# Optimal multi-reservoir Operation Based on a Combination of Short-term and Mid-term Forecasts

Project 2-5

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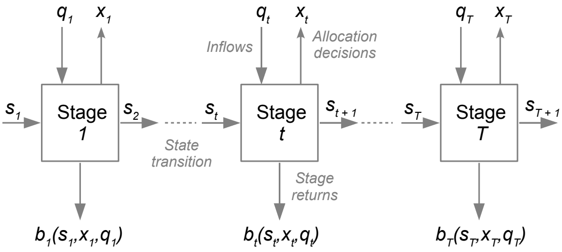
# Outline

# Background

- Projects 2-1 & 2-2 will produce short-term ensemble streamflow forecasts (ESF) for selected water resources systems
- Hydropower-dominated systems
- Project 2-5 seeks to assess the utility of these forecasts
- Incorporate short-term and seasonal forecasts into a multi-assets optimization framework → dynamic hedging policies
  - Physical assets = hydropower plants
  - Financial assets = portfolio of contracts, insurances, etc.

# Optimization

Multi-stage decision-making problem:



# Optimization

Multi-stage decision-making problem:

- High-dimensional optimization problem: computationally demanding
  - nbr of stages
  - nbr of reservoirs
  - nbr of hydrologic variables
  - ...
- Temporal decomposition of the optimization process
  - computationally efficient
  - different modelling approaches
  - institutional

# Optimization

**Long-term planning**

Strategic planning (investments)
Time step: year / month
Planning horizon: up to 20 years

**Mid-term planning**

Strategic & tactical planning (management)
Time step: month / week
Planning horizon: 1 to 5 years

**Short-term planning**

Tactical planning (operation)
Time step: day / hour
Planning horizon: 1 week to 1 month

**Real-time operation**

Real-time operation (load dispatching...)
Time step: hour
Planning horizon: 1 day

## Stochastic Dual Dynamic Programming (SDDP)

- Approximate dynamic programming technique
- Weekly time step
- Applicable to large water resources systems

## Non-linear Programming (NLP)

- Deterministic optimization along ensemble members
- Terminal water value function provided by SDDP

# Stochastic Dual Dynamic Programming (SDDP)

| Long-term |
| --- |
| Investments<br>year / month<br>up to 20 years |

| Mid-term |
| --- |
| Management<br>month / week<br>1 to 5 years |

| Short-term |
| --- |
| Operation<br>day / hour<br>1 week to 1 mon |

| Real-time |
| --- |
| Real-time<br>hour<br>1 day |

- Applicable to a potentially large network of reservoirs, power stations, diversions, financial assets, ...
- Code written in MATLAB and relies on the GUROBI LP solver. Currently recoded in PYTHON

# Stochastic Dual Dynamic Programming (SDDP)


- Applicable to a potentially large network of reservoirs, power stations, diversions, financial assets, ...
- Code written in MATLAB and relies on the GUROBI LP solver. Currently recoded in PYTHON
- SDDP provides
  - Statistical distributions of reservoir storages, allocation decisions, marginal water values, buy/sale decisions, etc.
  - Weekly water value functions, which are used as terminal value functions for short-term operation

# Stochastic Dual Dynamic Programming (SDDP)

**Long-term**
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year / month
up to 20 years

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**Short-term**
Operation
day / hour
1 week to 1 mon

**Real-time**
Real-time
hour
1 day

- Improved analytical representation of the hydrologic uncertainty
- Built-in analytical hydrologic model with eXogeneous variables
- Multiperiod multisite ARX model of order $p$ & $b$
- Snow water equivalent, precipitation, soil moisture, ..., sea surface temperature, seasonal forecasts
- Manuscript submitted to *Water Resources Research*

# Stochastic Dual Dynamic Programming (SDDP)

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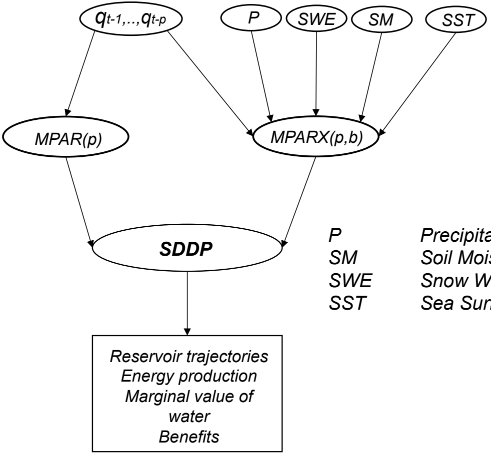
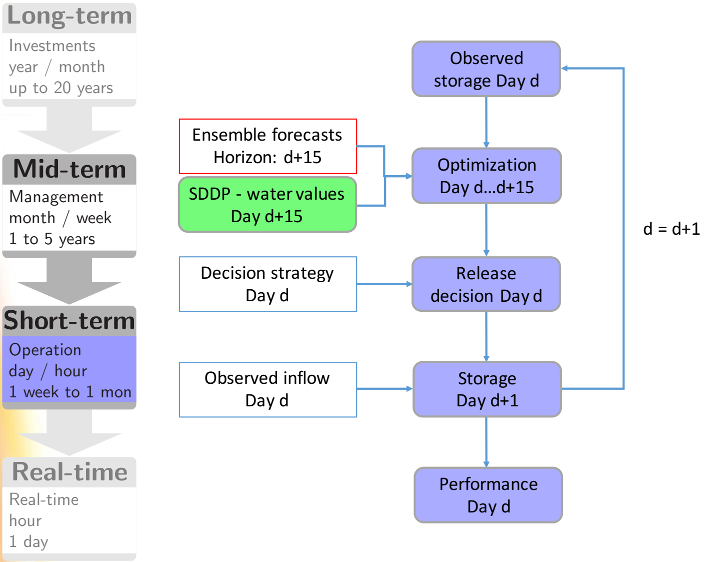



| | |
|---|---|
| *P* | *Precipitation* |
| *SM* | *Soil Moisture* |
| *SWE* | *Snow Water Equivalent* |
| *SST* | *Sea Surface Temperature* |

# Non-Linear programming (NLP)

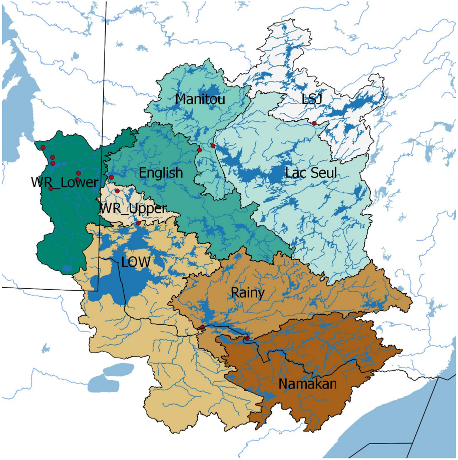

- Mid-term optimization is a boundary condition for short-term optimization
- Rolling horizon model using retrospective forecasts developed in projects 2-1 & 2-2
- Deterministic optimization along ensemble members
- Currently based on a Linear programming optimization but will be changed to a Non- Linear programming in the future
- Test different decision-making rules (max expected benefits, min regret, ...)

# Non-Linear programming (NLP)



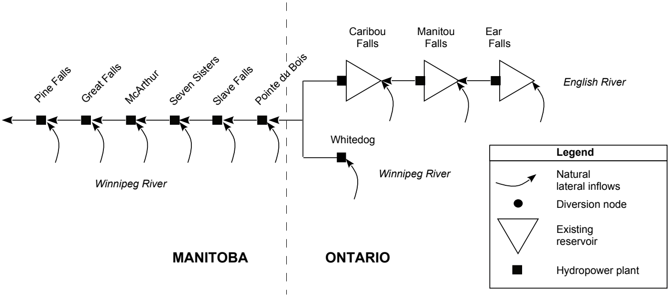
# Lake of the Woods

- Ontario and Manitoba
- English and Lower-Winnipeg Rivers



# Lake of the Woods

- Schematic representation of the system

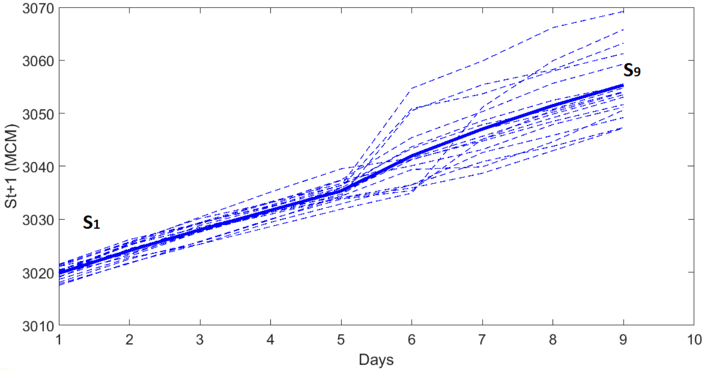


# Lake of the Woods

| ID | Storage ($10^6$ m$^3$) | Release (m$^3$/$s$) | Capacity (MW) |
|---|---|---|---|
| **1** | 7600 | 401 | 28 |
| **2** | 629 | 557 | 73 |
| **3** | 626 | 637 | 91 |
| **4** | - | 578 | 71 |
| **5** | - | 740 | 33 |
| **6** | - | 1122 | 68 |
| **7** | - | 1161 | 165 |
| **8** | - | 1041 | 55 |
| **9** | - | 1026 | 129 |
| **10** | - | 740 | 83 |

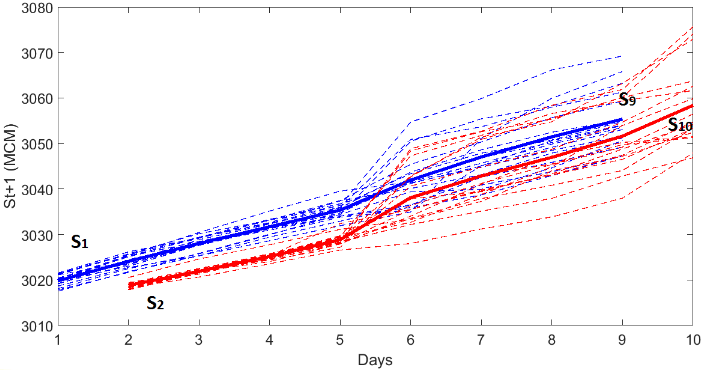
# Preliminary results - Synthetic case

- Results of the short-term optimization for 9 days ahead with 17 ESF members based on rolling horizon approach (optimal control) over a period of 309 days
- Optimal storages (days: 1..9)



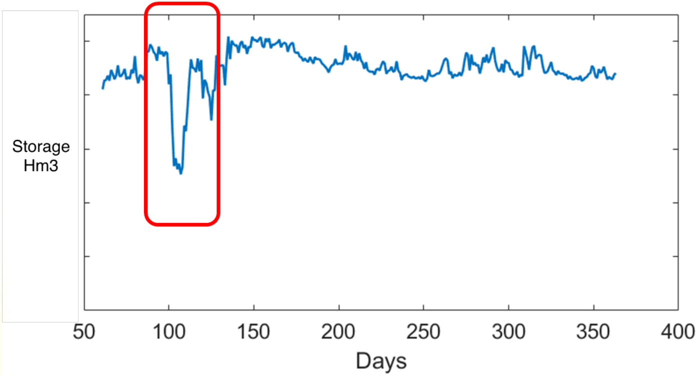
# Preliminary results - Synthetic case

- Results of the short-term optimization for 9 days ahead with 17 ESF members based on rolling horizon approach (optimal control) over a period of 309 days
- Optimal storages (day: 2...10)



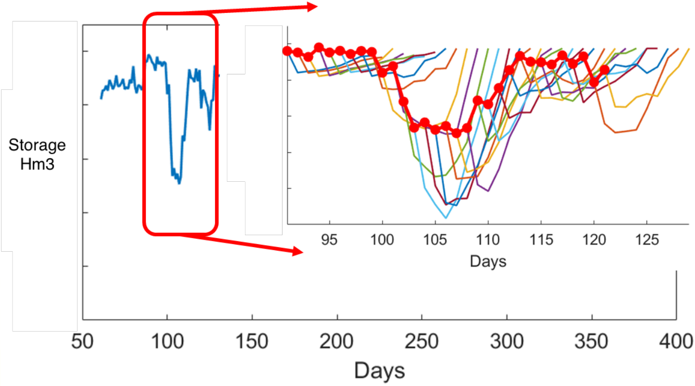
# Preliminary results - Synthetic case

- Results of the short-term optimization for 9 days ahead with 17 ESF members based on rolling horizon approach (optimal control)
- Optimal system's trajectory



# Preliminary results - Synthetic case

- Daily storages from day #91 to #121



# Conclusions and outlook

**Long-term**
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year / month
up to 20 years

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day / hour
1 week to 1 mon

**Real-time**
Real-time
hour
1 day

- First building block of the optimization framework = mid-term multi-reservoir optimization model
- Can now handle eXogenous hydrologic variables (e.g. snowpack) $\rightarrow$ seasonal forecasts
- Provide weekly benefit-to-go functions for short-term operation model
- Must be implemented on the Lake of the Woods system

# Conclusions and outlook

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- Development of the short-term reservoir optimization model has started
- Future work
  - LP $\rightarrow$ NLP formulation
  - Fine-tuning (interpolation of water values, travel time, etc.)
  - Must be implemented on the Lake of the Woods system
- How sensitive is the system to mid-term and short-term hydrologic forecasts?

THANK YOU