Optimization of Reservoir Operation Based on a Combination of Long-term and Short-term Hydrological Forecasts

Project 2-5

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Background

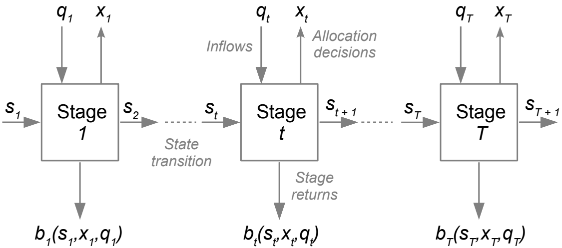
- Projects 2-1 & 2-2 will produce short-term ensemble streamflow forecasts (ESF) for selected water resources systems
- Hydropower-dominated systems
- Project 2-5 seeks to assess the utility of these forecasts
- Incorporate short-term and seasonal forecasts into a multi-assets optimization framework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

Optimization

Multi-stage decision-making problem:

$$\max_{s} Z = \mathbb{E}\left\{ \sum_{t=1}^{T} \alpha_t b_t(s_t, q_t, x_t) + \alpha_{T+1} v_{T+1}(s_{T+1}) \right\}$$

$$\text{s.t.} \quad s_{t+1} - x_t = s_t + q_t$$



Optimization

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$$\text{s.t.} \quad s_{t+1} - x_t = s_t + q_t$$

$\mathbb{E}$	expectation operator
α_t	discount factor at time t
s_t	storage in the system at time t
q_t	inflows at time t
x_t	decisions at time t
$v_t(s_t)$	terminal value function
$b_t(.)$	immediate benefit function

Optimization

Multi-stage decision-making problem:

$$\max_{s} Z = \mathbb{E}\left\{ \sum_{t=1}^{T} \alpha_t b_t(s_t, q_t, x_t) + \alpha_{T+1} v_{T+1}(s_{T+1}) \right\}$$

$$\text{s.t.} \quad s_{t+1} - x_t = s_t + q_t$$

- 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 studies
- Investments in infrastructure
- Planning horizon up to 20 years
- Yearly or monthly time step

Optimization

Long-term planning

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

Mid-term planning

- Strategic and tactical planning studies
- Management / operation
- Planning horizon of 1 to 5 years
- Monthly or weekly time step

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 studies
- Management / operation
- Planning horizon of 1 week to 1 month
- Hourly or daily time step

Optimization

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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
- e.g. load dispatching
- Planning horizon of 1 day
- Hourly time step

Optimization

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Time step: year / month
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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

Optimization

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Strategic & tactical planning (management)
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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

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Strategic planning (investments)
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Tactical planning (operation)
Time step: day / hour
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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 value function provided by SDDP

Stochastic Dual Dynamic Programming (SDDP)

Long-term
Investments
year / month
up to 20 years

Mid-term
Management
month / week
1 to 5 years

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

Real-time
Real-time
hour
1 day

- Applicable to a potentially large network of reservoirs, power stations, diversions, financial assets, ...

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- Applicable to a potentially large network of reservoirs, power stations, diversions, financial assets, ...
- SDDP provides
  - Statistical distributions of reservoir storages, allocation decisions, marginal water values, buy/sale decisions, etc.
  - Weekly benefit-to-go functions, which are used as terminal value functions for short-term operation

Stochastic Dual Dynamic Programming (SDDP)

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- Analytical representation of the hydrologic uncertainty
- Built-in analytical hydrologic model

$$\left(\frac{q_t - \mu_t}{\sigma_t}\right) = \sum_{i=1}^{p} \phi_{i,t} \left(\frac{q_{t-i} - \mu_{t-i}}{\sigma_{t-i}}\right) + \epsilon_t$$

- Multiperiod multisite AR model of order p
- Cross-correlated residuals
- Compatible with the Benders decomposition scheme of SDDP
- Parameters estimated from historical streamflow records (or streamflow projections/climate change)
- Site specific value of p (automatically adjusted)

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- Improved analytical representation of the hydrologic uncertainty
- Built-in analytical hydrologic model with eXogeneous variables

$$(\frac{q_t - \mu_t}{\sigma_t}) = \sum_{i=1}^{p} \phi_{i,t} \left(\frac{q_{t-i} - \mu_{t-i}}{\sigma_{t-i}} \right) + \sum_{i=1}^{b} \vartheta_{i,t} \left(\frac{x_{t-i} - \mu_{x,t-i}}{\sigma_{x,t-i}} \right) + \epsilon_t$$

- Multiperiod multisite ARX model of order p & b
- Snow water equivalent, precipitation, soil moisture, ..., sea surface temperature $\rightarrow$ seasonal forecasts

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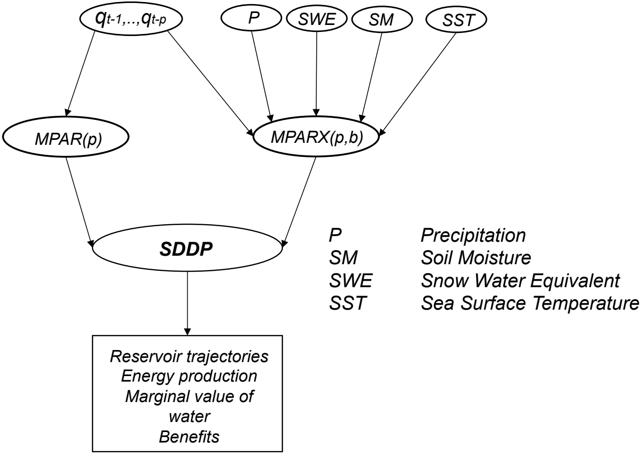
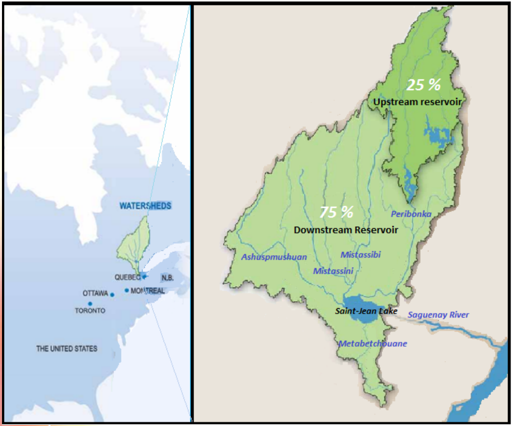
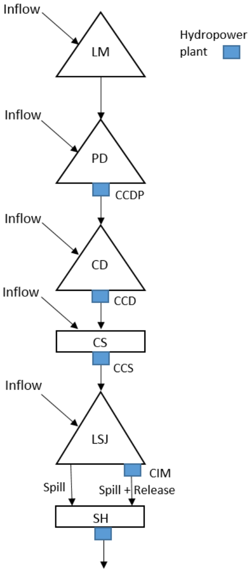


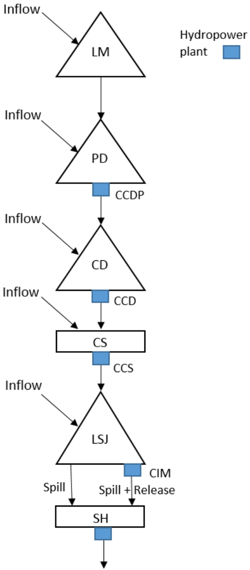
Rio Tinto Alcan power system





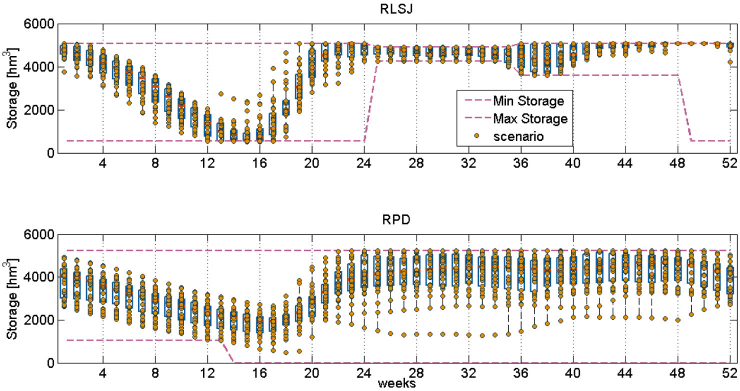
Rio Tinto Alcan power system

ID	Storage (10^6 m^3)	Release (m$^3/s$)	Capacity (MW)
LM	2657	-	-
PD	5228	570	750
CD	396	485	205
CS	-	810	210
LSJ	5083	1525	402
SH	-	2695	1587



Drawdown-refill cycle

- Reservoir trajectories

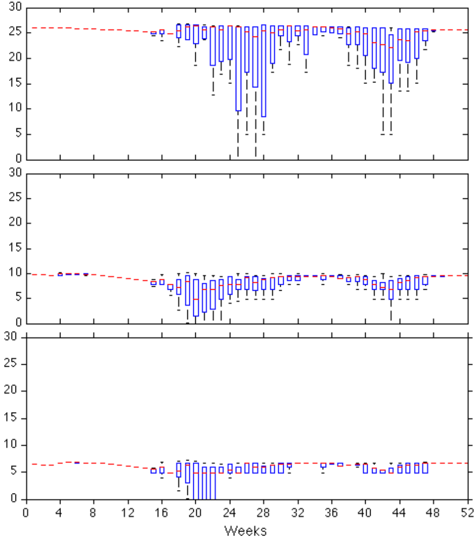


Weekly marginal water values ($\$/1000m^3$)

- Upstream reservoir

$\Downarrow$

- Downstrean reservoir



Conclusions and outlook

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year / month
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- First building block of the optimization framework = mid-term multi-assets optimization model
- Can now handle eXogenous hydrologic variables (snowpack) $\rightarrow$ seasonal forecasts
- Provide weekly benefit-to-go functions for short-term operation model
- This research activity is almost completed

Conclusions and outlook

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- Short-term reservoir optimization model remains to be developed (PhD student just started Sept 2016)
- Likely be based on an implicit stochastic Mixed Integer NonLinear Programming formulation
- Rolling horizon mode using retrospective forecasts developed in projects 2-1 & 2-2
- Deterministic optimization along ensemble members
- Test different decision-making rules (max expected benefits, min regret, ...)
- Madawaska River basin (Ontario Power Generation)

Conclusions and outlook

- Publications
  - Pina J., A. Tilmant and F. Anctil. A horizontal approach to assess the impact of climate change on water resources systems. To appear in *Journal of Water Resources Planning and Management*
  - Rouge C. and A. Tilmant (2016), Using stochastic dual dynamic programming in problems with multiple near-optimal solutions. *Water Resources Research*, 52, doi:10.1002/2016WR018608

THANK YOU