Uncertainty Modelling, Water Quality Management, Reservoir Operation and Irrigation Planning

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Outline of the Presentation

- Regional Water Resources System
- River Water Quality Management
- Irrigation Water Management
- Reservoir Operation
- Climate Change Impacts
- Adaptive Measures
Regional Water Resources System

Systems Involved

- Climate System
- Hydrological Modeling
- Water Inflow/Availability to Reservoir/Dam
- Downstream River Water Quality – Effluents
- Irrigation Water Management
- Hydropower Water Management
- Reservoir Operation, Optimum Releases, Water Demand
Regional Water Resources System

Systems Involved

• **Climate System**
  • Hydrological Modeling
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Climate System

- **Weather**: Characteristics of the atmosphere over a short period of time, in terms of few days or weeks. 
  Ex: *Current* Temperature, Rainfall, Humidity, Solar radiation

- **Climate**: The statistics of weather over a long period of time 
  Ex: *Average* Temperature, Rainfall, Humidity, Solar radiation

- **Climate Change**: Difference between climatic states, statistical description over a period of time, altered patterns.

- **Climate System**: Atmosphere, hydrosphere, biosphere and geosphere and their interactions
Earth’s Climate to Change

Changes in the Atmosphere:

- **Natural processes**
  - Volcanic eruption
  - Solar radiation fluctuations
  - Ocean circulation changes

- **Anthropogenic Processes**
  - Release of “Greenhouse Gases” into the atmosphere
  - Deforestation
Climate Change Impacts

- Increasing Temperatures
  - Evapotranspiration
  - Water Quality

- Change in Precipitation Patterns
  - Streamflow; Water availability
  - Intensity, Frequency and Magnitude of Floods and Droughts
  - Groundwater Recharge

- Rise in Sea Levels
  - Inundation of coastal areas
  - Salinity Intrusion
Climate Change Impact Assessment using Climate Models

- They represent the physical, ocean, cryosphere and land surface processes in the atmosphere
- Used to explore past climate events and to project future warming events
- Many climate models have been developed to perform climate projections, i.e. to simulate and understand climate changes in response to the emission of greenhouse gases and aerosols.
Climate Models (Contd..)

- GCMs perform reasonably well in simulating climatic variables at larger spatial scales, 2.0° latitude x 2.0° longitude, but poorly at the smaller space and time scales relevant to regional impact analyses.

- Accuracy of GCMs decreases from climate related variables, such as wind, temperature, humidity and air pressure to hydrologic variables such as precipitation, evapotranspiration, runoff and soil moisture, which are also simulated by GCMs.

- Poor performances of GCMs at local and regional scales have led to the development of downscaling models.
Climate Change Impact Assessment

- To bridge the spatial and temporal resolution gaps between what GCMs are currently able to provide and what impact assessment studies require.
- Involves deriving empirical relationships between large-scale features of the GCM climate variables and regional-scale variables.

Diagram:
- **GCM outputs:** Large scale Climate Variables (e.g. mean sea level pressure)
- **Regional Scale Hydro-meteorological Variables** (e.g. streamflow, rainfall, surface air temperature)
- **Predictors**
- **Predictands**
- **Transfer Function**
- **Statistical Downscaling**
Climate Change Impact Assessment (Contd..)

- Observed/Predictand Data
  - Source: IMD, CWC etc.

- Observed Climate Data/Predictors Data
  - Source: Reanalysis data

- GCM Current and Future Predictors Climate Data
  - Source: Different GCMs – About 23 Climate Modeling Centres
    - EX: Beijing Climate Center, Canadian Centre for Climate Modelling and Analysis, Meteorological Research Institute, NASA/GISS (Goddard Institute for Space Studies) USA
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\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \]
Water Availability or Inflows to Reservoirs

Hydrologic Budget \((\text{In} - \text{Out} = \Delta \text{Storage})\)

\[(P + GW_{\text{in}}) - (E + T + I + GW_{\text{out}} + Q) = \Delta \text{Storage}_{\text{reservoir}}\]

Physical characteristics affecting Runoff
- Land use
- Vegetation
- Soil type
- Drainage area
- Basin shape
- Elevation
- Topography
- Drainage network patterns
- Ponds, lakes, reservoirs etc. in the basin

Hydro - meteorological factors affecting runoff
- Rainfall intensity, amount, duration
- Distribution of rainfall over the basin
- Antecedent moisture content
Delineation of watershed
Obtaining hydro-meteorological variables and geographic data
Selection of modeling approach
Calibration and Validation
Use of the model for assessment/prediction/design
Hydrological Modelling (Contd.)

- Spatio-temporal scale of interest
- Hydrologic quantity of interest
- Availability of hydro-meteorological data of watershed
- Computational accuracy and requirement

Lumped  Semi-Distributed  Fully-Distributed
Projecting Climate Change Impacts on Hydrology

- Climate Change Projections (precipitation, temperature, radiation, humidity)
- Topography, Land-use Patterns; soil characteristics;

Downscaling

Hydrologic Model

Possible Future Hydrologic Scenarios on Basin Scale
(Streamflow, Evapotranspiration, Soil Moisture, Infiltration, Groundwater Recharge etc.)
Tunga - Bhadra Water Resources System

Schematic Diagram of Tunga-Bhadra River

- Tunga River = 147 km; Bhadra River = 178 km
- Tunga-Bhadra River through Karnataka = 382 km
- Tunga-Bhadra River Stretch under Study = 200 km
- Total Catchment Area = 69552 km²
$R = 0.824$
Streamflow Future Projections

Observed and predicted from MIROC 3.2 GCM (A1B) Streamflow at various locations along the Tunga-Bhadra river, (i) Shimoga along Tunga river, (ii) Lakkavalli along Bhadra river, (iii) Koppelur along Kumudavathi river, (iv) Byladahalli along Haridra river, (v) Honnali along Tunga-Bhadra river.
Case Study: Krishna River Basin
Case Study: Krishna River Basin
Regional Water Resources System

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A river system is subjected to a number of pollutants, and these pollutants change the water quality in the river.

For the estimation of extent of pollution, water quality indicators like DO will be checked at some check points by Pollution Control Agency (PCA), so that DO should be within desirable limit.
Waste Load Allocation Models

Hypothetical River System

• For the allocation of assimilative capacity of a river system Waste load allocation model (WLAM) is developed.

• WLA refers to determining the required pollutant treatment levels at a number of point and non point sources to attain a satisfactory water quality response in a receiving water body in an economically efficient manner.

• To arrive at optimal fraction removal levels addressing uncertainty due to randomness, fuzziness and partial ignorance due to missing data or limited data in the input variables.

Uncertainties

• Randomness in Streamflow, Effluent Flow, Temperature and Reaction Rates

• Fuzziness due to water quality standards, goals & objectives, and nonpoint source pollution

• Partial ignorance due to missing data or limited data

Non-point Source Pollution
The water quality parameter considered is Dissolved Oxygen

The linear membership function for the fuzzy goal of the Pollution Control Agencies (PCA) is given as follows:

\[
\mu_{F_a}(C_{ii}) = \begin{cases} 
0 & C_{ii} \leq C_{ii}^L \\
\left[\frac{C_{ii} - C_{ii}^L}{C_{ii}^D - C_{ii}^L}\right]^\alpha & C_{ii}^L \leq C_{ii} \leq C_{ii}^D \\
1 & C_{ii} \geq C_{ii}^D 
\end{cases}
\]

A non-increasing linear membership function for the fuzzy goal of the dischargers can be expressed mathematically as follows:

\[
\mu_{F_{mn}}(x_{imn}) = \begin{cases} 
1 & x_{imn} \leq x_{imn}^L \\
\left[\frac{x_{imn}^M - x_{imn}^L}{x_{imn}^M - x_{imn}^L}\right]^\beta & x_{imn}^L \leq x_{imn} \leq x_{imn}^M \\
0 & x_{imn} \geq x_{imn}^M 
\end{cases}
\]
The model maximizes the minimum satisfaction level

Maximize $\lambda$

subject to

$$\mu_{E_{il}}(c_{il}) \geq \lambda \quad \forall i,l$$

$$\mu_{F_{imn}}(x_{imn}) \geq \lambda \quad \forall i,m,n$$

$$c_{il}^L \leq c_{il} \leq c_{il}^D \quad \forall i,l$$

$$\max \left[ x_{imn}^L, x_{imn}^{MIN} \right] \leq x_{imn} \leq \min \left[ x_{imn}^M, x_{imn}^{MAX} \right] \quad \forall i,m,n$$

$$0 \leq \lambda \leq 1$$

<table>
<thead>
<tr>
<th>Discharger</th>
<th>Fractional Removal Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Limit</td>
</tr>
<tr>
<td>1</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>0.69</td>
</tr>
<tr>
<td>6</td>
<td>0.69</td>
</tr>
<tr>
<td>7</td>
<td>0.69</td>
</tr>
<tr>
<td>8</td>
<td>0.69</td>
</tr>
</tbody>
</table>
River Water Temperature

- Water temperature is a critical component of hydrologic systems having a direct impact on water quality (e.g., concentrations of dissolved oxygen).
- Temperature governs the varieties of organisms that can live in rivers and lakes. Fish, insects, zooplankton, phytoplankton, and other aquatic species all have a preferred temperature range.
- River temperature is of economic importance in water requirements for industry, electricity and drinking water production, and recreation.
- Weather conditions such as air temperature, solar radiation, relative humidity, wind speed, Flow and stream depth, ground-water inflow rate, Thermal conductivity of the sediments, Topography
Linear Regression Models

- Linear Equation Relating Stream Temperature with Air Temperature is
  \[ T_w(t) = A + BT_a(t) \]
- Where \( T_w(t) \) and \( T_a(t) \) represent mean stream and air temperatures for a specified time scale. The constants, \( A \) (°C) and \( B \) (dimensionless), results from linear least-square regression

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shimoga</th>
<th>Honnali</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>+ 0.54</td>
<td>+ 0.66</td>
</tr>
<tr>
<td>F</td>
<td>- 0.389</td>
<td>- 0.318</td>
</tr>
</tbody>
</table>

Correlations between Air Temperature (AT), Water Temperature (WT) and Streamflow (F)
Air and River Water Temperatures Future Projections

Results of observed and predicted from MIROC 3.2 GCM (A1B) scenarios for air and water temperatures at Shimoga along Tunga-Bhadra River
River Water Quality Responses under Climate Change along Tunga-Bhadra River

The steady state DO levels are simulated for the present and for the future time slices of 2010-2040, 2040-2070 and 2070-2100 (Rehana and Mujumdar 2012)

Fractional Removal Levels for Various Dischargers for Current and Future Scenarios

Adaptive Policies

• Drought can cause reduced streamflows affecting dilution capacity of pollutants, increase in salinity levels, and cause infectious diseases due to lack of enough water.

• Flooding can cause increase in sedimentation and turbidity levels. Increase in disease-carrying pathogens or overflow of human and animal waste from sewer lines.

• Even though the dischargers maintain the safe permissible limits for the effluents, due to the impacts of climate change on temperature and flows, a significant reduction in water quality can be observed.

• The current water quality standards will not be adequate even if there is a rise of 1°C in air temperature.

• Need to improve the water quality standards provided by Pollution Control Boards considering the future deterioration of water quality to account for the climate change conditions.
Regional Water Resources System

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Irrigation Water Demands

- The irrigation water requirement are affected by
  - **Crop factors:** type of crop, cropping pattern, crop season, growth stage of the crops, soil type and topography.
  - **Climatic factors:** rainfall and evapotranspiration

<table>
<thead>
<tr>
<th>Crop</th>
<th>Duration (days)</th>
<th>Sowing date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy</td>
<td>120</td>
<td>June 15</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>365</td>
<td>July 01</td>
</tr>
<tr>
<td>Permanent Garden</td>
<td>365</td>
<td>June 01</td>
</tr>
<tr>
<td>Semidry Crops</td>
<td>123</td>
<td>July 01</td>
</tr>
</tbody>
</table>
Evapotranspiration

• Evapotranspiration is the largest water flux next to rainfall, which is a prominent hydrological component and represents the atmospheric water demand.

• Evapotranspiration depends on air temperature, net radiation, wind speed, vapor pressure, relative humidity, soil moisture, type of vegetation/crop, season of vegetation/crop growth.

• Reference and Potential Evapotranspiration

\[ ET_{t,p}^c = ET_{t,R} X k_{t,c} \]

- \( ET_t^c \) is the potential evapotranspiration
- \( ET_{t,R} \) is the reference evapotranspiration
The total irrigation demand of the command area based on the net effect of rainfall in the command area and evapotranspiration of the crops grown over the command area.

\[
IWR_{t,c} = \begin{cases} 
  \left( ET_t^C - R_t \right) A_c & \text{for } R_t < ET_t^C \\
  0 & \text{for } R_t > ET_t^C 
\end{cases}
\]

- \( R_t \): Rainfall contribution for month, \( t \).
- \( A_c \): Area of crop, \( c \).
- \( ET_t^C \): Potential evapotranspiration of a crop, \( c \), for a month of \( t \).
- \( IWR_{t,c} \): Irrigation Water Requirement of crop, \( c \), for a month of \( t \).
Projections of Various Meteorological Variables from CCA Model

Downscaling results of various meteorological variables over Bhadra command area (a) denote annual scale observed, simulated from NCEP and simulated from MIROC 3.2 GCM with 20c3m experiment for the training period of 1971 to 1995. (b) denote monthly scale projections with the green box plots are for 2020-2044, blue box plots are for 2045-2065 and red box plots are for 2070-2095.
Projected Annual Irrigation Water Requirements

Projected Annual Irrigation Water Requirements at each location for each crop for Bhadra Command Area

Case Study: Bhadra Command Area
Projected Changes in Rainfall, Evapotranspiration and Irrigation Water Demands

Change in (a) rainfall and evapotranspiration in terms of monthly percentage change for 2020-2060 corresponding to period of the 1984-2004, (b) in irrigation demands for various crops in terms of monthly difference for 2020-2060 corresponding to period 1984-2004.
Climate Change Scenarios for Agriculture of Afghanistan

- East, South and West zone has the relatively lower irrigation water demands
- North and South-West zone has the relatively higher irrigation water demand
- East and West zone has the relatively lower irrigation water demand
- North and South-West zone has the relatively higher irrigation water demand.
Adaptive Policy

• More than 70% of India’s population lives in rural areas with main occupation as agriculture. Around 93% of farmers cultivate nearly 55% of the arable land (FAO).

• It is estimated that every 10 °C increase in temperature is likely to lead to a 5-10% reduction in yields of some crops (Pachauri 2009)

• Therefore, significant impact on food security as changes in patterns of extreme weather events will affect the stability of food supplies

• Need to modify the irrigation strategies accounting for the shifts in the monsoon
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Overview of the Integrated Reservoir Operation under Climate Change

Hydro-Climatic Variable Projection Model

GCM output: Global Climate Variables

Projects of Local/Regional Variables (Inflow, Rainfall, Maximum and Minimum Temperatures, Relative Humidity, Wind Speed)

Use of Multiple GCMs/Scenarios: Weighted Mean of Hydro-Climatic Variables from Entropy Weights

Statistical Downscaling

Climate Model Uncertainty

Projected Demands from Weighted Mean Hydro-Climatic Variables

Uncertainty due to Stochasticity

Weighted Mean Reservoir Inflow

Transition Probabilities for Current and for 2020-2040 and 2040-2060

Water Available for Allocation

Membership Functions for Current and Future Scenarios

Optimal Operating Policies for Current SDP, 2020-2040 SDP and 2040-2060 SDP

Stochastic Dynamic Programming

Fuzzy Water Quantity Control Model (FWQCM) for Current and Future Periods of 2020-2040 and 2040-2060

Optimal Fractional Removal Levels

System Performance Measure

Projected Optimal Water Allocation to Irrigation, Water Quality and Hydropower

Uncertainty due to Imprecision and Conflicting Interests

Operating Policy
Projected Water Demands - Irrigation

The irrigation demands quantified accounting for the future scenarios of rainfall and evapotranspiration can be used to obtain optimal water allocations for irrigation user. Linear membership function for irrigation user is given as:

\[
\mu(q_\alpha) = \begin{cases} 
0 & q_\alpha \leq q_{\alpha}^{Min} \\
\left(\frac{q_\alpha - q_{\alpha}^{Min}}{q_{\alpha}^{D} - q_{\alpha}^{Min}}\right) & q_{\alpha}^{Min} \leq q_\alpha \leq q_{\alpha}^{D} \\
1 & q_\alpha \geq q_{\alpha}^{D}
\end{cases}
\]

where \( q_{\alpha}^{D} \) and \( q_{\alpha}^{Min} \) are the desirable and minimum irrigation requirement of the irrigation user computed based on the projected irrigation demand.
Projected Water Demands – Hydropower

- The hydropower demand, $Q_p$, is computed based on the available head which in turn depends on the storage of the reservoir. The flow required for generating maximum hydropower is given by

$$Q_p = \frac{\tau P_p}{\eta \omega H}$$

where net head, $H = H_p - H_0$, $H_p$ is the head for a given average storage, $C_{Res}$, with respect to the riverbed after losses and $H_0$ is tailrace water level, $P_p$ is power in kW, $\tau$ is plant factor, $\eta$ is plant efficiency and $\omega$ is unit weight of water (9.81 kN). $Q_p$ is considered as the desirable release $q^D$. The minimum permissible limit, $q^{Min}$ is considered as zero.

$$H_p = 12.004 \times \ln(C_{Res}) - 36.42$$

The storage-elevation relationship derived based on historical data is assumed to remain unchanged for the future scenarios. Therefore, the membership function for hydropower demand remains unchanged for the future scenarios.
Projected Water Demands – Water Quality

- The degree of acceptability for any downstream water allocation resulting in a discrete state of river flow is determined using the Fuzzy Waste Load Allocation Model

$$\mu(q_\beta) = \begin{cases} 
0 & q_\beta < q_\beta^{\text{Min}} \\
\frac{f(q_\beta)}{f_{\text{q}_\beta^{\text{Min}}}} & q_\beta^{\text{Min}} \leq q_\beta \leq q_\beta^D \\
1 & q_\beta \geq q_\beta^D
\end{cases}$$

- The FWLAM is run for a number of discrete flow values to derive the response of the water quality according to the future projected changes of streamflow and water temperature, which can be used in the FWQCM.
Operating Policy Model – Water Quantity Control Model (WQCM)

Maximize $\lambda$

$$\frac{q_{\alpha} - q_{\alpha}^{\text{Min}}}{q_{\alpha}^{D} - q_{\alpha}^{\text{Min}}} \geq \lambda$$
$$f(q_{\beta}) \geq \lambda$$
$$q_{\beta}^{\text{Min}} \leq q_{\beta} \leq q_{\beta}^{D}$$
$$q_{\alpha} + q_{\beta} + q_{X} \leq W_{A}$$

$$\frac{q_{X} - q_{X}^{\text{Min}}}{q_{X}^{D} - q_{X}^{\text{Min}}} \geq \lambda$$
$$q_{\alpha}^{\text{Min}} \leq q_{\alpha} \leq q_{\alpha}^{D}$$
$$q_{X}^{\text{Min}} \leq q_{X} \leq q_{X}^{D}$$
$$0 \leq \lambda \leq 1$$

where $W_{A}$ is the amount of water available for allocation, which is the reservoir release; $R_{kilt}$, for a given $k$, $i$, $l$ and $t$. The solution of the resulting optimization problem will be $q^*$ and $\lambda^*$ where $q^* = \{q_{\alpha}^*, q_{\beta}^*, q_{X}^*\}$ corresponds to optimum water allocation among the three water users; viz., irrigation, water quality and hydropower, and $\lambda^*$ is the maximized minimum satisfaction level in the system.
Climate Change Impacts on Reservoir Operation

<table>
<thead>
<tr>
<th>Month</th>
<th>Irrigation Allocation</th>
<th>Hydropower Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current 2020-2040 2040-2060</td>
<td>Current 2020-2040 2040-2060</td>
</tr>
<tr>
<td>Jun</td>
<td>20.58 99.18 115.99</td>
<td>190.48 190.48 190.48</td>
</tr>
<tr>
<td>Jul</td>
<td>0.00 4.74 4.93</td>
<td>182.70 182.70 190.48</td>
</tr>
<tr>
<td>Aug</td>
<td>0.00 6.92 2.70</td>
<td>180.80 0.00 190.48</td>
</tr>
<tr>
<td>Sep</td>
<td>12.88 44.74 39.70</td>
<td>180.80 182.70 190.48</td>
</tr>
<tr>
<td>Oct</td>
<td>13.09 94.00 105.04</td>
<td>180.80 69.50 190.48</td>
</tr>
<tr>
<td>Nov</td>
<td>95.22 137.94 142.50</td>
<td>47.28 0.00 0.00</td>
</tr>
<tr>
<td>Dec</td>
<td>183.60 206.31 220.21</td>
<td>180.80 182.70 190.48</td>
</tr>
<tr>
<td>Jan</td>
<td>144.12 191.46 202.34</td>
<td>0.00 0.00 0.00</td>
</tr>
<tr>
<td>Feb</td>
<td>171.60 240.53 215.65</td>
<td>0.00 0.00 0.00</td>
</tr>
<tr>
<td>Mar</td>
<td>210.44 220.21 230.83</td>
<td>0.04 0.00 0.00</td>
</tr>
<tr>
<td>Apr</td>
<td>242.43 250.04 263.73</td>
<td>67.36 49.28 59.45</td>
</tr>
<tr>
<td>May</td>
<td>203.93 254.93 241.60</td>
<td>40.04 132.14 2.36</td>
</tr>
</tbody>
</table>

Downstream Water Quality Response from FWLAM

<table>
<thead>
<tr>
<th>Month</th>
<th>Downstream Allocation (Mm³)</th>
<th>Fractional Removal Level (%)</th>
<th>DO levels at 3 check points (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>45.04</td>
<td>86 85 86 61 61 61 90 90 90</td>
<td>6.19 6.02 4.24 6.49 6.56 5.82 5.34 4.84 2.28</td>
</tr>
</tbody>
</table>
Various Levels of Uncertainties in the Implication of Regional Impacts of Climate Change in the Bhadra River Basin

Reservoir inflow projection from hydro-climatic projection model

Demand quantification from irrigation demand model

Operating rule curves for the steady state policies

Summary

• Climate change is likely to impact most hydrologic systems
• Impacts need to be assessed at regional/river basin and smaller scales
• Developing adaptive responses such as long term reservoir operating policies; modifications in hydrologic designs; change in cropping patterns; water use adjustments etc.
• Climate Change should be considered as Driving Force in Water Resources Systems
• Adaptive measures towards sustainable water management
Water = Life

Thank you

Conservation = Future