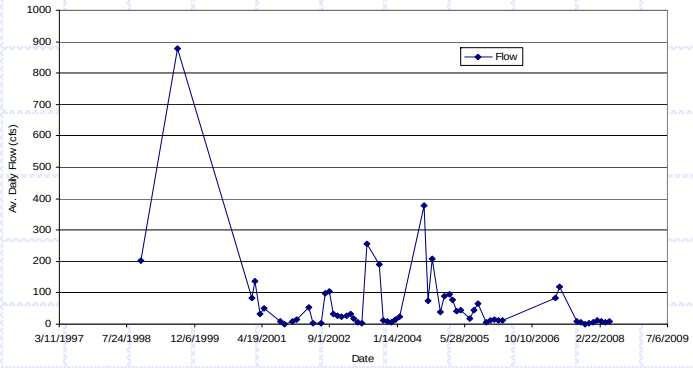
Research Question

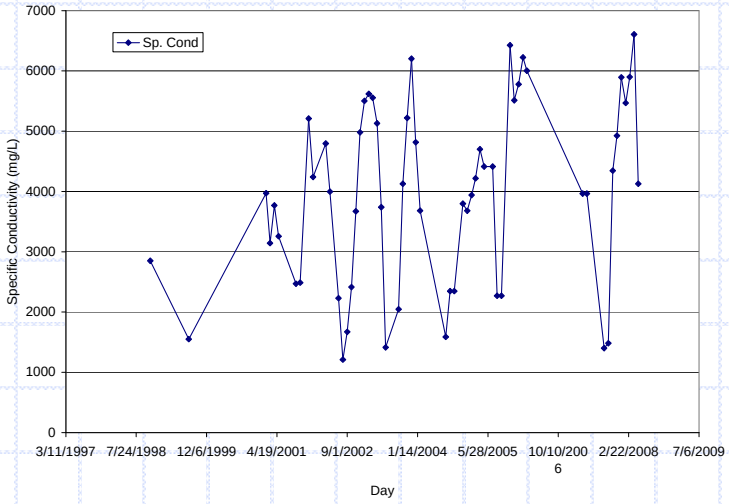
Evaluate the interplay between the Climatic and Water Quality in the Canadian River Watershed

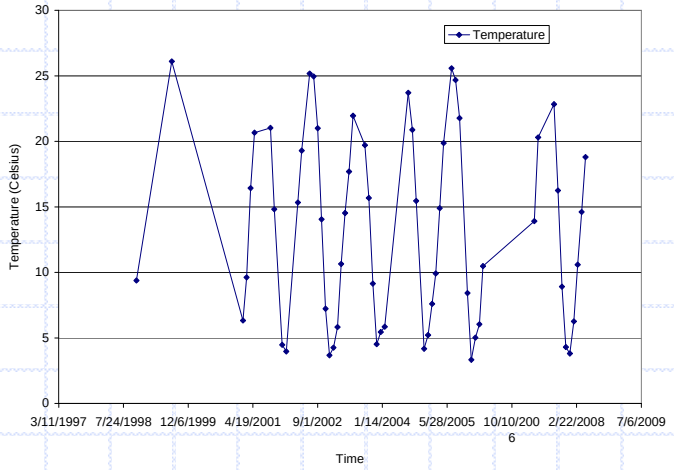
- Streamflow, Temperature and specific conductance (a surrogate for salinity)
- Model the dependencies among parameters using copula theory

Study Site and Data Compilation









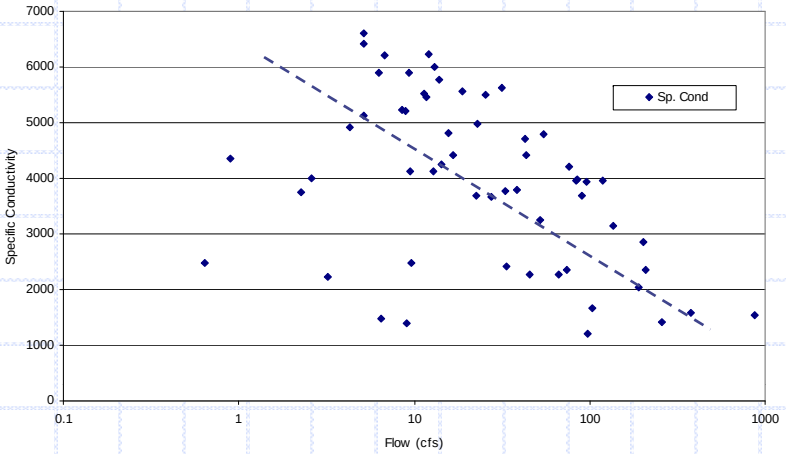
Data from USGS Gaging Station
Canadian River Nr Amarillo, TX
1997 – 2008 Period

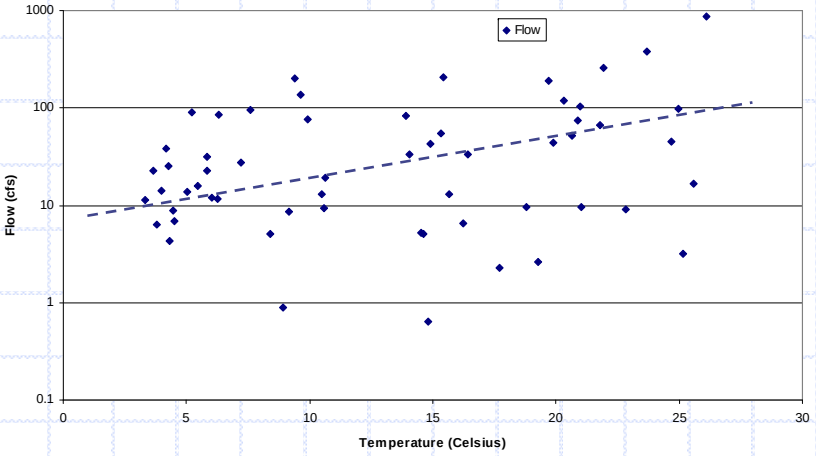
Climate-Quality Correlations

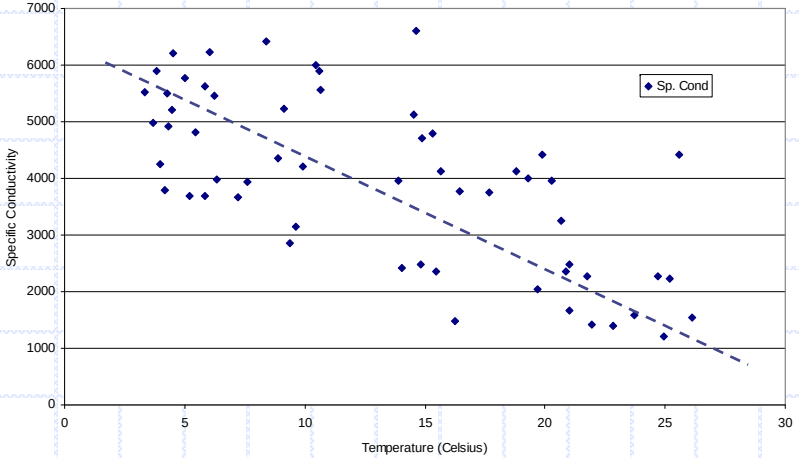
Non-parametric correlation measure

Kendall Tau

	Flow	Sp. Cond	Temperature
Flow	1.000	-0.368	0.180
Sp. Cond	-0.368	1.000	-0.474
Temperature	0.180	-0.474	1.000







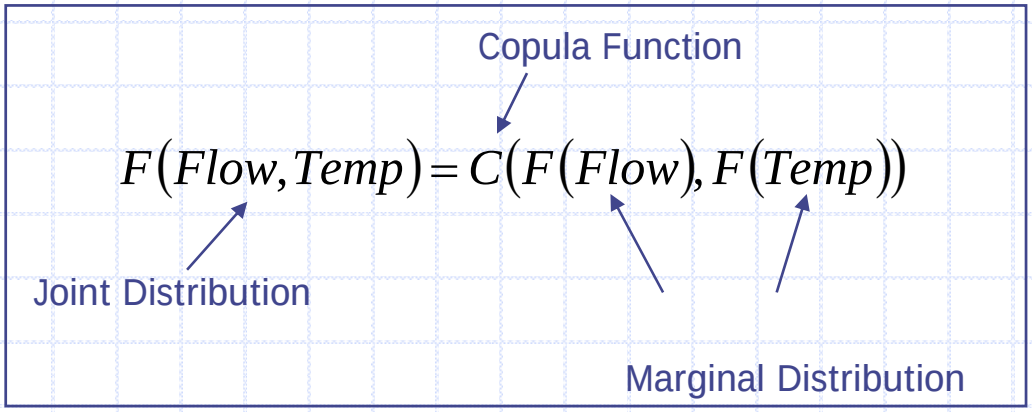
- Specific Conductance inversely related to Flow and Temperature
- Flow and Temperature are positively correlated (low correlation)
- Specific Conductance has a higher correlation with Temperature

Summer → Rainfall

Summer → Artesian Pressure

Stochastic Evaluation using Copulas

- Copulas help model the joint distribution of two or more random variables
  - The joint cumulative probability distribution can be constructed from marginal distributions
    - From distributions of individual variables
  - If the marginals are continuous the copula function is unique
- Copula models offer great flexibility
  - The marginals need not have the same distribution
  - Have been used extensively in finance and risk applications
  - Increasingly used in hydrology in recent years
- Copulas have not been used to evaluate climate-quality interactions



Copulas - Background

- There are several copula functions proposed in the literature
  - Elliptical Copulas
    - Gaussian Copula
  - One-Parameter Archimedian Copulas
    - Gumbel-Hougard Family
    - Ali-Mikhail Haq Family
    - Frank Family
    - Clayton Family
  - Archimedian copula parameter is a function of Kendall Tau
    - Kendall tau is a non-parametric measure of correlation
    - Kendall tau is not affected by transformations while Pearson Product moment correlation is

$$F(Flow, Temp) = C(F(Flow), F(Temp))$$

$$C = f(\theta)$$

Archimedian Copula Parameter

Copulas Background

- The copula function can be defined using the Kendall-tau
  - Numerical computations are required for Ali-Mikhail-Haq and Frank family copulas
- Not all copulas are applicable for all variable pairs
  - Gumbel-Hougard and Cook-Johnson are only applicable for positively correlated variables
    - Temperature and Streamflow
  - Ali-Mikhail-Haq and Frank family are applicable for both positive and negatively correlated variables
- As there are several copulas one has to empirically determine the best model for the data at hand
  - Very similar to fitting a probability distribution or a regression equation
  - A standardized procedure has been put-forth for the bi-variate case (Genest and Rivest, 1993) and widely-accepted

Copula Estimation – The Six Step Program

- Step 1: Select the random variable pairs to be evaluated
  - Temp-Flow; Flow-Sp. Cond.; Temp-Sp. Cond
- Step 2: Define correlation structure among the variables
  - Calculate Kendall tau statistic
  - If the parameters are not correlated then copulas are not necessary
  - If the parameters are perfectly correlated than copulas are not necessary
- Step 3: Identify appropriate marginal distributions for each variable
  - Use Method of moments or maximum likelihood
- Step 4: Compute the copula parameter for all suitable copula families
  - Limited when the parameters are negatively correlated
- Step 5: Identify suitable copula family for modeling joint distribution
  - Compare theoretical and empirical quantile plots
- Step 6: Use copula to evaluate joint dependence
  - Joint frequency
  - Return period

Copula Analysis – Canadian River

- Step 1: Random Variables to be Evaluated
  - Three pairs of random variables were evaluated
    - Flow – Sp. Conductance (µs/cm)
    - Temp – Sp. Conductance
    - Flow and Temp
  - Data from 1997 – 2008 was used in the study
    - Missing data were excluded
    - Staggered data minimized autocorrelation
- Step 2: Define Correlation structure & identify copula families

Kendall Tau

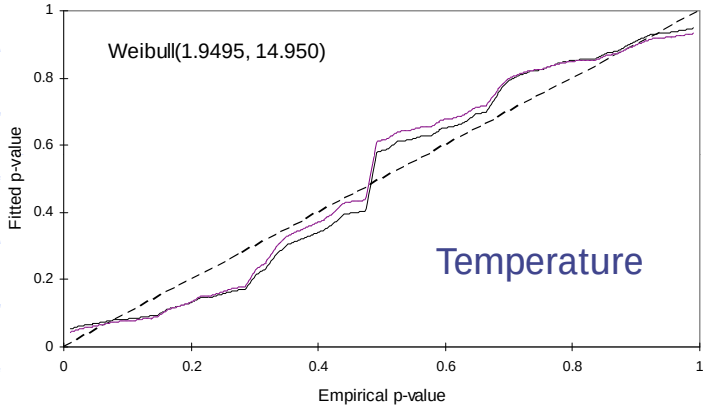
	Flow	Sp. Cond	Temperature
Flow	1.000	-0.368	0.180
Sp. Cond	-0.368	1.000	-0.474
Temperature	0.180	-0.474	1.000

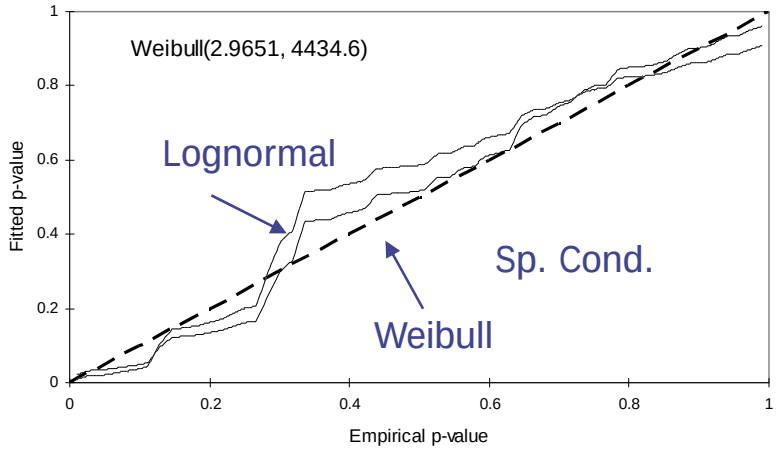
Random Variables		Gumbel	Ali-Mikhail-Ha	Frank	Cook-Johnson
Flow	Sp. Cond	NA	Yes	Yes	NA
Temp	Sp. Cond	NA	Yes	Yes	NA
Flow	Temp	Yes	Yes	Yes	Yes

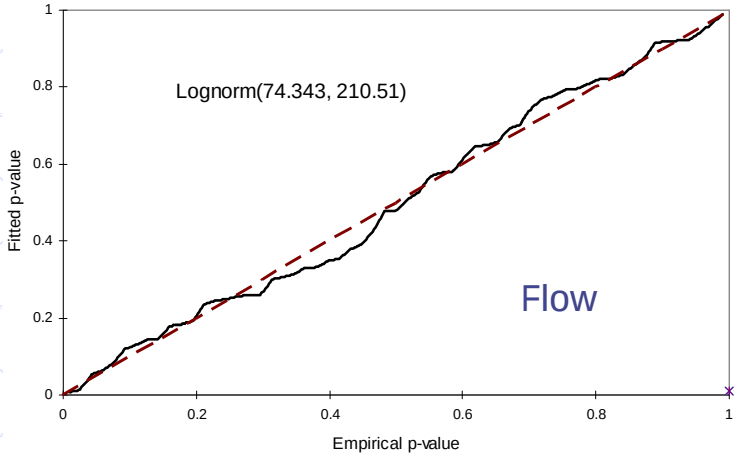
Step 3: Marginal Distribution

- Step 3: Define Marginal Distributions
  - Marginal Distributions were computed using Maximum Liklihood and MOM methods
  - Goodness-of-fit evaluated using Chi-square, Anderson-Darling and K-S statistics

Marginal Distributions				
Flow	LogNorm	74.343	210.51	
Sp. Cond	Weibull	2.9651	4434.6	
Temperature	Weibull	1.9495	14.95	A-D and K-S
Temperature	Gamma	2.9408	4.4929	Chi-square







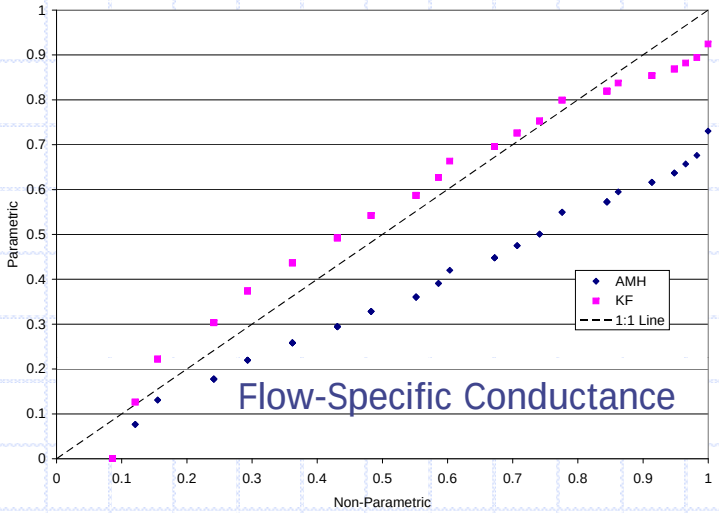
Step 4: Copula Parameter Identification

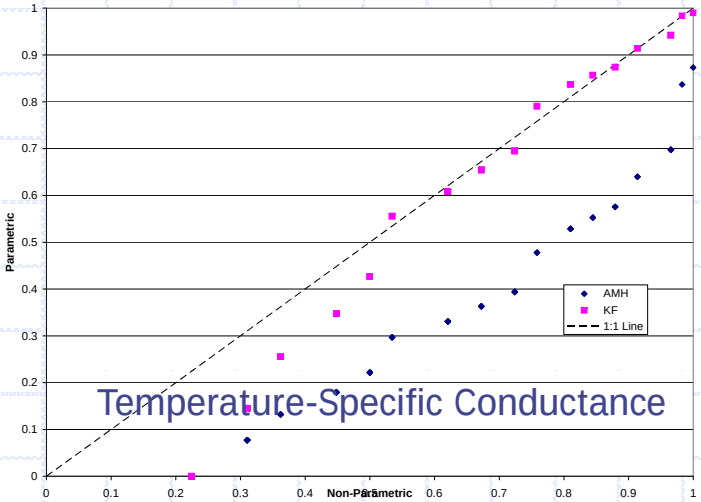
- Copula Parameters were identified from Kendall-tau statistic
  - Ali-Mikhail-Haq relationship was solved using secant method
  - Frank relationship was solved using Secant and Gaussian quadrature

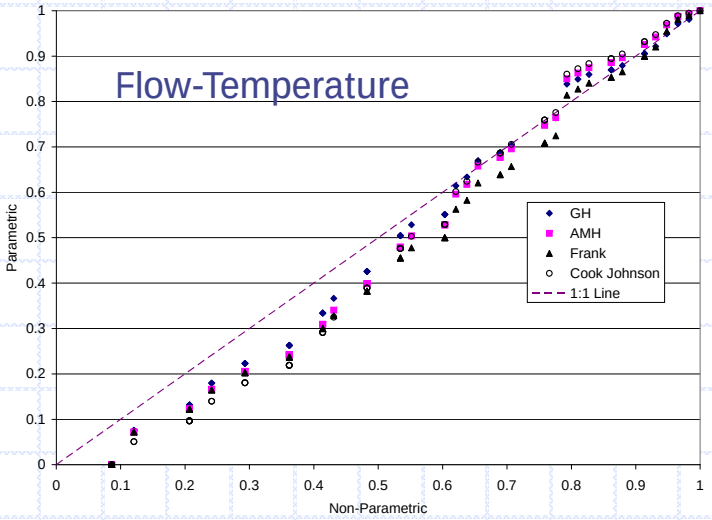
Theta-Value	Random Variable Pairs		
Copula	Q-Sp.Cond	Cond-Temp	Q-Temp
Gumbel-Hougard	NA	NA	1.220
Ali-Mikhail-Haq	0.532	0.512	0.666
Frank	3.745	5.288	-2.579
Cook-Johnson	NA	NA	0.439

Copula	Relationship
Gumbel	$\tau = 1 - \frac{1}{\theta}$
Frank	$\tau = 1 - \frac{4}{\theta}\left[\frac{1}{\theta}\int_0^{\theta} \frac{t}{\exp(t)-1}dt + \frac{\theta}{2} - 1\right]$
Ali-Mikhail-Haq	$\tau = \left(\frac{3\theta-2}{\theta}\right) - \frac{2}{3}\left(1-\frac{1}{\theta}\right)^2 \ln(1-\theta)$
Cook	$\tau = \frac{\theta}{\theta+2}$

Step 5: Identification of Suitable Copula







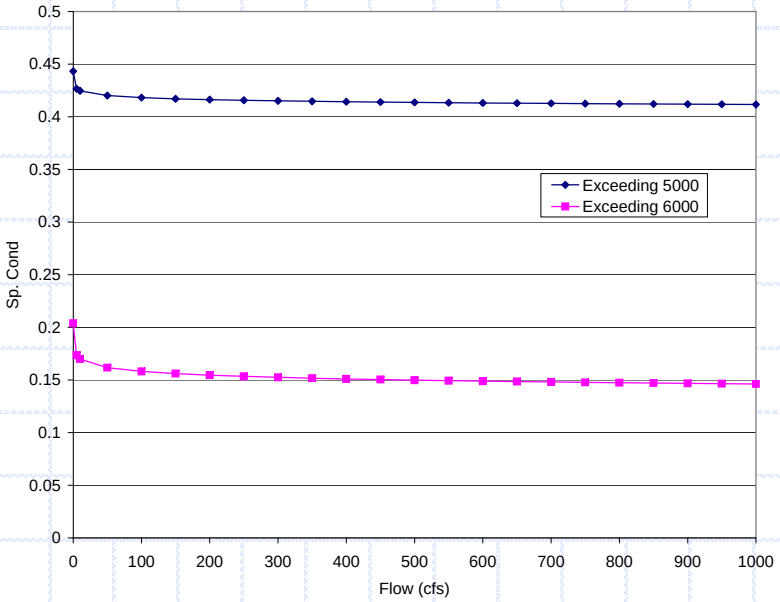
Random Variables		Appropriate Copula
Flow	Sp.Cond	Frank
Temp	Sp.Cond	Frank
Flow	Temp	Gumbel-Hougard

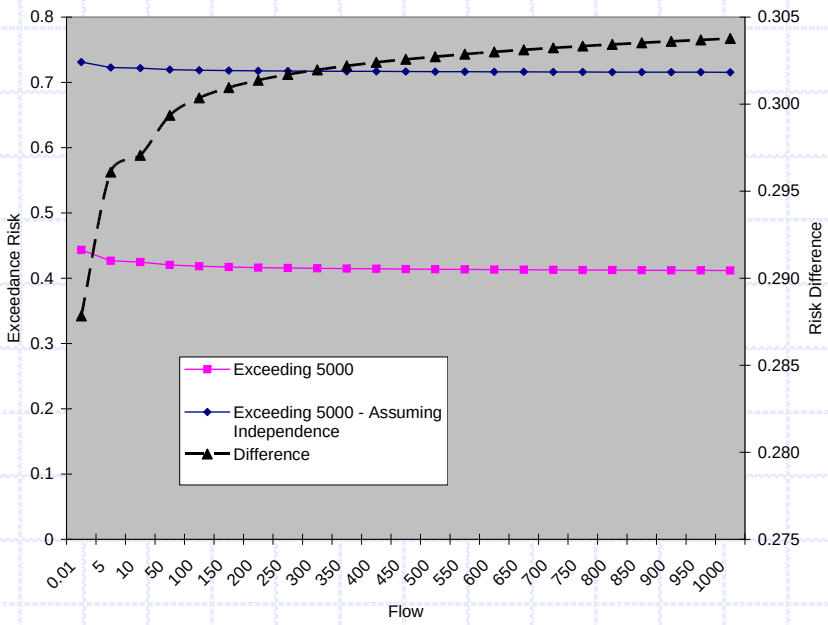
Copulas have difficulties modeling tails (especially lower end tail)

Frank Copula was better than Ali-Mikhail-Haq (for specific conductance relationships)

Step 6: Analysis of Joint Events

- The copula models can be used for a variety of joint analysis
  - Estimating exceedance risks $P(Q > Q_T, C > C_T) = 1 - P(Q \le Q_T, C \le C_T)$
  - Estimating joint return periods





Exceedance risks are highly over-estimated when the correlation is not factored in

Summary and Conclusions

- Impacts of climate change on water quality is poorly understood
- Water quality impacts do affect the long-term sustainability
  - Particularly important in fast-growing regions with poor water quality
    - Canadian River in the Texas Pan-handle
- Copula theory can be used to assess water quality risks due to climatic influences
  - Joint probability of correlated random variables
- Inclusion of correlation provides a better picture of risks
  - At least gives an idea of the magnitude of over-estimation caused due to independence assumption

Thank You!

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