Short course on ensemble streamflow forecasting and reservoir optimization

27th IUGG General Assembly, Montréal, Canada

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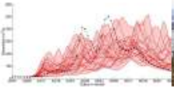
[2]Université du Québec à Chicoutimi & GERAD, sara.seguin@uqac.ca

July 9th 2019

Round of introductions...



Marie-Amélie Boucher

- Hydrologist
- Professor at Université de Sherbrooke (Canada)
- Research interests: multi-model forecasting, short and long term forecasting, data assimilation, pre and post-processing, assessing the socio-economic value of forecasts.
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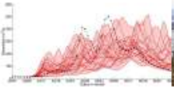

Sara Séguin

- Operations research specialist
- Professor at Université du Québec à Chicoutimi (Canada)
- Research interests: short term hydropower optimization, mathematical formulations (nonlinear, linear, linear integer), unit commitment, stochastic optimization.
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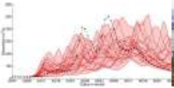
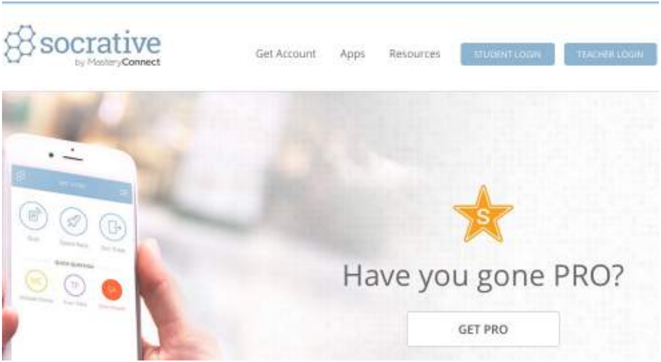


- ...And you?



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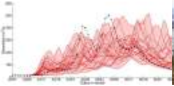
Outline



Ensemble streamflow forecasting

- First, some basics!
- Sources of uncertainty
- Verification
- Data Assimilation
- Pre- and Post-processing

Hydropower

- Basics
- Hydropower optimization
  - Decision making process
  - Uncertainty
  - Reservoir optimization
  - Short-term optimization

References

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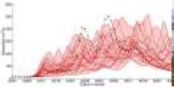
Ensemble streamflow forecasting

Some basics: Why Forecasting?



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http://ici.radio-canada.ca/nouvelle/516710/richelieu-inondations-monteregie

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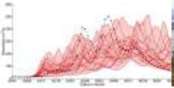
Some basics: Simulation vs forecasting



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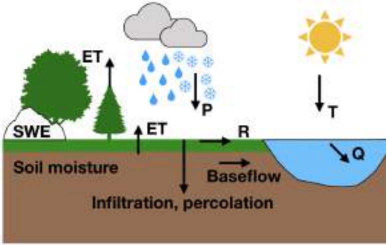
- It also contains equations, with free, initially undetermined parameters



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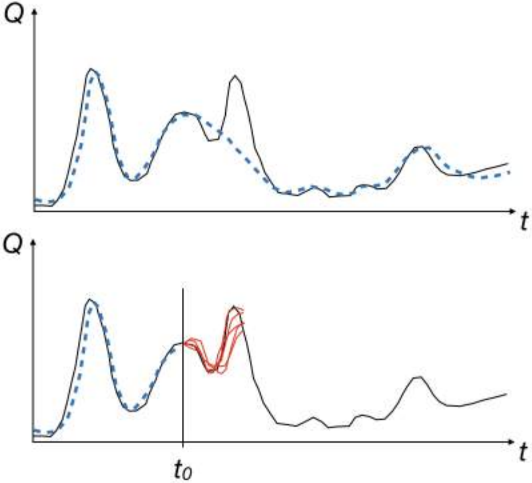

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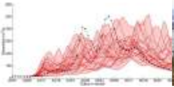

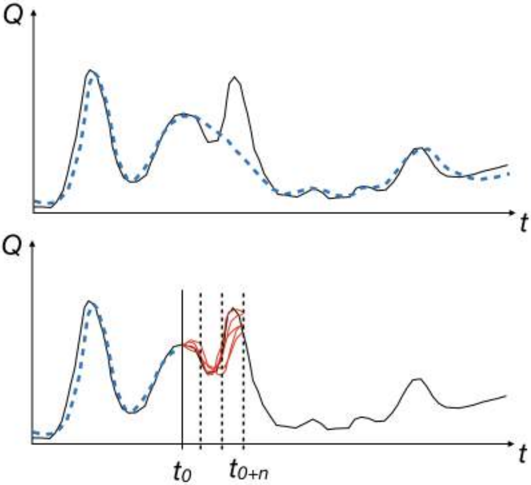

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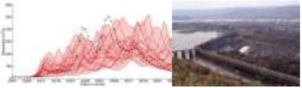

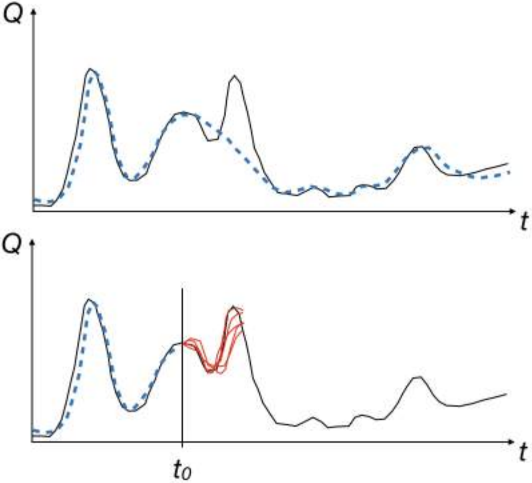

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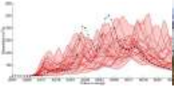

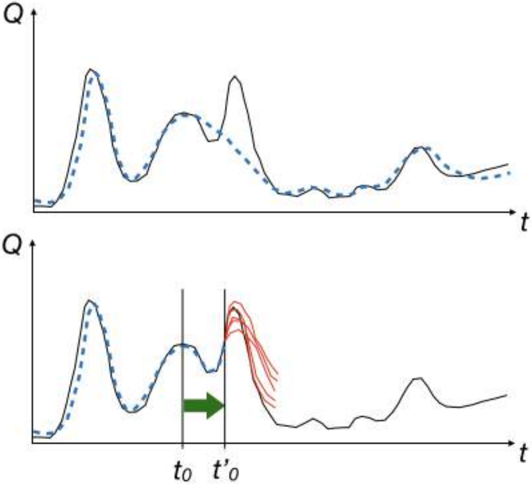

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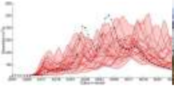
Sources of uncertainty



According to you, what are the main sources of uncertainty in hydrological forecasting?

Zoom

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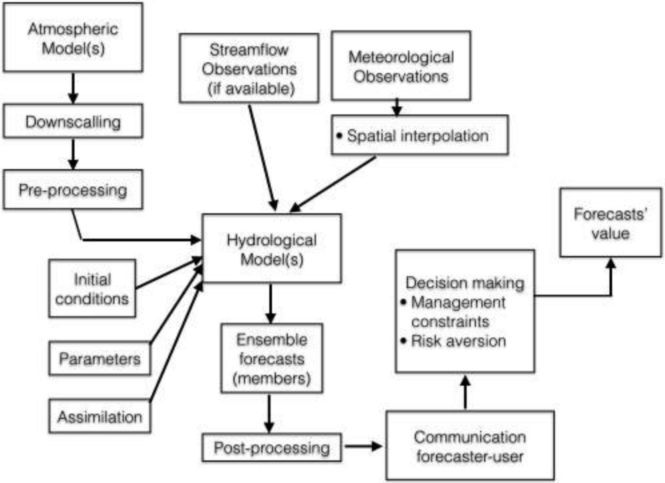
Sources of uncertainty



Verification

Zoom

What is a "good" ensemble or probabilistic forecast?

Enter Answer Here

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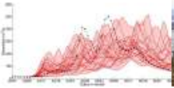
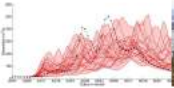


- Sharpness and reliability
  - **Sharpness:** "concentration of the predictive distributions and is a property of the forecasts only. The more concentrated the predictive distributions are, the sharper the forecasts, and the sharper the better, subject to [reliability]" [13]
  - **Reliability:** "refers to the statistical consistency between the distributional forecasts and the observations and is a joint property of the predictions and the observed values." [13]

    The predictive confidence intervals must be in agreement with their definition. E.g. The 95% confidence interval should include, on average, 95% of the observations.

Verification




- Continuous Ranked Probability Score [19]

$$CRPS(F, y) = \int_{\infty}^{\infty} (F(t) - H(x \geq y))^2 dx \tag{1}$$

- F: Forecast (cumulative distribution function)
- y: observation
- x: streamflow values
- H: Heavyside function
- For an ensemble of M members:

$$CRPS(x, y) = \frac{1}{M} \sum_{i=1}^{M} |x_i - y| - \frac{1}{2M^2} \sum_{i=1}^{M} \sum_{j=1}^{M} |x_i - x_j| \tag{2}$$

- This reduces to the Mean Absolute Error (MAE) for deterministic forecasts ($M = 1$)

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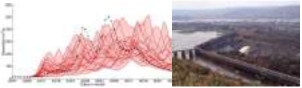

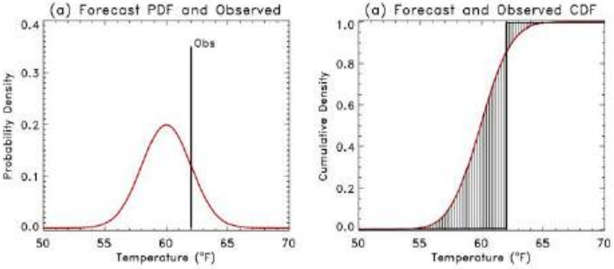

https://www.met-learning.eu/pluginfile.php/5277/mod_resource/content/6/www/english/msg/ver_prob_forec/uos3b/uos3b_ko1.htm

- Logarithmic (or ignorance) score [14]

$$ign(f, y) = -\log(f(y)) \tag{3}$$

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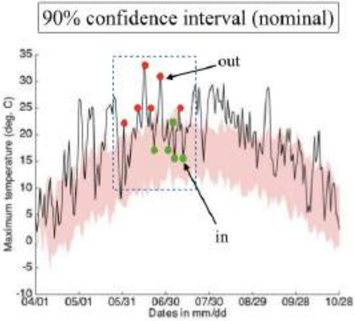
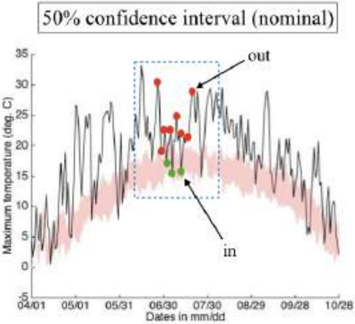
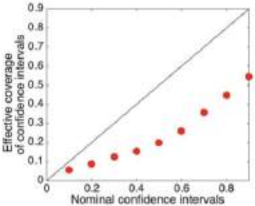


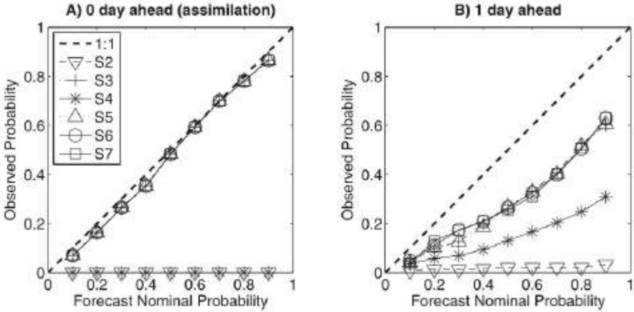


- For each level of confidence, verify if the observation is *inside* or *outside* the confidence interval
- Do it for *each time step*, each *forecasting horizon*, etc.



Verification

- Reliability diagram [33]



From Ouellet-Proulx S., Chimi-Chiadjeu O., Boucher M.-A., and St-Hilaire A. 2017 : Assimilation of water temperature and discharge for ensemble water temperature forecasting *Journal of Hydrology*, 554, 342-359

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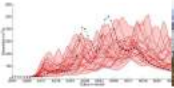

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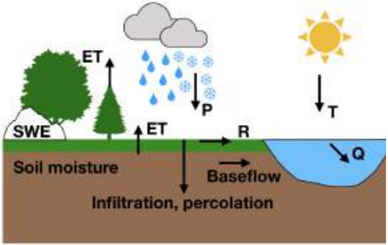

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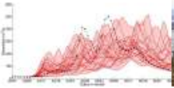

Distinction between calibration, post-processing and DA:

- Calibration: Obtaining values for the **free parameters** that provide good results **on average**, over a long period.
- Post-processing: **statistically** correcting the model **output** a posteriori so that it is more in agreement with the observation(s).
- DA: Updating the **state variables** (and sometimes parameters...) at time t_0, just before issuing a forecast for the next N days.

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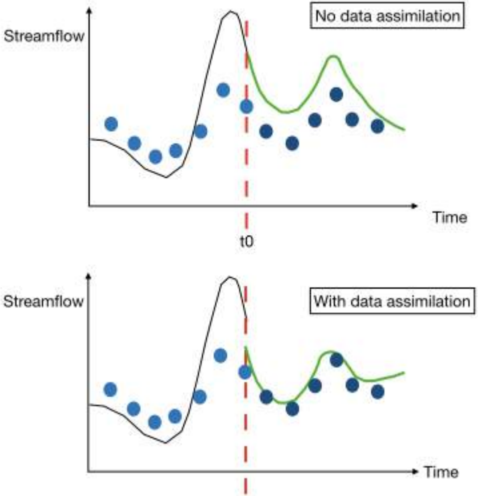

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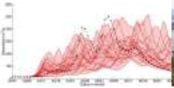

- Compromise between the model simulation ("background") and the observations
- Many variants exist!
  - Direct insertion: the forecaster trusts the observations entirely
  - Manual data assimilation
  - Ensemble Kalman filter
  - Variational DA
  - Particle filter

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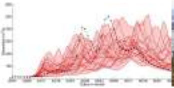

Manual, expert-judgement based DA

- The most widespread method among operational agencies
- Pros
  - Very simple to understand and to implement!
- Cons
  - Hardly reproducible
  - Not systematic: highly dependant on individual forecaster's knowledge and experience

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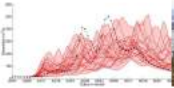

Manual, expert-judgement based DA

1. Add noise to the model's input(s) for the last T days before t_0
   - Additive or multiplicative
   - There are guidelines / rules of thumb
2. Re-run the model, to compute new state variables
3. Check (visually or using a numeric criteria) that the simulated flow from T to t_0 matches the observed flow better than the **open loop** simulation.
4. Better? Leave it like that, proceed with forecasting
5. Not better? Worst? Try again!

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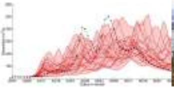

Basic Principles

- Based on Bayes theorem:

$$p(H|E) = \frac{p(E|H)p(H)}{p(E)} \tag{4}$$

- H: A hypothesis (here regarding the state of the model)
- E: Event (here, streamflow observations)

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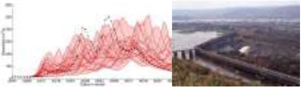

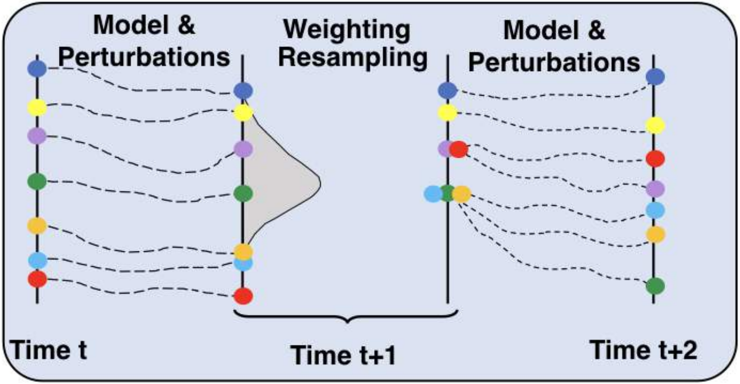

(Modified from [29])

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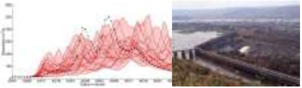
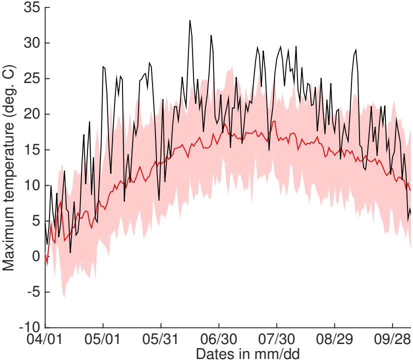
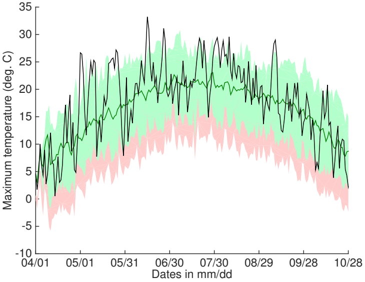
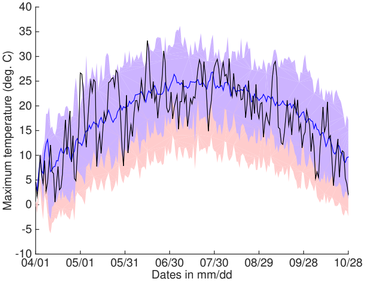


Pre- and Post-processing

- Modified from SEAS5 ensemble forecasts over the Kénogami Lake watershed (Quebec, Canada)
- Initally biased and under dispersed







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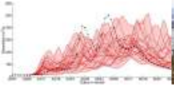
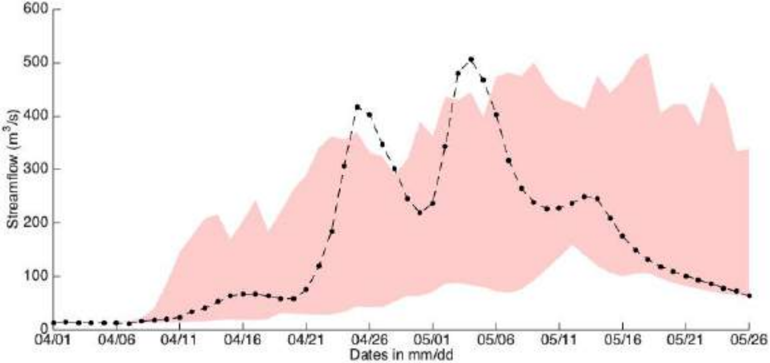


It is important to get the traces right! Problematic example for seasonal hydrological forecasts for Lake Kénogami (Canada)



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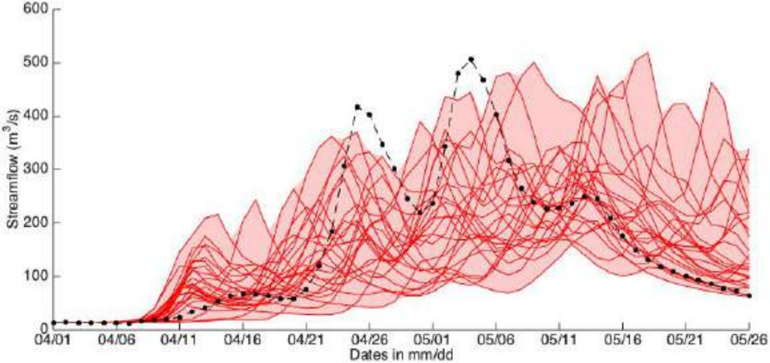

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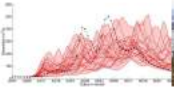
Ens. streamflow forecasting: wrap-up

We have discussed:

- Some definitions: simulation vs forecast, calibration vs data assimilation, etc.
- Sources of uncertainty
- Verification: CRPS, logarithmic score, reliability diagram
- Data Assimilation: basic ideas
- Pre- and Post-processing: basic ideas

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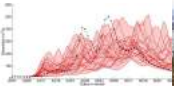
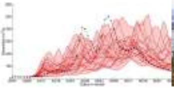


We have not yet discussed:

- Structural uncertainty
- Seamless forecasting and how long-term forecasts are different than short-term forecasts
- Data Assimilation: details of popular methods
- Pre- and Post-processing: details of popular methods + is is better to pre- or post-process?
- Forecasts communication and use for flood mitigation
- ...

Hydropower

What's next?



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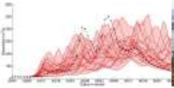
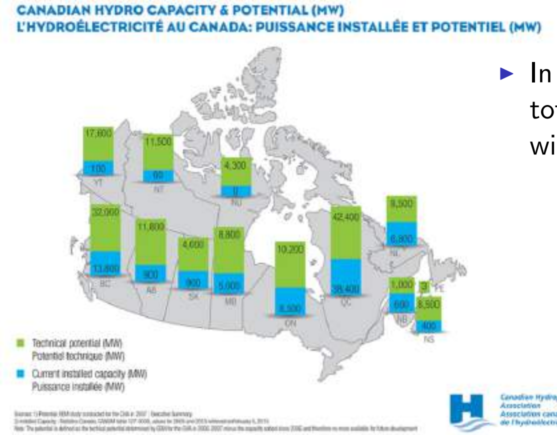
Hydropower





- In Canada, 63% of the total energy is produced with hydropower

Canadian Hydropower Association, 2019.[4]

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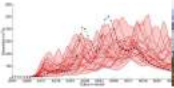
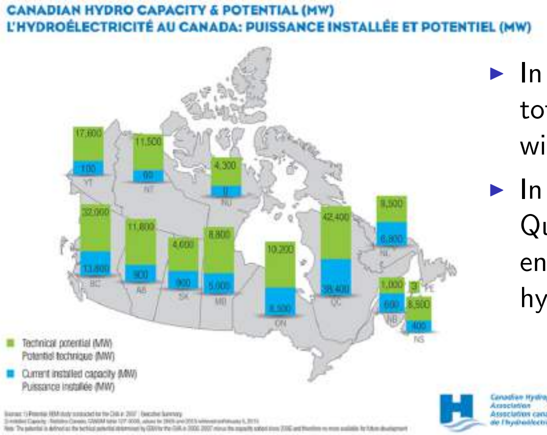
Hydropower

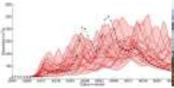


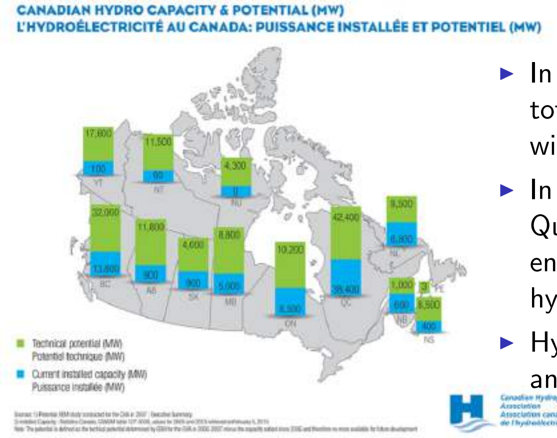



- In Canada, 63% of the total energy is produced with hydropower
- In the province of Québec, 97% of the energy is produced with hydropower

Canadian Hydropower Association, 2019.[4]

Hydropower





- In Canada, 63% of the total energy is produced with hydropower
- In the province of Québec, 97% of the energy is produced with hydropower
- Hydropower is a clean and renewable energy

Canadian Hydropower Association, 2019.[4]

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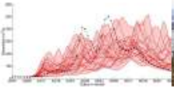
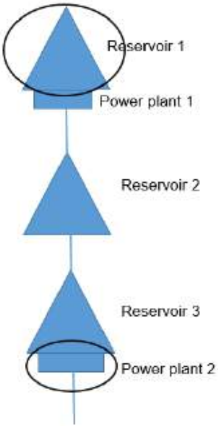
Hydropower system



An hydropower system is constituted of multiple power plants:



Each power plant contains one or more turbines

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Power plants: two types

Reservoir

Alaindg, 2007.[30]

Run-of-the-river

Iguanebobo, 2010.[31]

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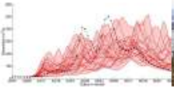
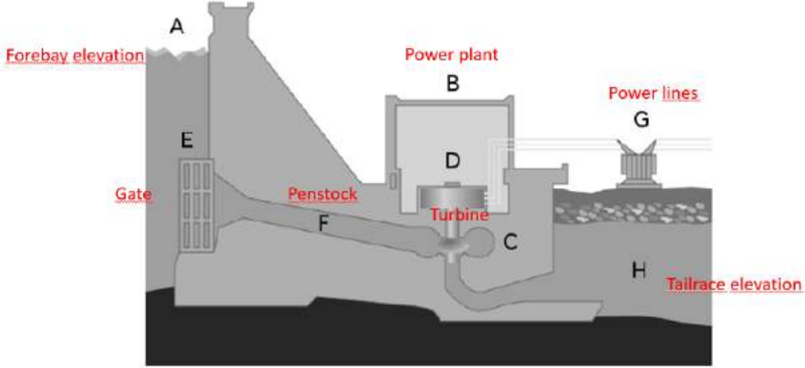
Power plant





Hydropower plant. Adapted with permission from « Hydroelectric dam » by Tomia, 2008. Image under license GFDL and CC-BY-2.5.

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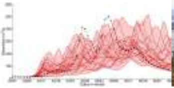
Turbine

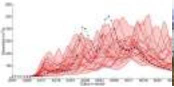
Florival fr, 2010.[32]

Power production



- Water is brought to the turbine by the penstock.

Power production



- Water is brought to the turbine by the penstock.
- The turbine turns with the force of water and the mechanical energy is transformed in electrical energy with the alternator.

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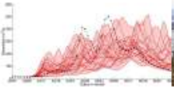
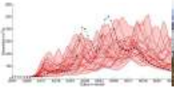
Power production



- Water is brought to the turbine by the penstock.
- The turbine turns with the force of water and the mechanical energy is transformed in electrical energy with the alternator.
- The power produced depends on two variables: the water flowing through the turbine and the net water head.

Power production



- Water is brought to the turbine by the penstock.
- The turbine turns with the force of water and the mechanical energy is transformed in electrical energy with the alternator.
- The power produced depends on two variables: the water flowing through the turbine and the net water head.
- For run-of-the-river plants, power produced is usually dependent only on water flow.

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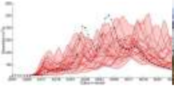
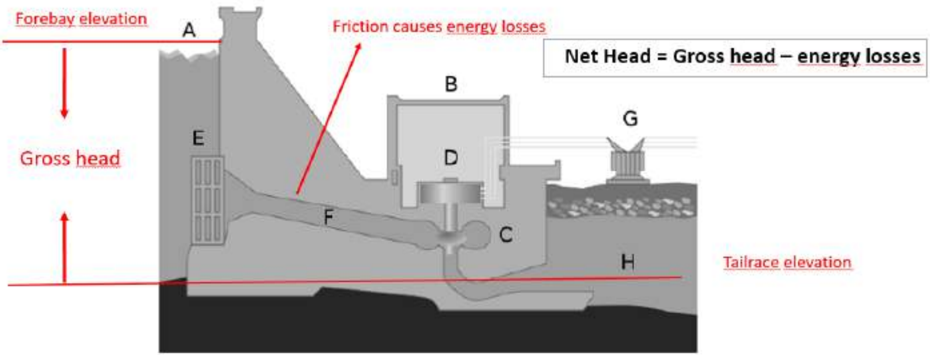
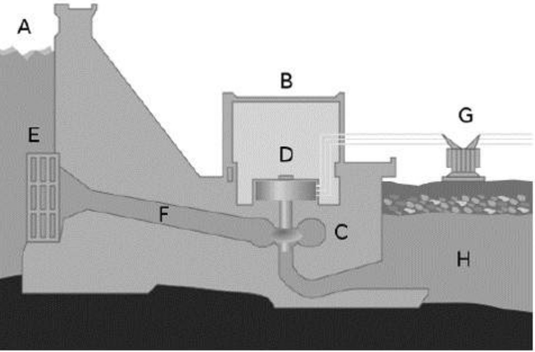
Power production





Tailrace elevation



- The water flow is processed by the turbines.

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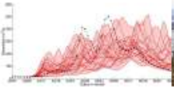
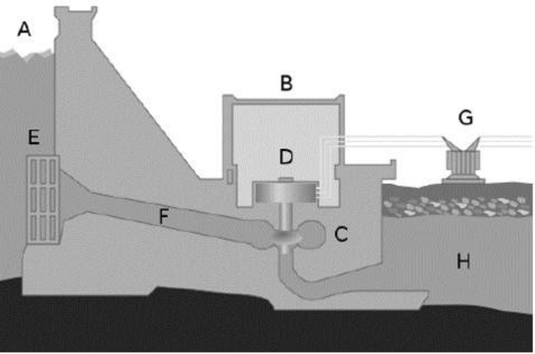
Tailrace elevation





- The water flow is processed by the turbines.
- The water then moves to H.

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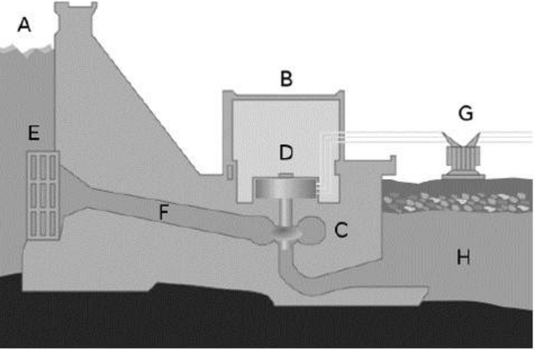
Tailrace elevation



- The water flow is processed by the turbines.
- The water then moves to H.
- The tailrace elevation varies.

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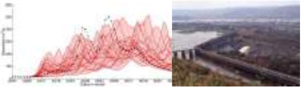
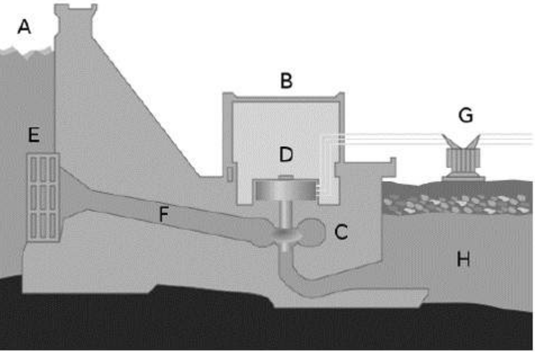
Tailrace elevation





- The water flow is processed by the turbines.
- The water then moves to H.
- The tailrace elevation varies.
- Which in turn, varies the net water head.

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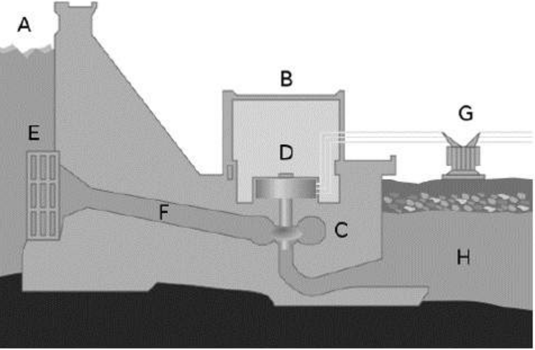
Tailrace elevation



- The water flow is processed by the turbines.
- The water then moves to H.
- The tailrace elevation varies.
- Which in turn, varies the net water head.
- The tailarce elevation is a function of the **total** water discharge.

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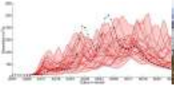
Power production



Power produced by a single turbine is given by:

$$P = ((h_f - h_t(Q_{tot})) - \text{energy losses}) \times \mu(Q) \times Q, \qquad (5)$$

where
h_f is the forebay elevation, h_t the tailrace elevation, Q_{tot} the total water discharge, Q the unit water discharge and μ the efficiency.

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Hydropower optimization

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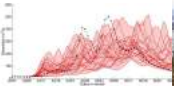
Hydropower optimization



The goal of hydropower optimization is to **manage efficiently** the hydropower system.
On an operational basis, daily decisions must be taken:

- The net water head (or volume)
- The water discharge
- The turbines working

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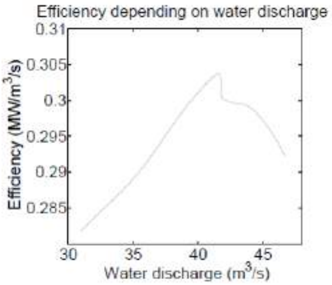
Other considerations

Besides power production itself, other considerations need to be accounted for when making decisions.

- Efficiency



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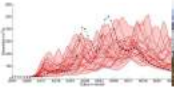
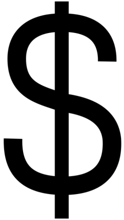
Other considerations



Besides power production itself, other considerations need to be accounted for when making decisions.

- Turbine startups



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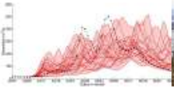
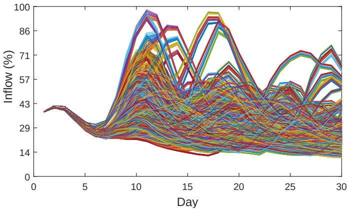
Other considerations



Besides power production itself, other considerations need to be accounted for when making decisions.

- Uncertainty



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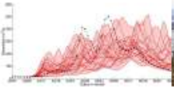
The decision making process



In practice, medium term and short term optimization models are used.

- **Medium term or reservoir optimization**. Estimate the quantity of water available for production. Determine reservoir trajectories based on water travel times between plants, reservoir levels, natural inflows uncertainty.
- **Short term**. Dispatch the water available between the turbines and the plants.

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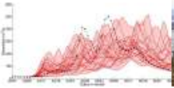
Optimization

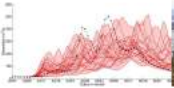


Optimization seeks to minimize a cost function or maximize a profit by finding the optimal value of **x** (decision variable):

$$\min c^T x$$

$$\text{s.t.} \quad Ax \leq b,$$
$$x \geq 0.$$

Optimization

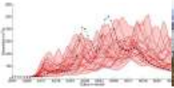


Optimization seeks to minimize a cost function or maximize a profit by finding the optimal value of **x** (decision variable):

Objective function

$$
\begin{aligned}
\text{s.t.} \quad Ax &\leq b, \\
x &\geq 0.
\end{aligned}
$$

Optimization



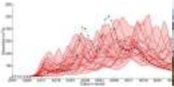
Optimization seeks to minimize a cost function or maximize a profit by finding the optimal value of **x** (decision variable):

Objective function

s.t.

Constraints
Bounds

Objective function



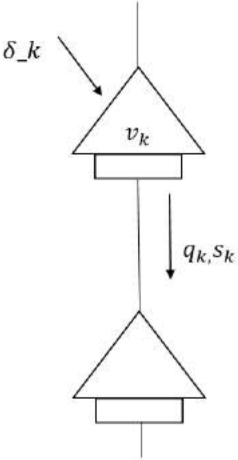
Usual objective functions:

- Maximize energy production
- Minimize operation costs
- Maximize profits
- Minimize efficiency losses

Constraints and considerations

- Water conservation

$$v_{k+1} = v_k - q_k - s_k + \delta_k$$



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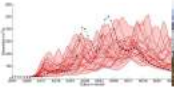
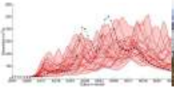
Constraints and considerations



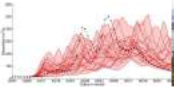
- Boats, beaches (bounds on water flows, volumes)

Constraints and considerations



- Boats, beaches (bounds on water flows, volumes)
- Energy demand

Constraints and considerations



- Boats, beaches (bounds on water flows, volumes)
- Energy demand
- Turbine startups

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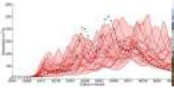
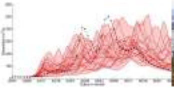
Constraints and considerations



- Boats, beaches (bounds on water flows, volumes)
- Energy demand
- Turbine startups
- Flooding

Constraints and considerations



- Boats, beaches (bounds on water flows, volumes)
- Energy demand
- Turbine startups
- Flooding
- Environmental constraints

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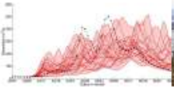
Constraints and considerations



- Boats, beaches (bounds on water flows, volumes)
- Energy demand
- Turbine startups
- Flooding
- Environmental constraints
- **Uncertainty**

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Uncertainty

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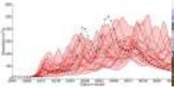
Uncertainty

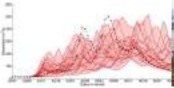


In the context of hydropower, uncertainty arises from:

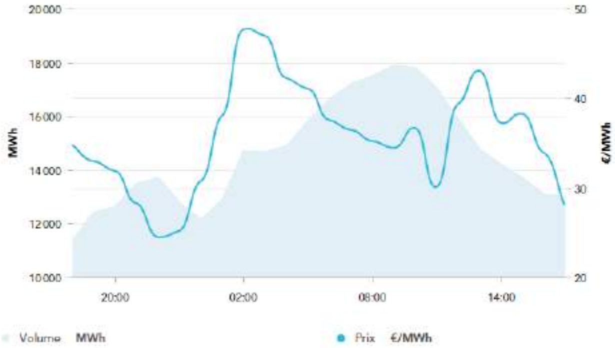
- Inflows

A. Vicente, U.S. Forest Service[28]

Uncertainty

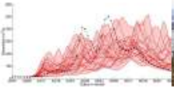


- Prices



EPEX SPOT SE, 2019.[9]

Uncertainty




In the province of Québec, since the electricity market is owned and operated by Hydro-Québec, producers negociate fixed price contracts.

The only uncertainty that we consider in our models is related to the **inflows**.

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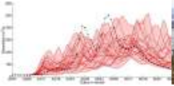
Stochastic optimization



- Stochastic optimization methods solve problems which contain uncertain parameters at the moment of taking a decision.

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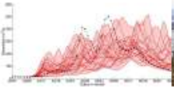
Stochastic optimization



- Stochastic optimization methods solve problems which contain uncertain parameters at the moment of taking a decision.
- Reservoir optimization (medium term) and short term optimization use different methods to solve stochastic problems.

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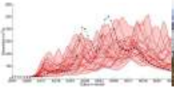
Reservoir optimization (medium term)



- Weekly decisions on yearly horizons

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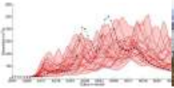
Reservoir optimization (medium term)



- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes

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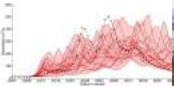
Reservoir optimization (medium term)



- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes
- Uncertain inflows

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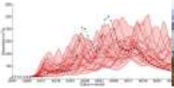
Reservoir optimization (medium term)



- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes
- Uncertain inflows
- Turbines are aggregated

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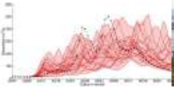
Reservoir optimization (medium term)

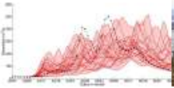


- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes
- Uncertain inflows
- Turbines are aggregated

Commons algorithms:

- Stochastic dynamic programming (SDP)

Reservoir optimization (medium term)



- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes
- Uncertain inflows
- Turbines are aggregated

Commons algorithms:

- Stochastic dynamic programming (SDP)
- Stochsatic dual dynamic programming (SDDP)

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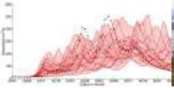
Reservoir optimization (medium term)




- Weekly decisions on yearly horizons
- Total water discharge and reservoir volumes
- Uncertain inflows
- Turbines are aggregated

Commons algorithms:

- Stochastic dynamic programming (SDP)
- Stochsatic dual dynamic programming (SDDP)
- Sampling stochastic dynamic programming (SSDP)

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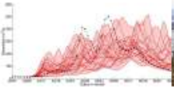
Dynamic programming (DP)




- Separates a complex problem into sub-problems (stages)
- Is based on the Bellman optimality principle: *An optimal policy has the property that watever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision* [1]
- Stochastic dynamic programming: extension of DP

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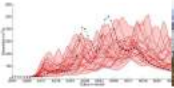
Stochastic Dynamic Programming (SDP



Many discretizations are required:

- Stages: time periods
- State variables: reservoir storage
- Decision variables: water discharge
- Random inflows: Required to calculate the transition probabilities (markov process) between each discrete inflow.

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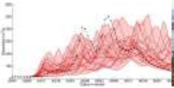
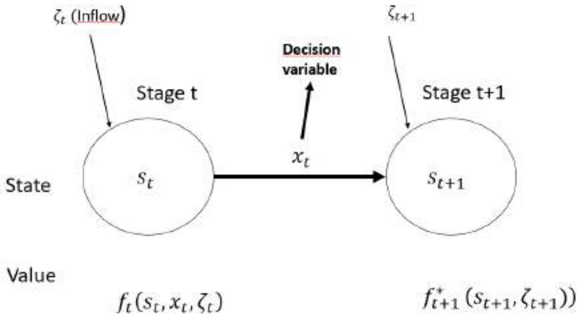
SDP

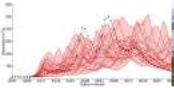


We maximize the expected energy production.



$$f_t(s_t, x_t, \zeta_t) = f^*_{t+1}(s_{t+1}, \zeta_{t+1}) + g_t(s_t, x_t, \zeta_t)$$

Short-term optimization



- Hourly decisions on weekly horizons

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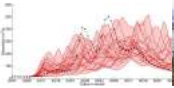
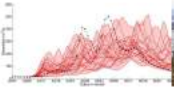
Short-term optimization



- Hourly decisions on weekly horizons
- Result: Water discharges, reservoir volumes and turbines working

Short-term optimization



- Hourly decisions on weekly horizons
- Result: Water discharges, reservoir volumes and turbines working
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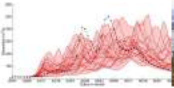
Short-term optimization



- Hourly decisions on weekly horizons
- Result: Water discharges, reservoir volumes and turbines working
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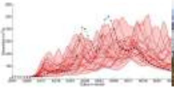
Common algorithms:

- Linear and nonlinear programming

Short-term optimization



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Common algorithms:

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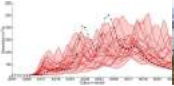
Short-term optimization



- Hourly decisions on weekly horizons
- Result: Water discharges, reservoir volumes and turbines working
- Uncertain inflows

Common algorithms:

- Linear and nonlinear programming
- Integer programming
- Stochastic programming

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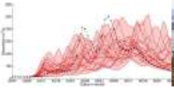
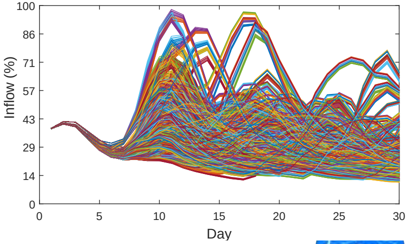
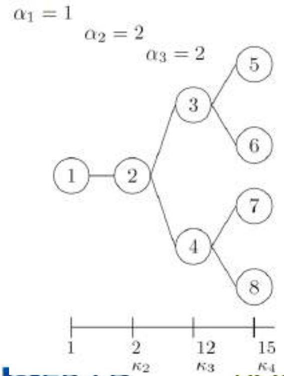
Inflows



From the forecasting team, we receive multiple inflow scenarios.
Their number is too large for the stochastic program.
An approximation, with a scenario tree, is then required.





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Séguin et al., 2017[23]

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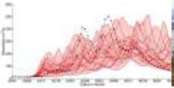
Model



Example of a short-term stochastic problem:

$$\max_{y,q,v} \sum_{c\in C}\sum_{s=1}^{n_0^c} \chi_{s0}^c y_{s0}^c \zeta_0 + \sum_{c\in C}\sum_{j\in K}\pi_j^c \left(\sum_{i\in N_j}\sum_{s=1}^{n_i^c}\chi_{si}^c y_{si}^c \zeta_i + \sum_{p\in E_j}\Phi_p^c(v_p^c)\right) \tag{12}$$

$$\text{subject to:} \quad \chi_{si}^c \le \Psi_s^{Ac}(q_i^c, v_i^c), \quad \forall c\in C, \quad \forall i \in N, \quad \forall s \in \{1,2,\ldots,n_i^c\}, \tag{13}$$

$$\chi_{si}^c \le \Psi_s^{Bc}(q_i^c, v_i^c), \quad \forall c\in C, \quad \forall i \in N, \quad \forall s \in \{1,2,\ldots,n_i^c\}, \tag{14}$$

$$\delta_i^c = v_{i+1}^c - v_i^c + \gamma w_i q_i^c - \sum_{m=1}^{u^c} \gamma w_m q_i^m, \quad \forall i \in N_j, \quad \forall j \in K, \quad \forall c \in C, \tag{15}$$

$$\sum_{s=1}^{n_i^c} y_{si}^c \le 1, \quad \forall i \in N, \quad \forall c \in C, \tag{16}$$

$$y_{s0}^c = \bar{y}_{s0}^c, \quad \forall s \in \{1,2,\ldots,n_i^c\}, \quad \forall c \in C, \quad \forall i \in N, \tag{17}$$

$$v_{min}^c \le v_i^c \le v_{max}^c, \quad \forall i \in N, \quad \forall c \in C, \tag{18}$$

$$q_{min}^c \le q_i^c \le q_{max}^c, \quad \forall i \in N, \quad \forall c \in C, \tag{19}$$

$$q_i^c \ge 0, \quad \forall i \in N, \quad \forall c \in C, \tag{20}$$

$$v_i^c \ge 0, \quad \forall i \in N, \quad \forall c \in C, \tag{21}$$

$$y_{si}^c \ge 0, \quad \forall s \in \{1,2,\ldots,n_i^c\}, \quad \forall i \in N, \quad \forall c \in C \tag{22}$$

Séguin et al., 2017.[24]

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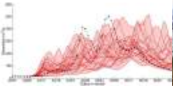
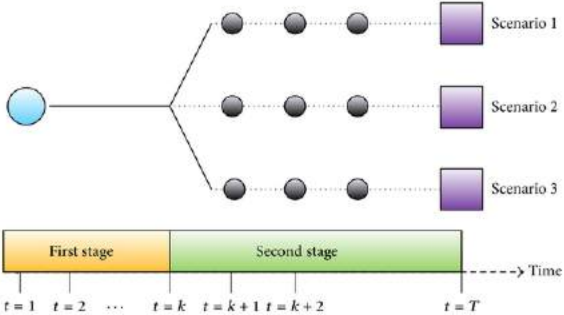
Stochastic programming



The scenario tree, which is a discrete representation of the distribution of inflows, is then used to solve the deterministic-equivalent of the stochastic program.



Y.-Y. Chen and H.-Y. Fan, 2015.[6]

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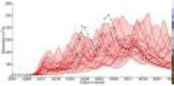
Stochastic programming



The model maximizes first stage decisions (no uncertainty), the expectancy of future production (second stage) and the expected value of water remaining in the reservoirs.

From mid-term

$$\boxed{\max_{q,v} \chi(v_1, q_1, \delta_1)} + \boxed{\sum_{j\in K} \pi_j \left(\sum_{i\in N_j} \chi(v_i, q_i, \delta_i) \right)} + \boxed{\sum_{t\in K} \pi_t \left(\sum_{p\in E_t} \Phi_p(v_p) \right)}$$

$$\begin{aligned}
\text{s.t.} \quad \delta_i = v_{i+1} - v_i + q_i \quad &, \quad \forall i \in N_j, \forall j \in K, \\
v_{min} \leq v_i \leq v_{max} \quad &, \quad \forall i \in N, \\
q_{min} \leq q_i \leq q_{max} \quad &, \quad \forall i \in N, \\
v_i, q_i \geq 0 \quad &, \quad \forall i \in N,
\end{aligned}$$

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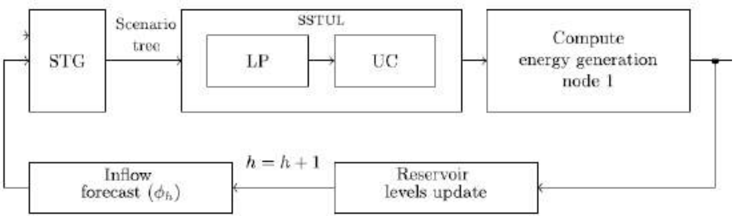
Rolling horizon scheme

The stochastic solution provides optimal policies: for each scenario, the solution varies. Rolling horizon schemes are used to "build" the solution.



Adapted from Séguin et al. 2017 [23]

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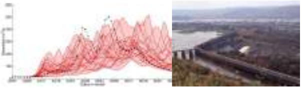
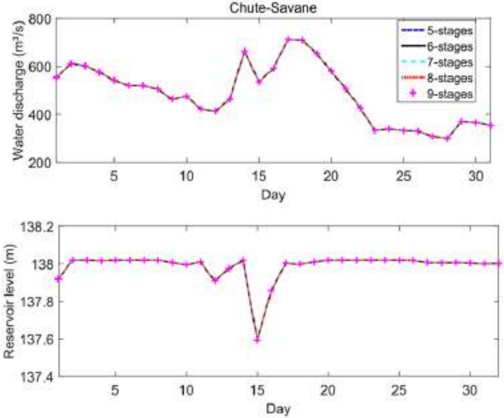
Short term optimization

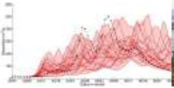


Example of results:



Séguin et al., 2017[23]

Recap...



Hydropower scheduling is complex and requires many interactions:

- Hydrologists, statisticians: inflow scenarios
- Operations research: mathematical formulations
- Programmers: implementation of the models
- Analysts & engineers: Final decision

It is a rich and various field to study and/or work in!
Do not hesitate to contact me: sara.seguin@uqac.ca

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SOME RESOURCES TO GO FURTHER

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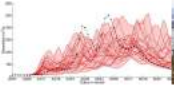

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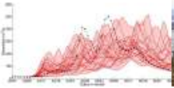


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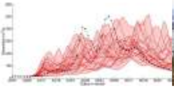


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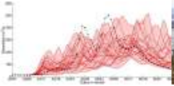

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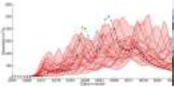

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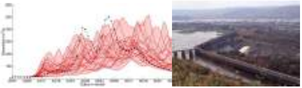
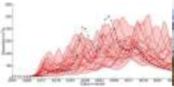
Books




Handbook of Hydrometeorological Ensemble Forecasting
Springer
STATISTICAL METHODS IN THE ATMOSPHERIC SCIENCES
DANIEL S. WILKS
STATISTICAL POSTPROCESSING OF ENSEMBLE FORECASTS
Edited by
Economic Value of Weather and Climate Forecasts
Edited by
Richard W. Katz and Allan H. Murphy
Forecast Verification
WILEY
SUPER FORECASTING
The Art and Science of Prediction
PHILIP E. TETLOCK
DAN GARDNER

HEPEX



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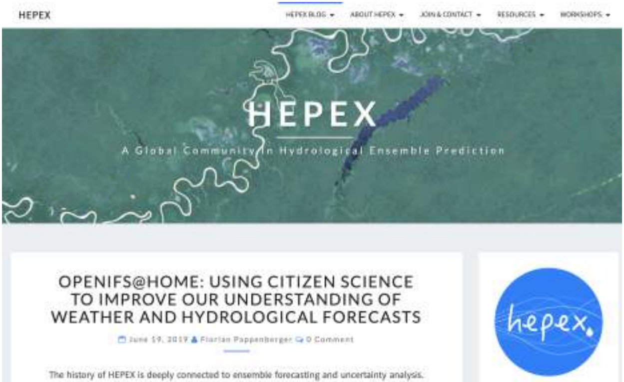

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