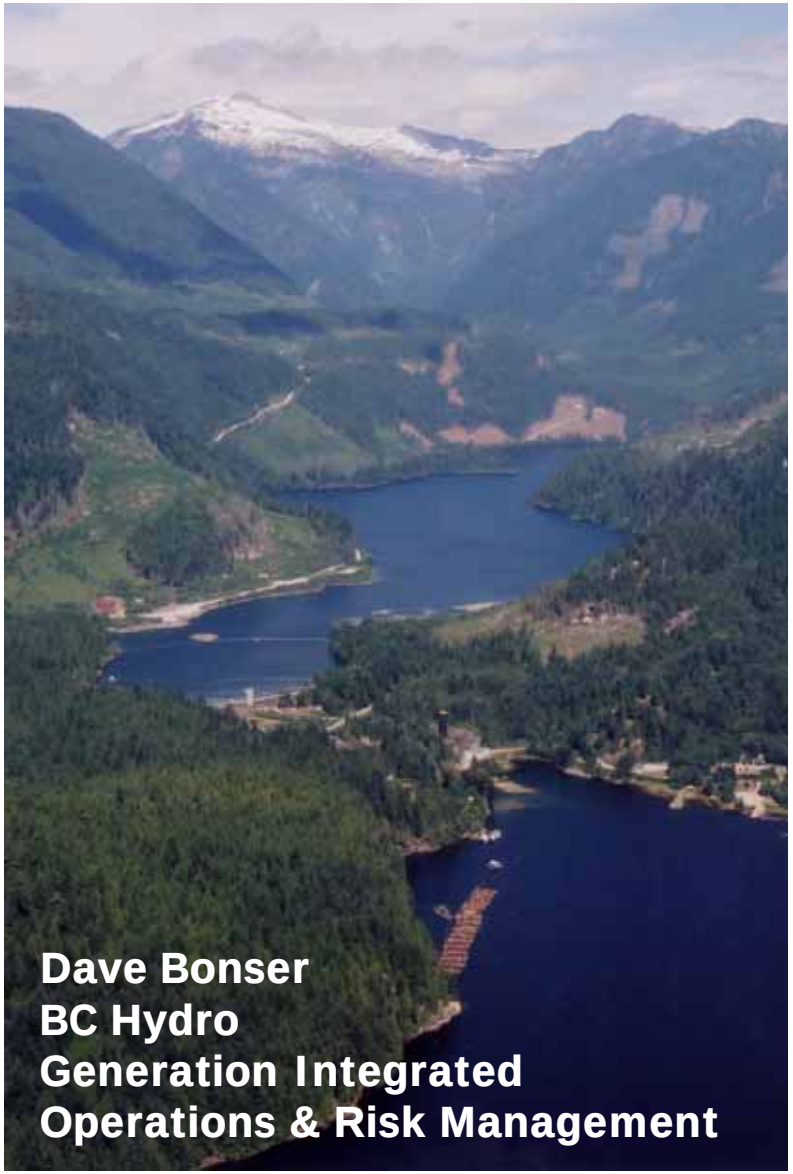


Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Dave Bonser
BC Hydro
Generation Integrated
Operations & Risk Management

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Outline

1. Water Use Planning
2. Clowhom WUP
3. Performance Measures
4. Interactive Model
5. Results
6. Summary/Credits

Water Use Planning

- **Water Use Planning program started in 1998**
- **Review of existing water licenses to improve balance between economic, social, and environmental values**
- **Goal to achieve regulatory certainty, with basis for measuring compliance**

Water Use Planning

- **WUP Stakeholders:**
  - **BC Hydro**
  - **Federal DFO**
  - **Provincial WLAP, SRM**
  - **Local and Regional Governments**
  - **First Nations**
  - **Local Businesses**
  - **Community Groups**
  - **General Public**

Water Use Planning

- **Steps in Developing a Water Use Plan:**
  1. **Identify Issues**
  2. **Gather Information**
  3. **Develop and Evaluate Alternatives**
  4. **Make Recommendations**
  5. **Water Comptroller Review**
  6. **Implementation and Monitoring**

Clowhom WUP

- **Small, remote facility, no major pre-existing social or environmental issues**
- **Decision to use shortened process with fewer meetings, with interactive modeling process to specify and evaluate alternatives at the final meeting**
- **Only WUP to use this process/model**

Clowhom WUP

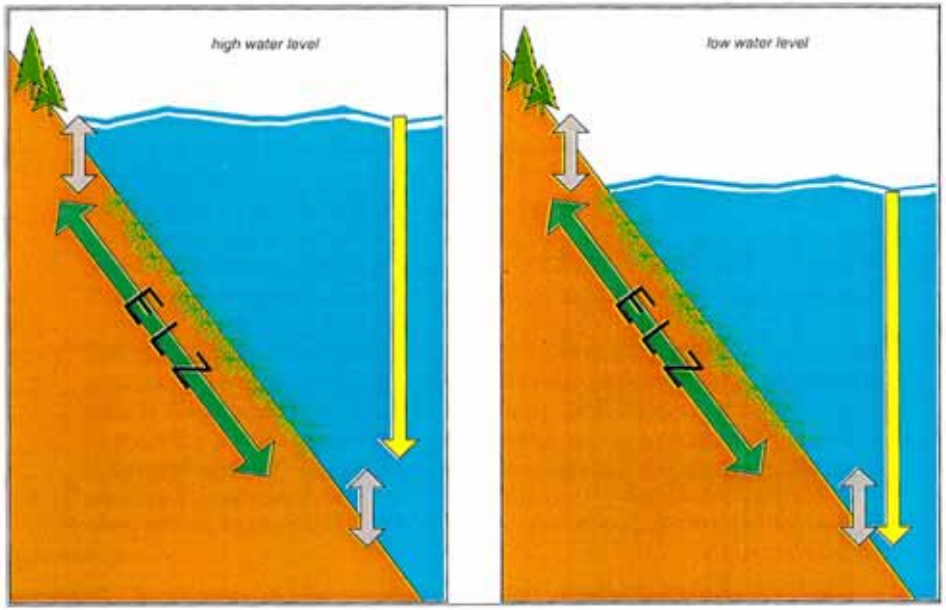
- **Open House and first meeting to determine issues and interests Sept 2002**
- **Meeting to create preliminary alternatives and assess trade-off objectives Mar 2003**
- **Final meeting to create operating alternatives and reach consensus recommendation May 2003**

Performance Measures

- **Trade-offs between competing interests were made by evaluating the impacts of each alternative on numeric performance measures**
- **Sub-committees representing fish, power, recreation, etc. developed effective performance measures with assistance from BC Hydro staff**

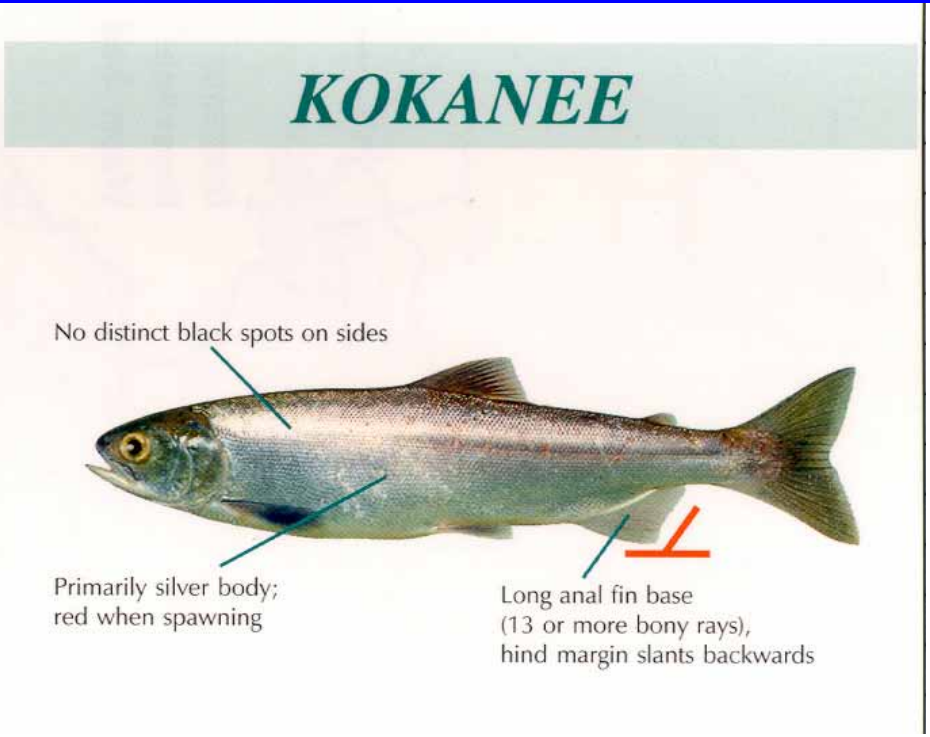
PM - Effective Littoral Zone (Fish)

- **Area of productive fish habitat (ELZ), measured in ha**
- **Increasing reservoir fluctuations decreases ELZ**



PM - Number of Spill Days (Fish)

- **Number of days on which a spill occurs each year**
- **Accounts for spillway entrainment of fish**



PM - Revenue (Power)

- **Total annual revenue from power generation, measured in $CDN**
- **Price of energy varies seasonally and within day**
- **Revenue is price * energy, summed hourly**
- **Measures value to province of energy production**

PM - Energy (Power)

- **Total annual energy production from the facility, measured in MWh**
- **Doesn't include station services, transformer losses, nor transmission losses**
- **Energy is summation of hourly average power output**
- **Can have higher energy and lower revenue if timing a factor**

PM - Capacity (Power)

- **Instantaneous available power, measured in MW**
- **Based on maximum output of the generator**
- **Capacity is counted whenever the unit is available, even if it is not running**
- **Measures ability to supply power to the Sunshine Coast abd Vancouver Island during short outages**

PM - Available Firm Energy (Power)

- **Available firm energy is the energy in the reservoir between the current elevation and the min elev constraint, assuming no inflows, measured in MWh**
- **Measures ability to supply power to the Sunshine Coast and Vancouver Island during extended outages**

PM - Greenhouse Gas Emissions (Power)

- It is assumed that reductions in energy will be made up by increased production at gas-fired thermal plants, measured in tonnes of CO_2e/yr
- GHG is a total value over a year

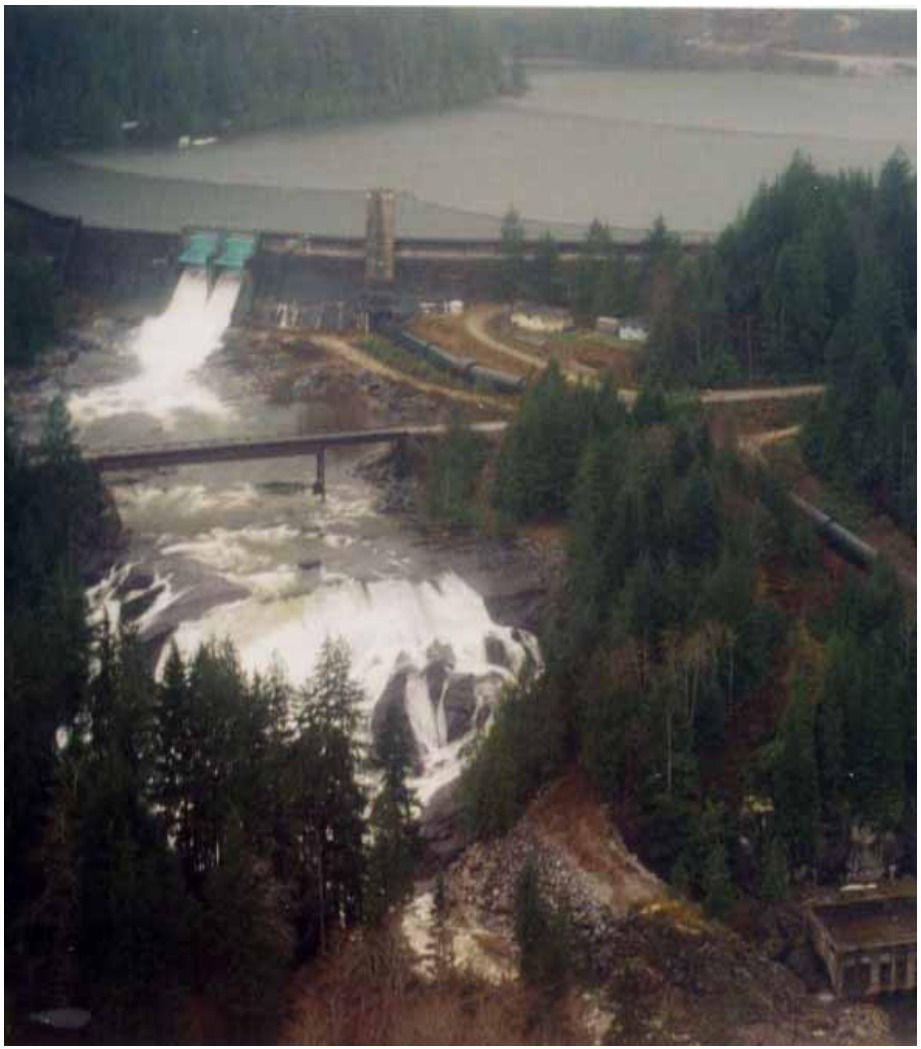
PM - Weighted Rec Days (Recreation)

- **Number of days in the year weighted by preferred reservoir elevations**
- **Captures aesthetic, safety, dock utility and access issues**

Reservoir Elevation (m)	Means Objective				Average Weight
	Aesthetic	Boat Safety	Dock utility	Access	
52 – full pool	1.00	1.00	1.00	1.00	1.00
50 – 52	0.67	0.67	0.67	0.67	0.67
49 – 50	0.25	0.25	0.25	0.25	0.25
< 49	0.00	0.00	0.00	0.00	0.00

PM - High Spill (Industry)

- **Expected return period of daily average spills > 100 m^3/s**
- **Accounts for instantaneous spills > 200 m^3/s which may damage log booms**



PM - Very High Spill (Industry)

- **Expected return period of daily average spills > 300 m^3/s**
- **Accounts for instantaneous spills > 600 m^3/s which may damage logging road bridge or berm protecting powerhouse**

Performance Measures - Operational Levers

Operational Lever / Modeling Parameter	*Spill Impact*	*Generation Impact*	*Fish Impact*	*Recreation Impact*
1. Increase minimum reservoir elevation (i.e. limit drawdown)	↑	↓	↑	↑
2. Decrease maximum reservoir elevation (i.e. limit refill)	↑	↓	↑	↓
3. Limit daily reservoir draft (i.e. limit within day drawdown)	↑	↓	↑	↑
4. Limit daily reservoir fluctuation (i.e. limit within day drawdown and refill)	↑	↓	↑	↑
5. Change dates of annual maintenance (i.e. timing of reservoir drawdown for spill gate testing and turbine/generator overhaul)	↑	↓	↑	↑
6. Increase maximum turbine discharge (i.e. instantaneous diversion rate)	↓	↑	-	-

Interactive Model

- **Interactive modeling used in final meeting to quickly evaluate new alternatives**
- **Model is a combination of an Excel-based performance measure evaluator and graphical user interface with SOPHOS, a Java optimizer/simulator running in the background**

SOPHOS Model

- **SOPHOS = Stochastic Optimization Program for Hydro Operations Studies**
- **SOPHOS is a stochastic dynamic programming model using three stochastic state variables: inflows, price level, and price ratio**
- **A daily time step is used for the model stages**

SOPHOS Model

- **Decision variable is the number of hours of generation within a 24 hour period**
- **Generation is assumed to be at maximum efficiency, except maximum output if spill is imminent**
- **Model is coded in Java**

SOPHOS Model

- **Reservoir and plant data curves as well as objective function implemented using interpolation tables**
- **Reservoir, plant, facility modeled as separate components**
- **Uses 3 or 24 simulation time steps per day to shape generation into peak hours**

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SOPHOS Model

- **Optimizer generates best generation decision as a function of state variables**
- **Simulator applies decision under historic inflow sequences**
- **40 different sequences modeled over 15 month period, from which 12 months extracted for results**

SOPHOS - Inflow Stochastic Variable

- **Derived state values and probabilities from 40 years of historic times series data (1960 to 2000)**
- **Parameter values are averaged over multi-day period to provide smoother values**

Clowhom (Coastal Mountain Basin) Hydrology			
Dates	**Description**	**Mean (cms)**	**Std Dev (cms)**
Dec 01 – Mar 14	Cold and wet, snowpack accumulating	26.5	33.3
Mar 15 – Apr 14	Cool and dry, Snowpack stable	23.2	19.9
Apr 15 – Aug 14	Warm and dry, snowpack melting	52.7	30.0
Aug 15 – Sep 30	Warm and dry, no snowpack	24.7	28.8
Oct 01 – Nov 30	Cool and very wet, stormy, snowpack begins to accumulate	40.2	53.2

SOPHOS - Inflow Stochastic Variable

- Determination of state discretization based on analysis of historic data and knowledge of the hydrology

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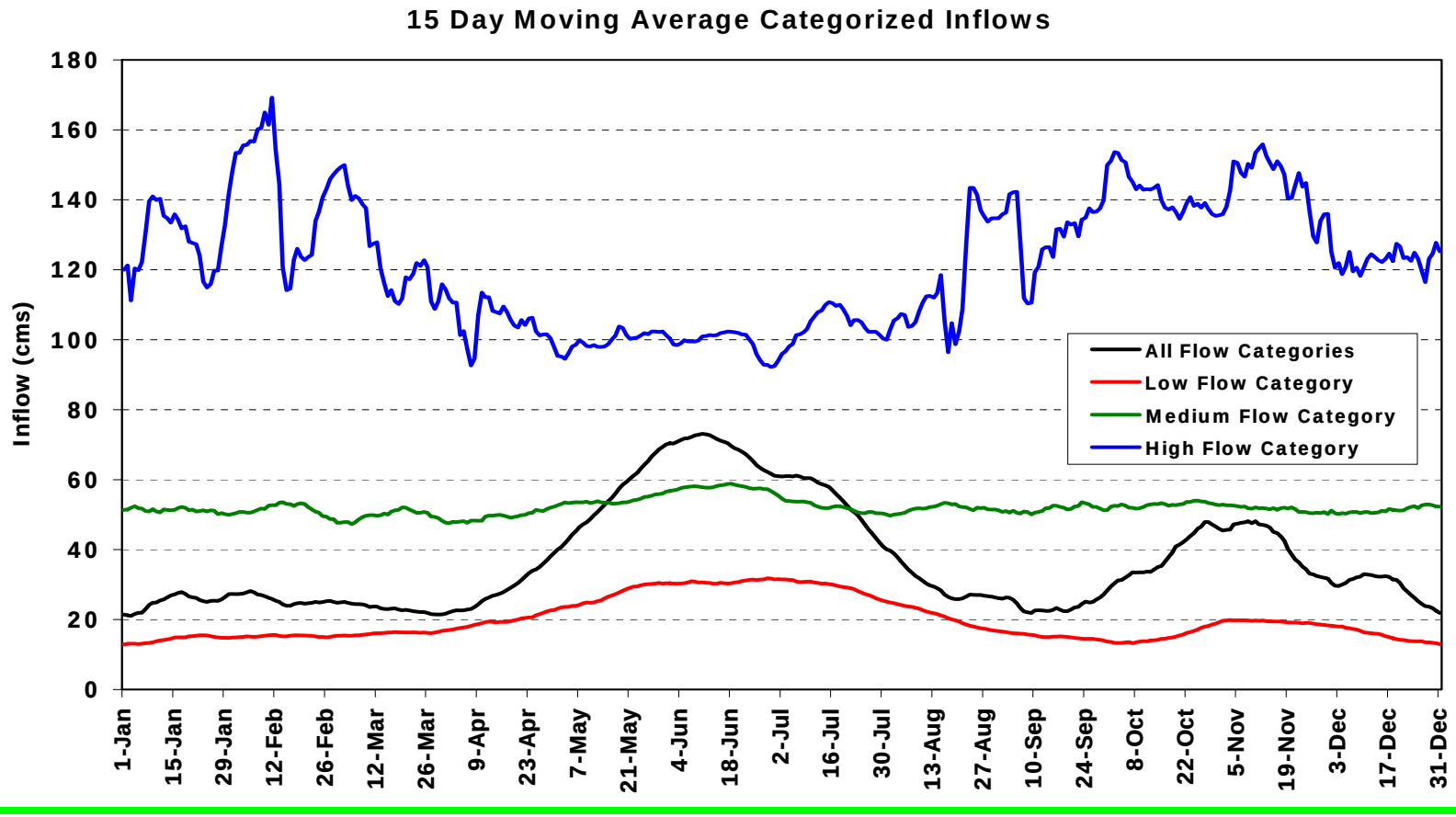
SOPHOS - Inflow Stochastic Variable



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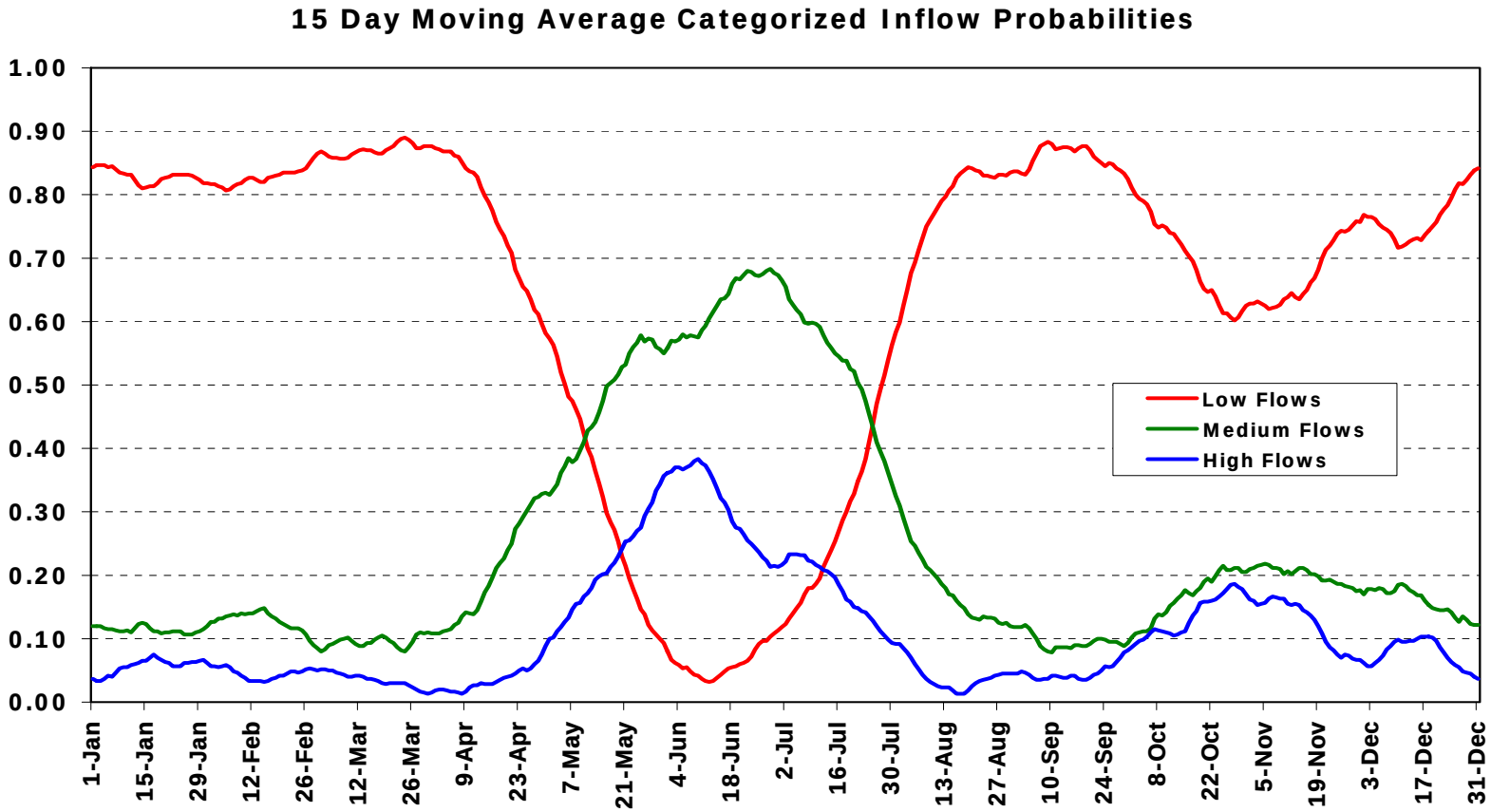
SOPHOS - Inflow Stochastic Variable



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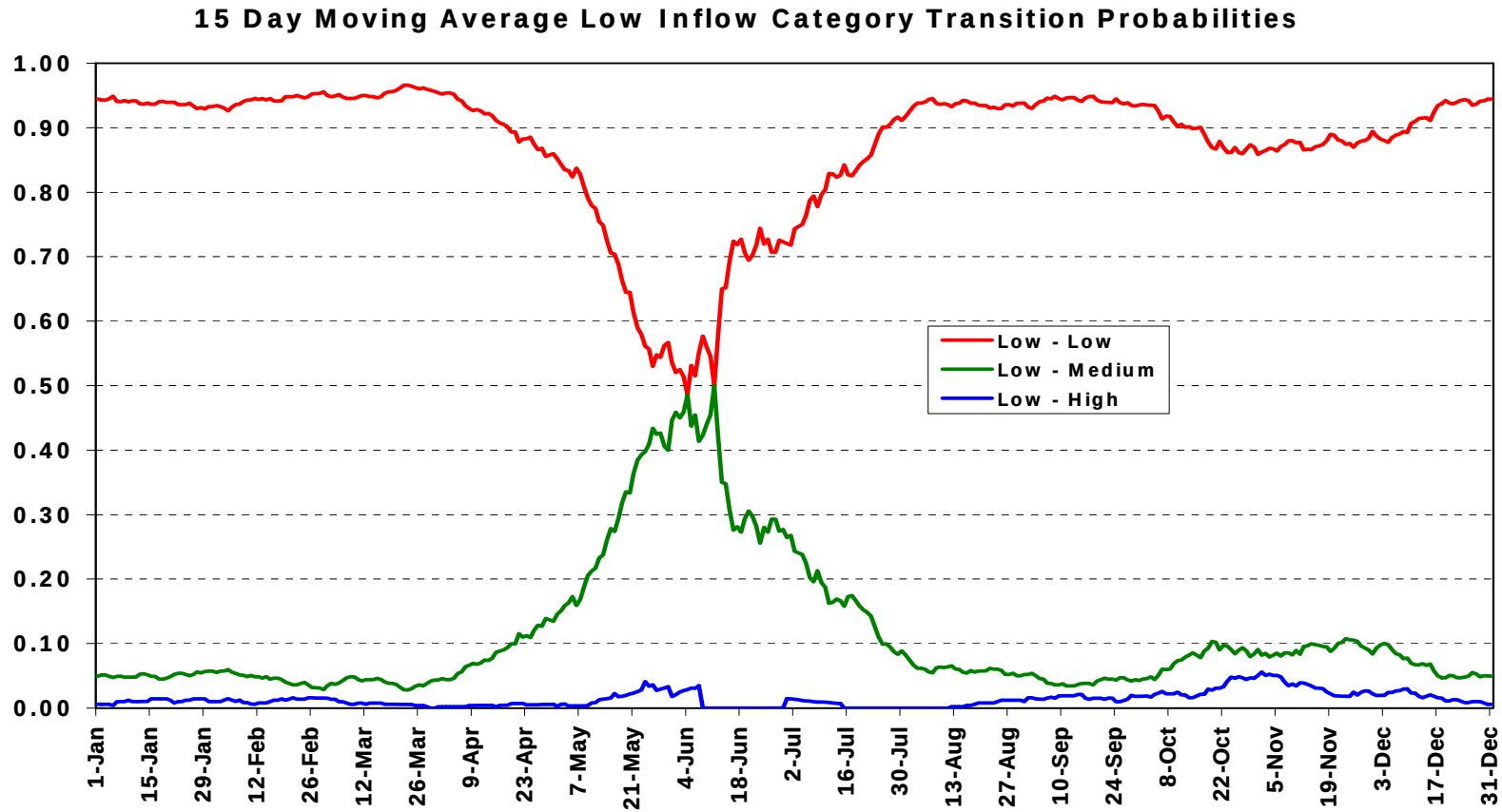
SOPHOS - Inflow Stochastic Variable



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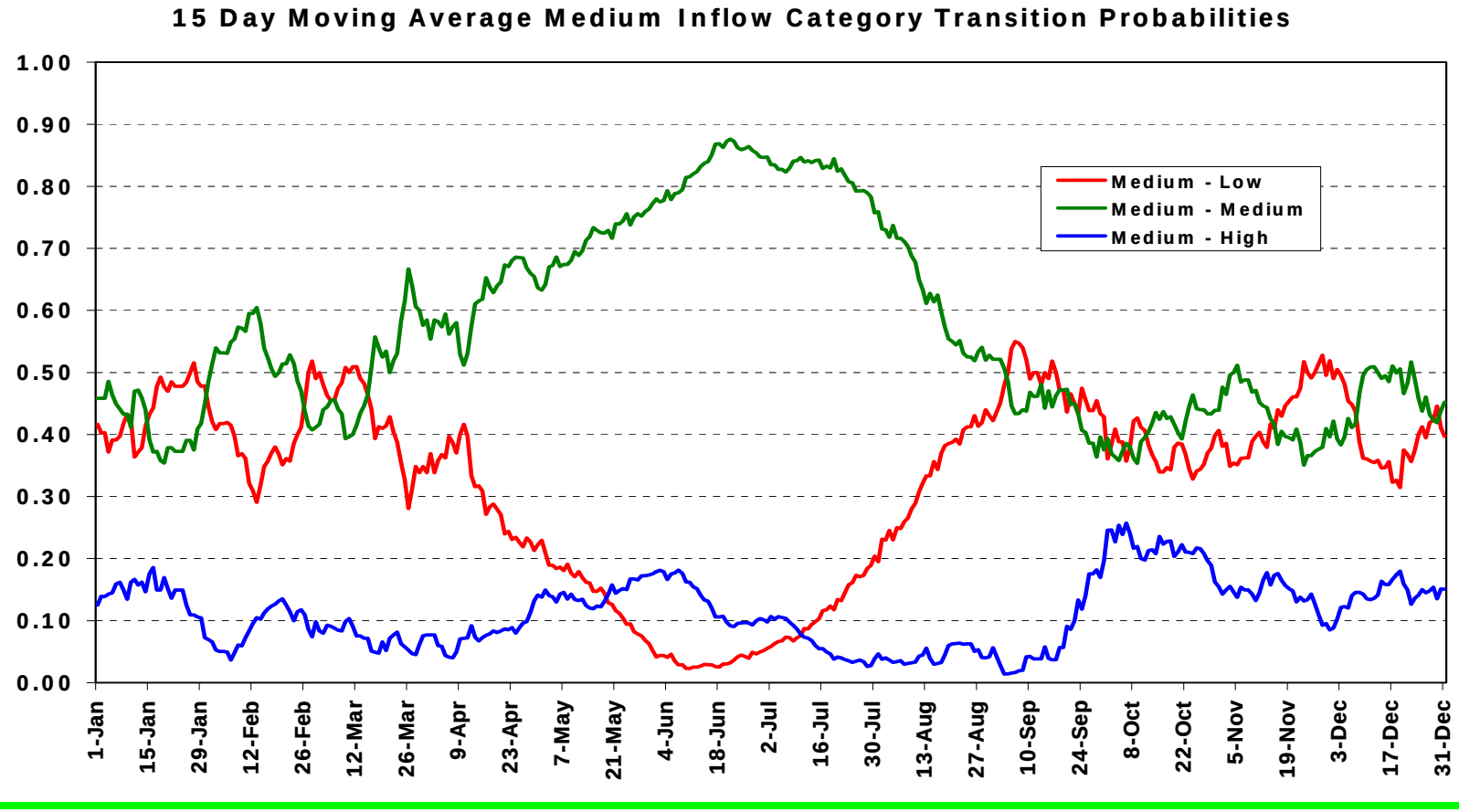
SOPHOS - Inflow Stochastic Variable



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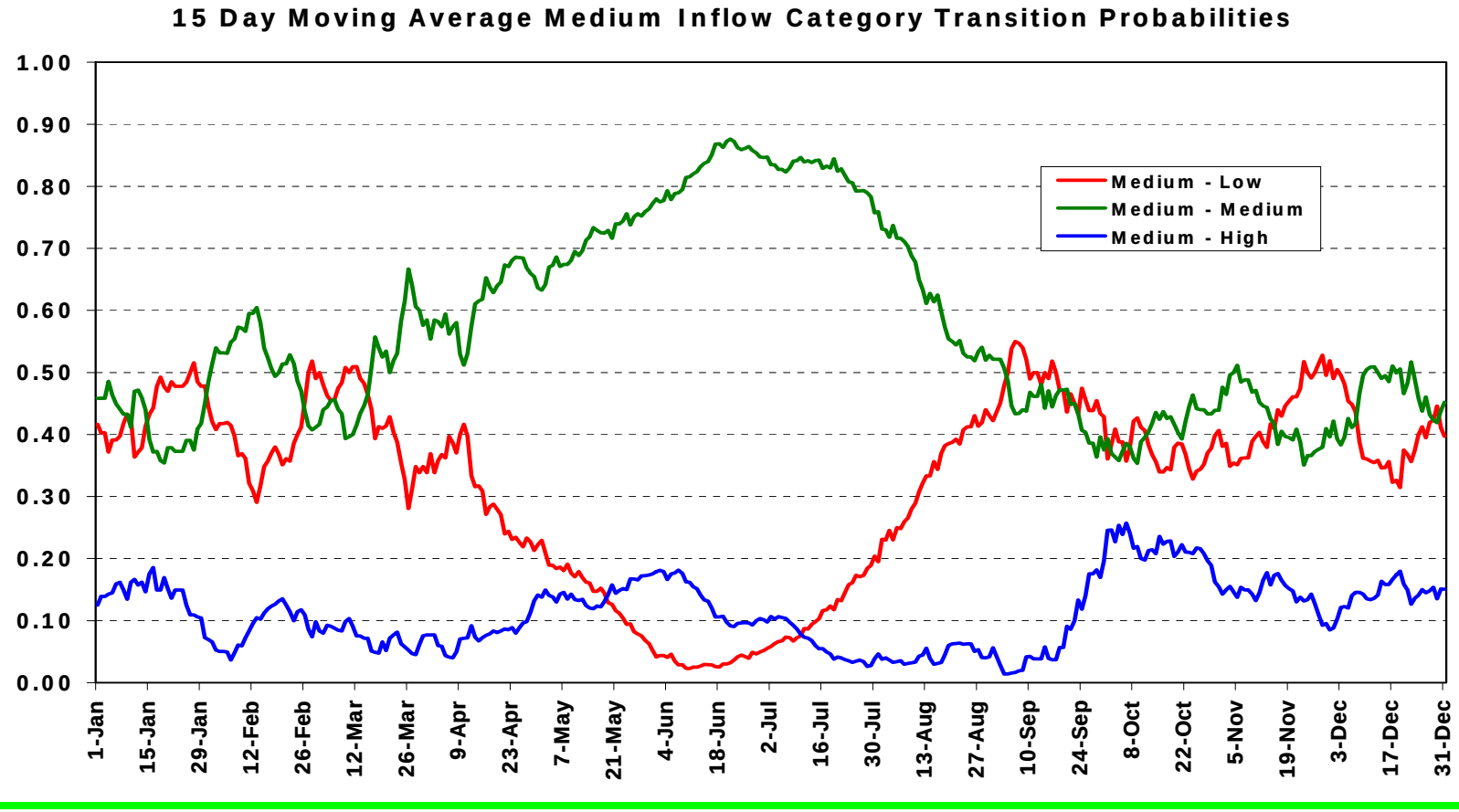
SOPHOS - Inflow Stochastic Variable



SOPHOS - Price Stochastic Variables

- **Price variables are computed from Value of Electricity (VOE) forecast for water use planning**
- **VOE produced standard prices used in all WUPs to achieve consistent results - not stochastic in WUP models**

SOPHOS - Price Stochastic Variables

- **Price level variable is the average price for ATC generation**
- **Price ratio variable is the ratio of the peak instantaneous price to the average price**

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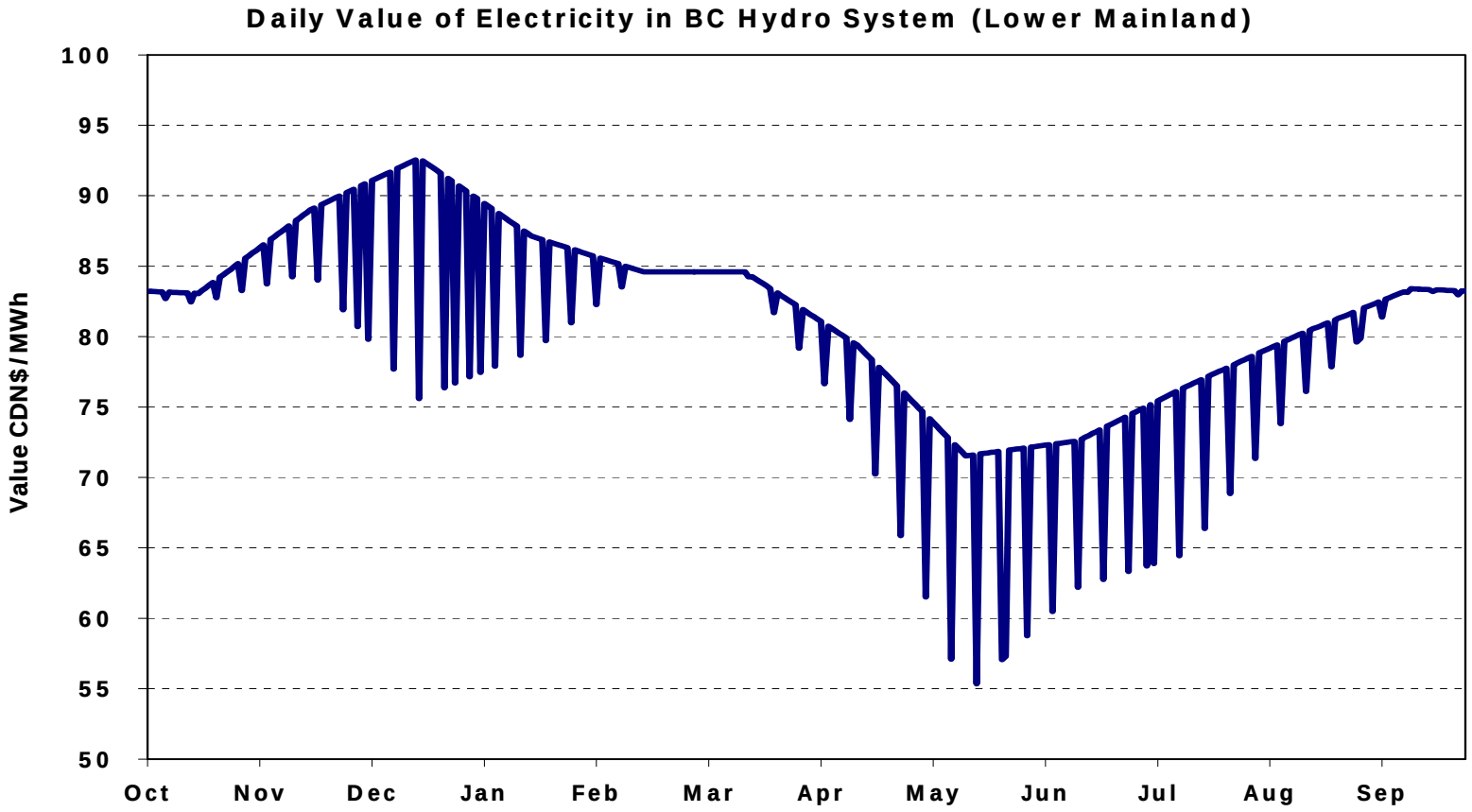
SOPHOS - Price Level Variable



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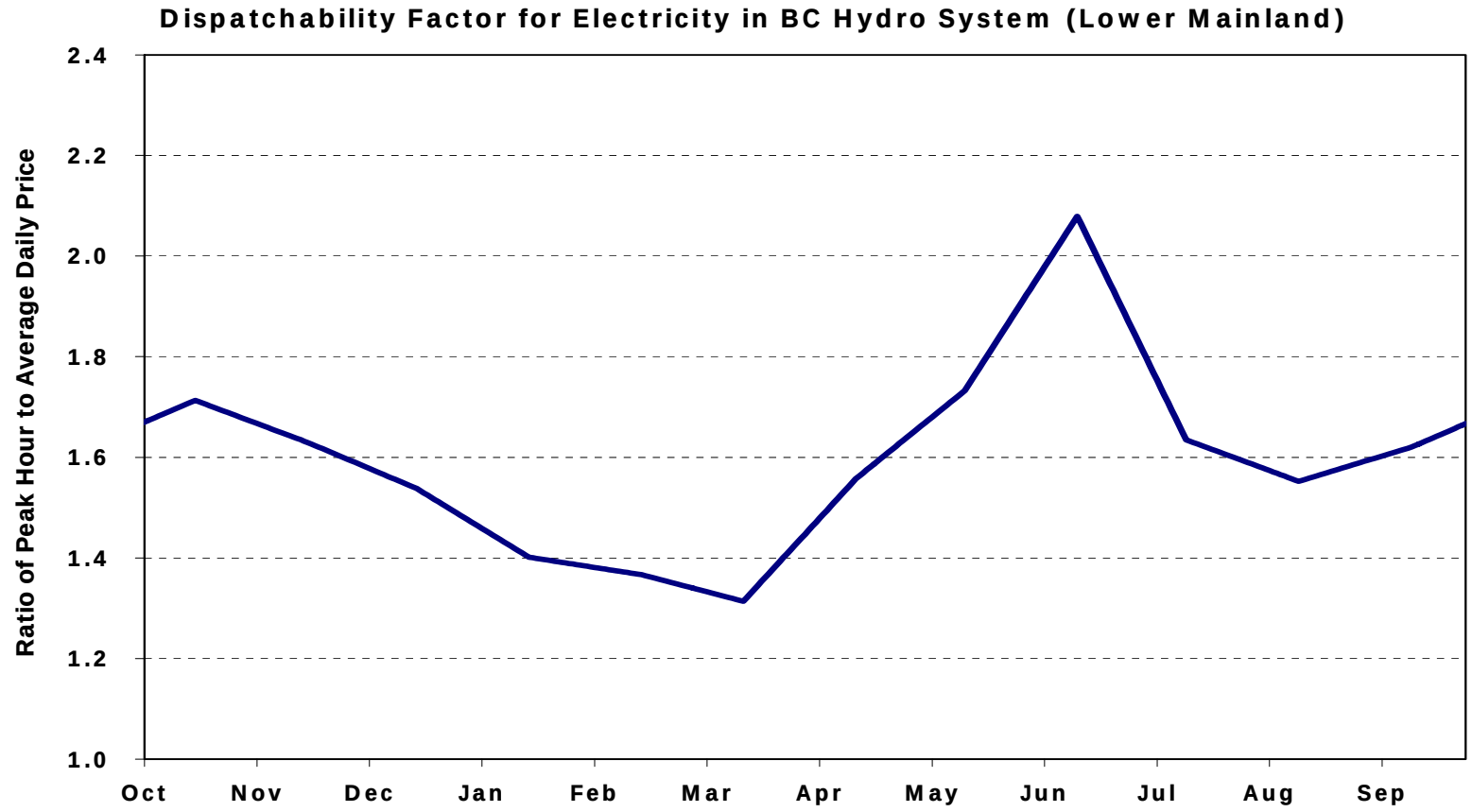
SOPHOS - Price Ratio Variable



Excel PM Calculator and Interface

- Interactive front end allows evaluation of different alternatives 'on the fly'
- Resource valuation model computes performance measures
- Graphs of inflows, elevations, discharges, spills, energy production, capacity and revenue produced

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Excel User Interface

Alt-G

Clowhom Reservoir Model Constraints

Period	Dates		Reservoir Elevation (m)		d (Elevation)/d t ($m \cdot d^{-1}$)		Max. Turbine Discharge ($m^3 s^{-1}$)
	Start	End	Min.	Max.	Min.	Max.	
1	Oct 01/ 02	Oct 31/ 02	50.0	53.34			79.25
2	Nov 01/ 02	Feb 28/ 03	49.0	53.34			79.25
3	Mar 01/ 03	Mar 01/ 03	49.0	53.34			0.00
4	Mar 02/ 03	Mar 19/ 03	49.0	53.34			0.00
5	Mar 20/ 03	Apr 30/ 03	49.0	53.34			79.25
6	May 01/ 03	May 31/ 03	50.0	53.34			79.25
7	Jun 01/ 03	Sep 30/ 03	52.0	53.34			79.25

		Percentile			
PM	*Approach*	*10 th*	*50 th*	*90 th*	
Fish	ELZ (ha)	-	**5.87**	-	(Cumulative Value)
	Spill-Days	1	**10**	33	(Annual Sum)
Power	Energy (MWh)	1	**13**	25	(Annual Sum)
	Revenue ($CDN)	$6,815,106	**$7,932,097**	$9,164,475	(Annual Sum)
	Capacity (MW)	30	**31**	31	(Hourly Average)
	Discharge (cms)	6666808	**7869649**	9363798	(Annual Sum)
	Available Energy (MWh)				(Annual Sum)
Recreation	Weighted Recreation-days	99	**146**	192	(Annual Sum)
Spill	Return Period > 100 $m^3 s^{-1}$	-	**0.5**	-	(Spill-Day in Years)
	Return Period > 300 $m^3 s^{-1}$	-	**3.4**	-	(Spill-Day in Years)

Constraints

- **Operational changes implemented as constraints**
- **Excel interface writes constraints to text file which is picked up by the SOPHOS model**
- **Each line specifies dates, limit type, period, constraint type, and value**

Constraints Input File

```
// Alternative G
// Operational limits on reservoir elevation
1-Jan  30-Apr  MULTIPLE MAXIMUM  INSTANTANEOUS  RESERVOIRELEVATION      53.34
1-Jan  30-Apr  MULTIPLE MINIMUM  INSTANTANEOUS  RESERVOIRELEVATION      49.0
1-May  31-May  MULTIPLE MINIMUM  INSTANTANEOUS  RESERVOIRELEVATION      50.0
1-Jun  30-Sep  MULTIPLE MINIMUM  INSTANTANEOUS  RESERVOIRELEVATION      52.0
1-Oct  31-Oct  MULTIPLE MINIMUM  INSTANTANEOUS  RESERVOIRELEVATION      50.0
1-Nov  31-Dec  MULTIPLE MINIMUM  INSTANTANEOUS  RESERVOIRELEVATION      49.0

// Water license limit 82.18 - using 79.25 gives PSOSE compliance room
1-Jan  31-Dec  MULTIPLE MAXIMUM  INSTANTANEOUS  TURBINEFLOW             79.25

// Generator heat limit maximum power output
1-Jan  31-Dec  MULTIPLE MAXIMUM  INSTANTANEOUS  GENERATORPOWER          40.0

// Planned outages for annual maintenance
1-Mar  19-Mar  MULTIPLE MAXIMUM  INSTANTANEOUS  GENERATORPOWER          0.0
```

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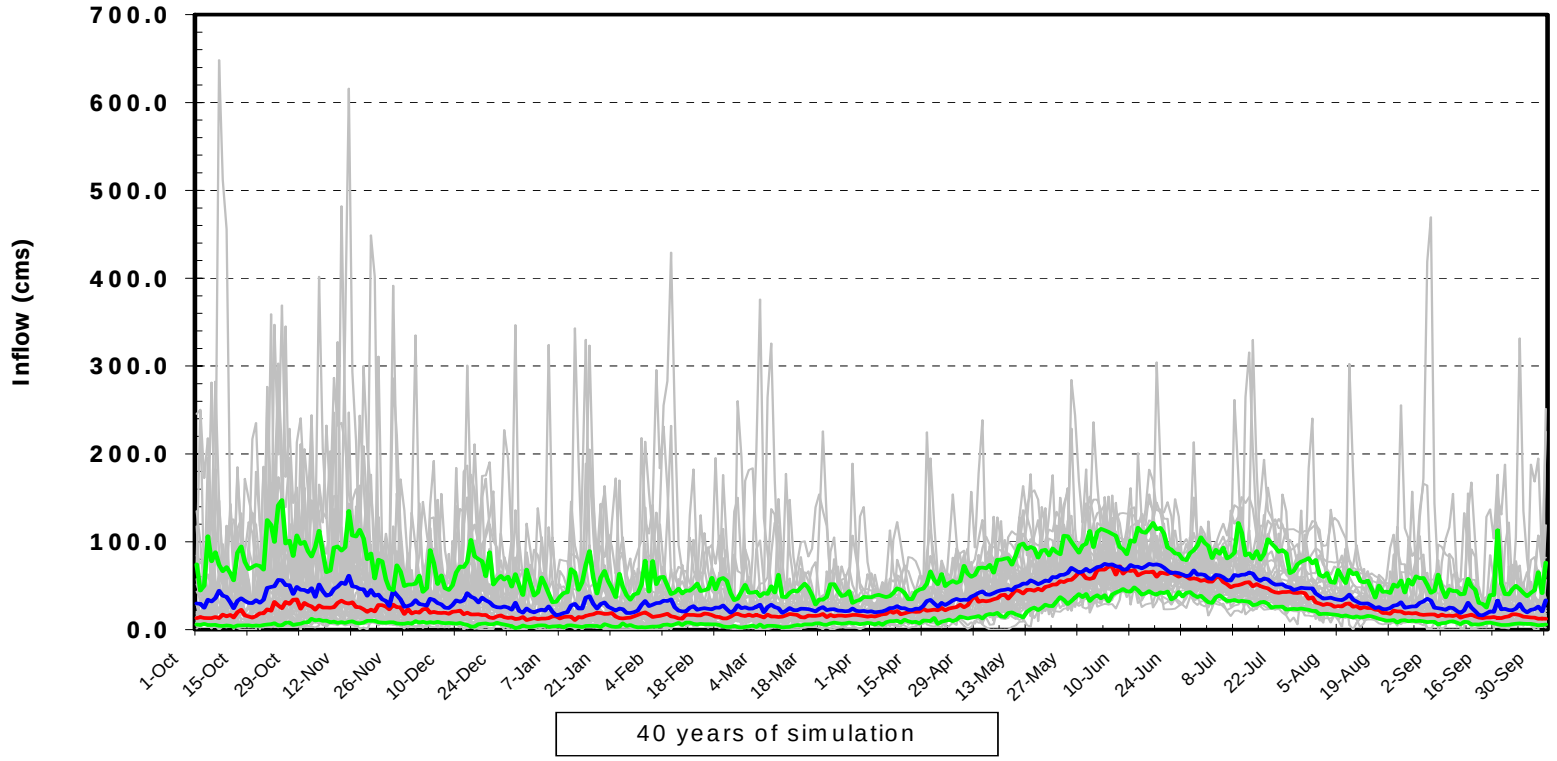
Graphical Output - Inflow

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Inflow



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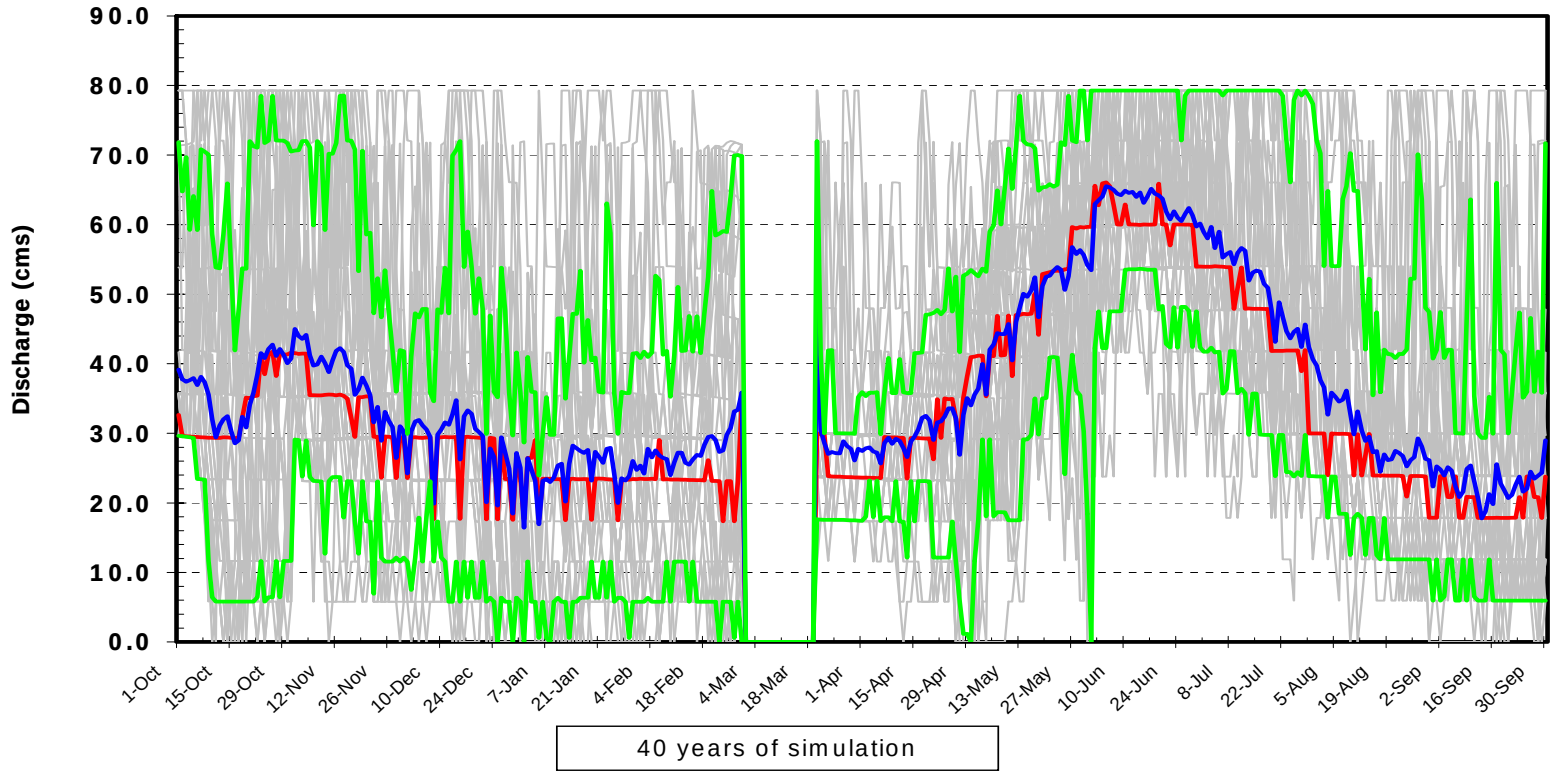
Graphical Output - Discharge

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Discharge



40 years of simulation

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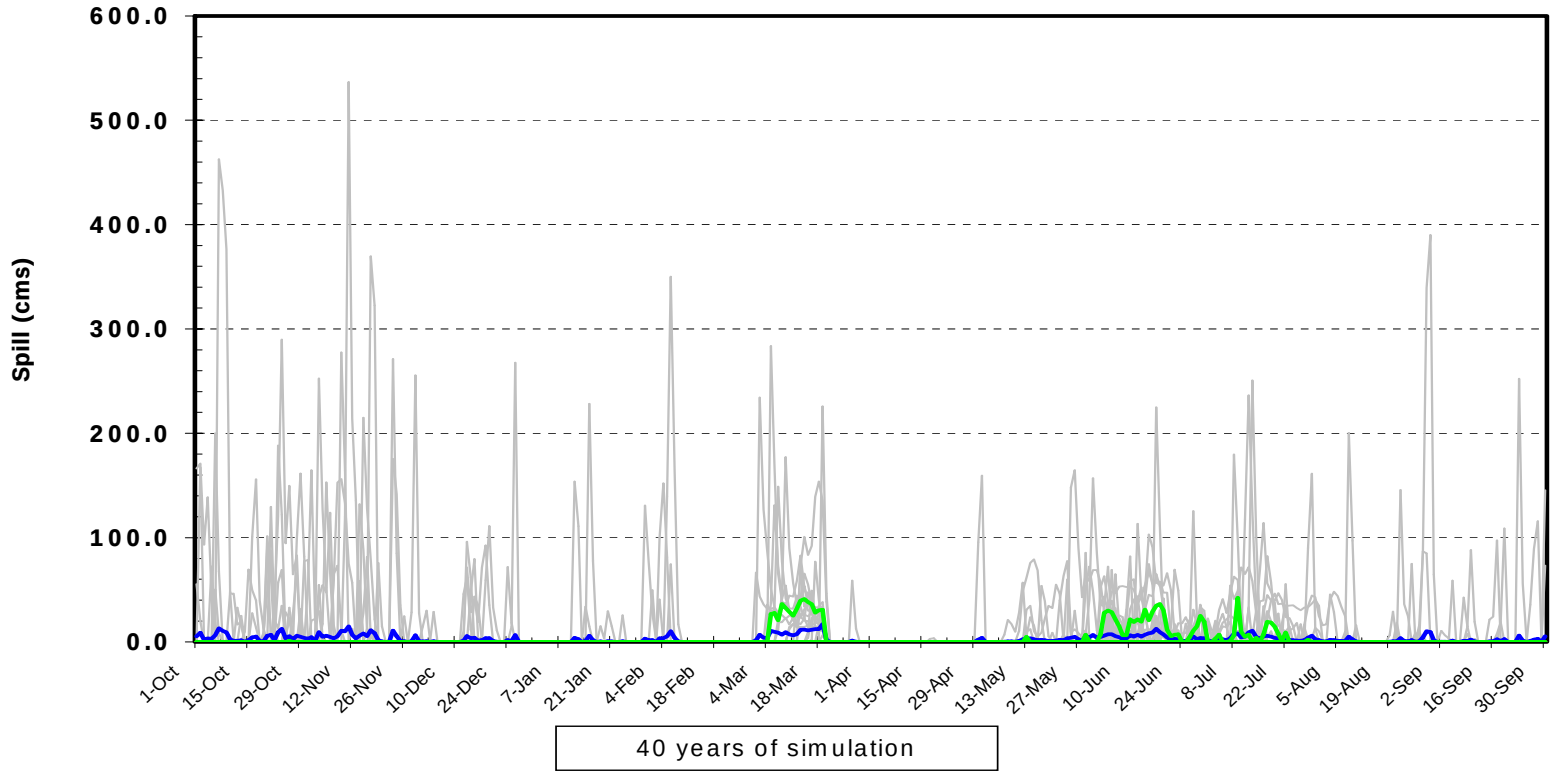
Graphical Output - Spill

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Spill



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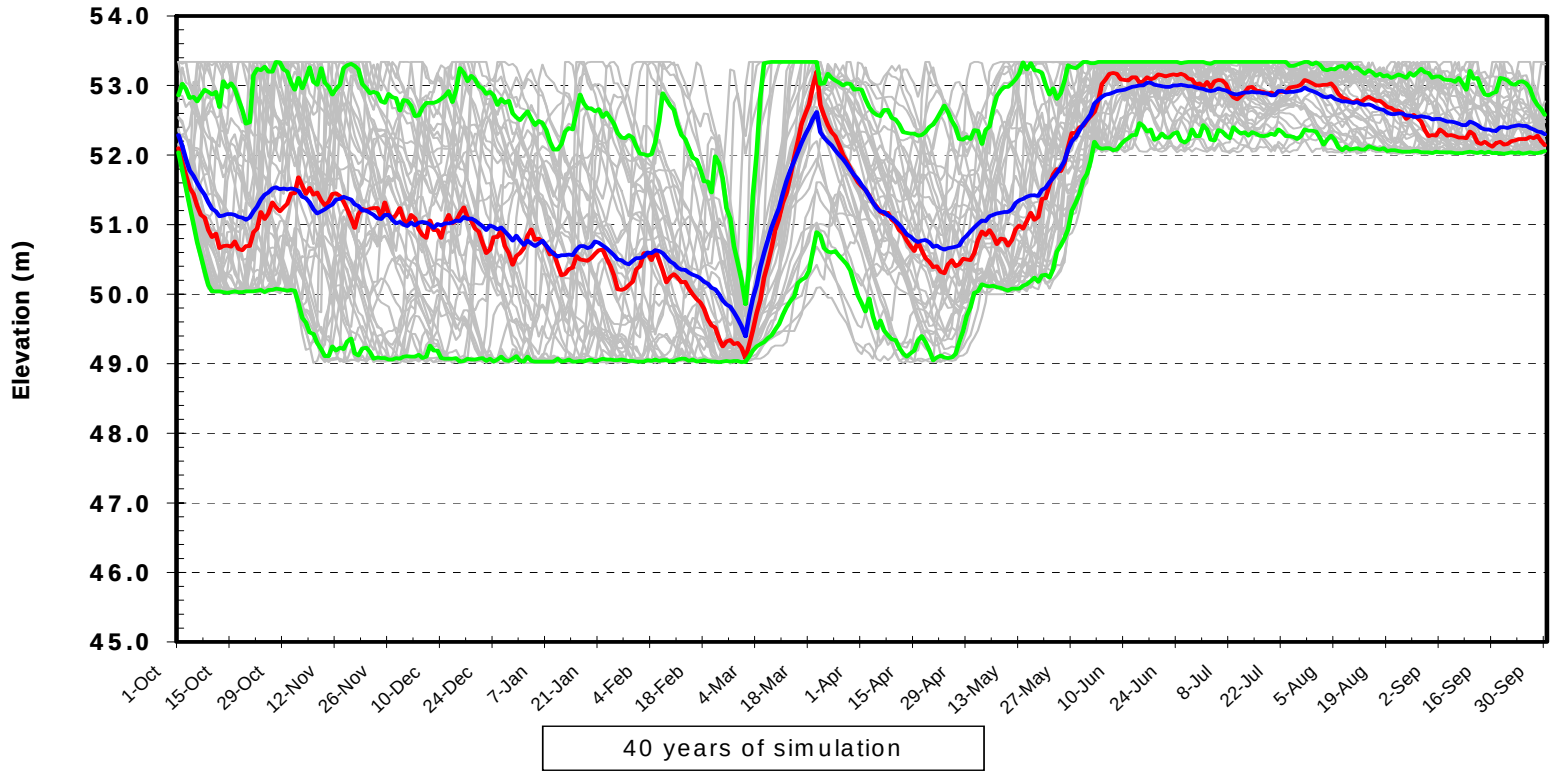
Graphical Output - Reservoir Elevation

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Elevation



40 years of simulation

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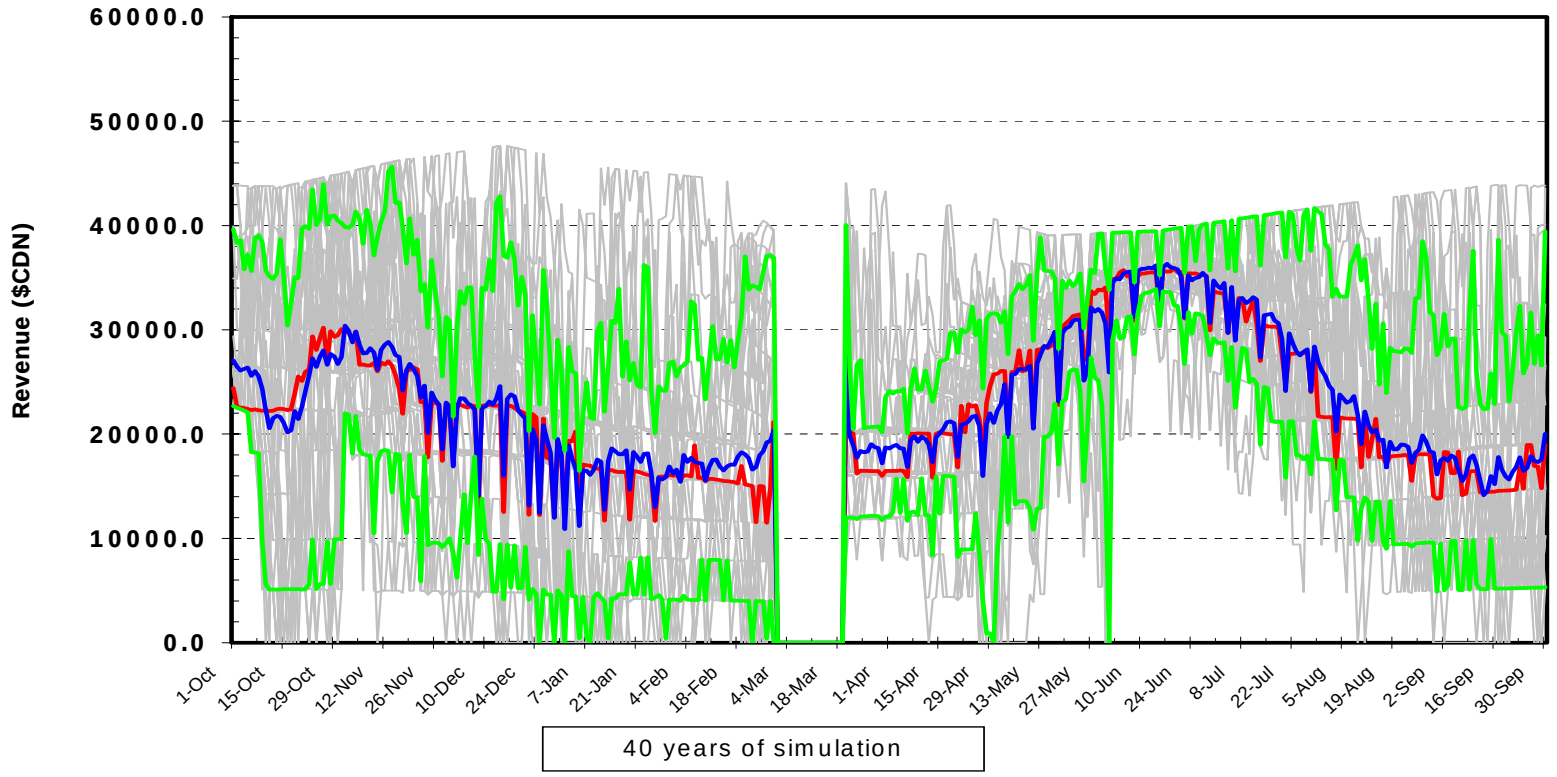
Graphical Output - Revenue

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Revenue



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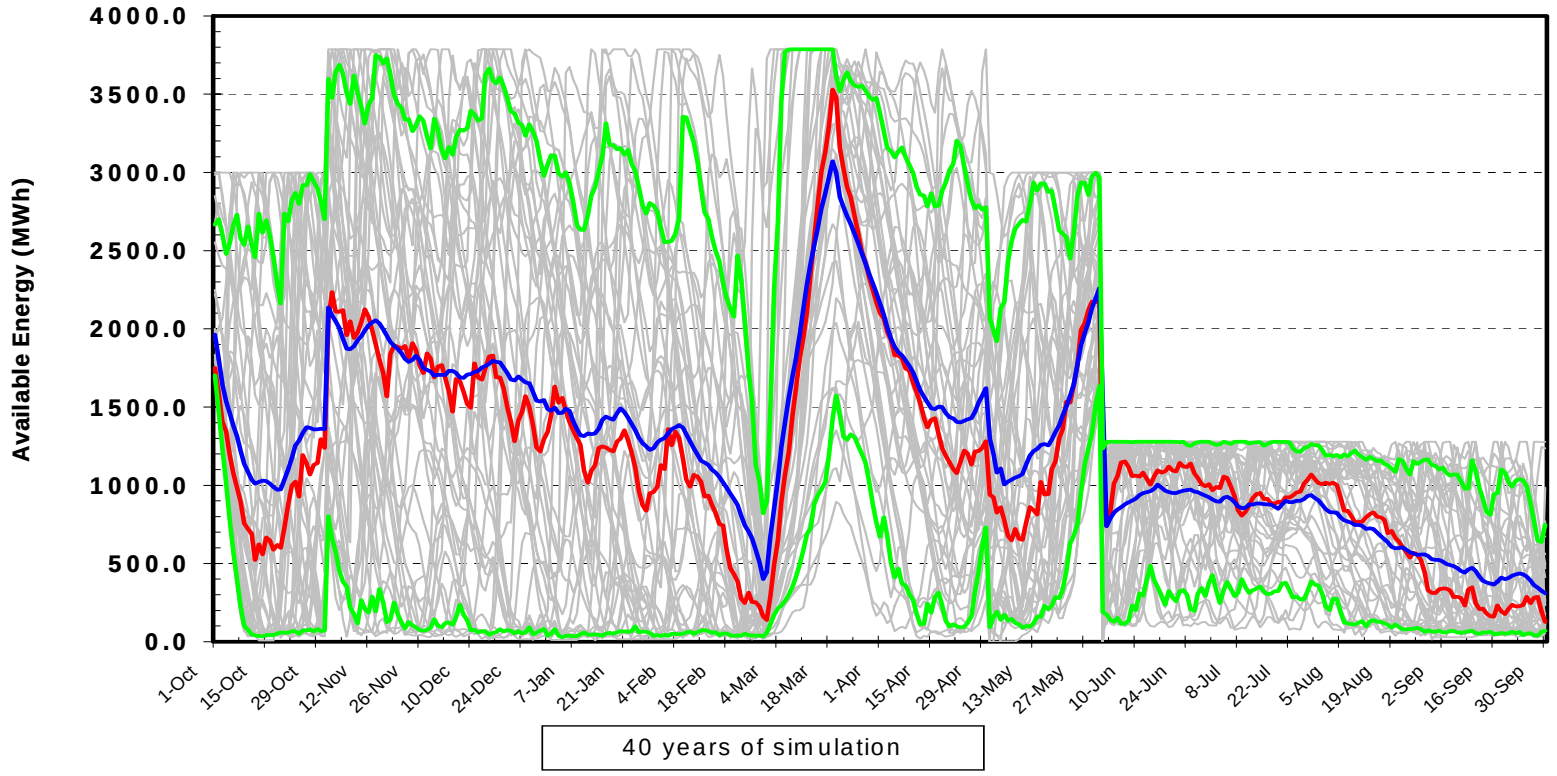
Graphical Output - Available Energy

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Available Energy



40 years of simulation

BC Hydro Generation Integrated Operations & Risk Management
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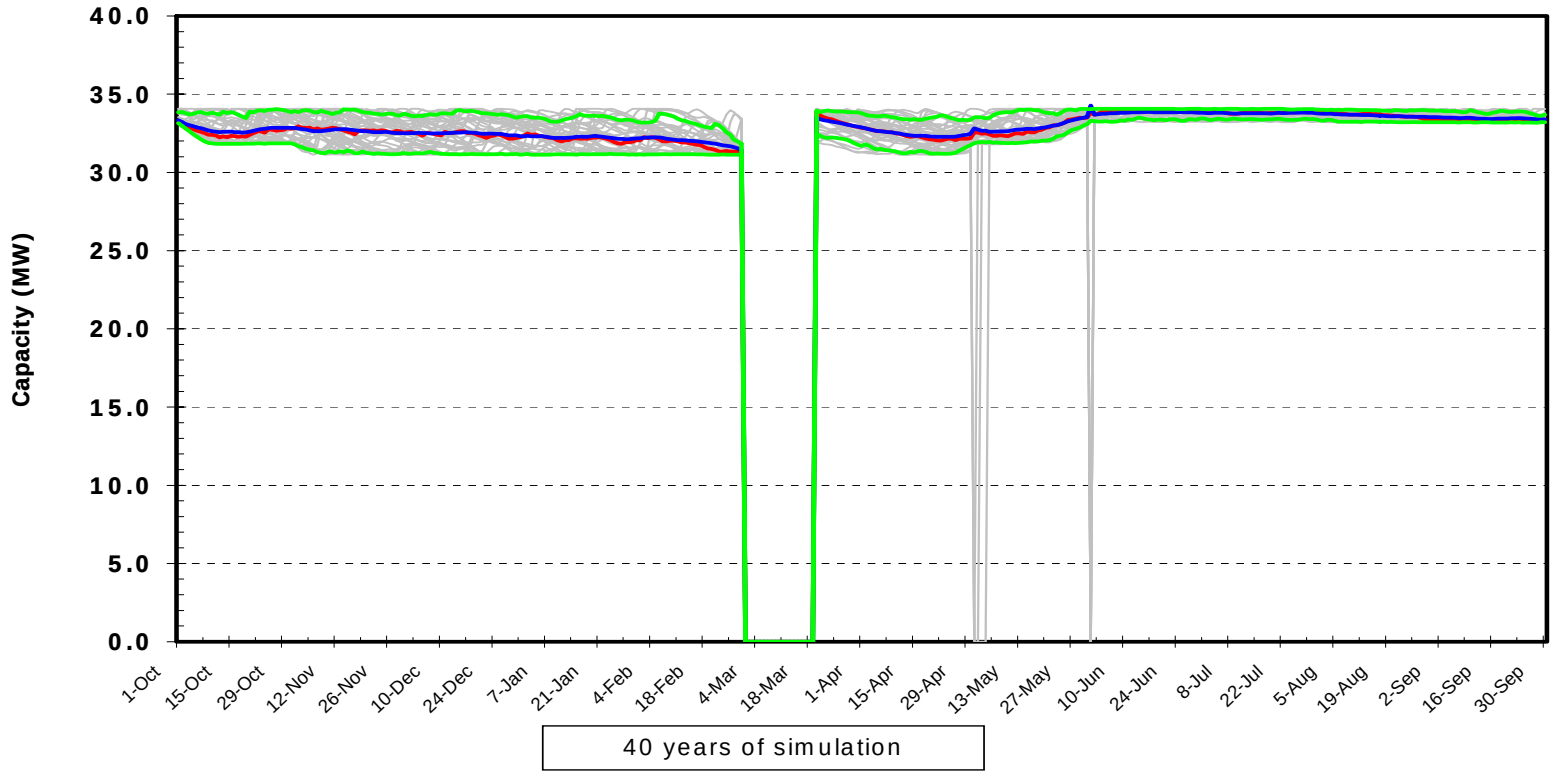
Graphical Output - Capacity

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Capacity



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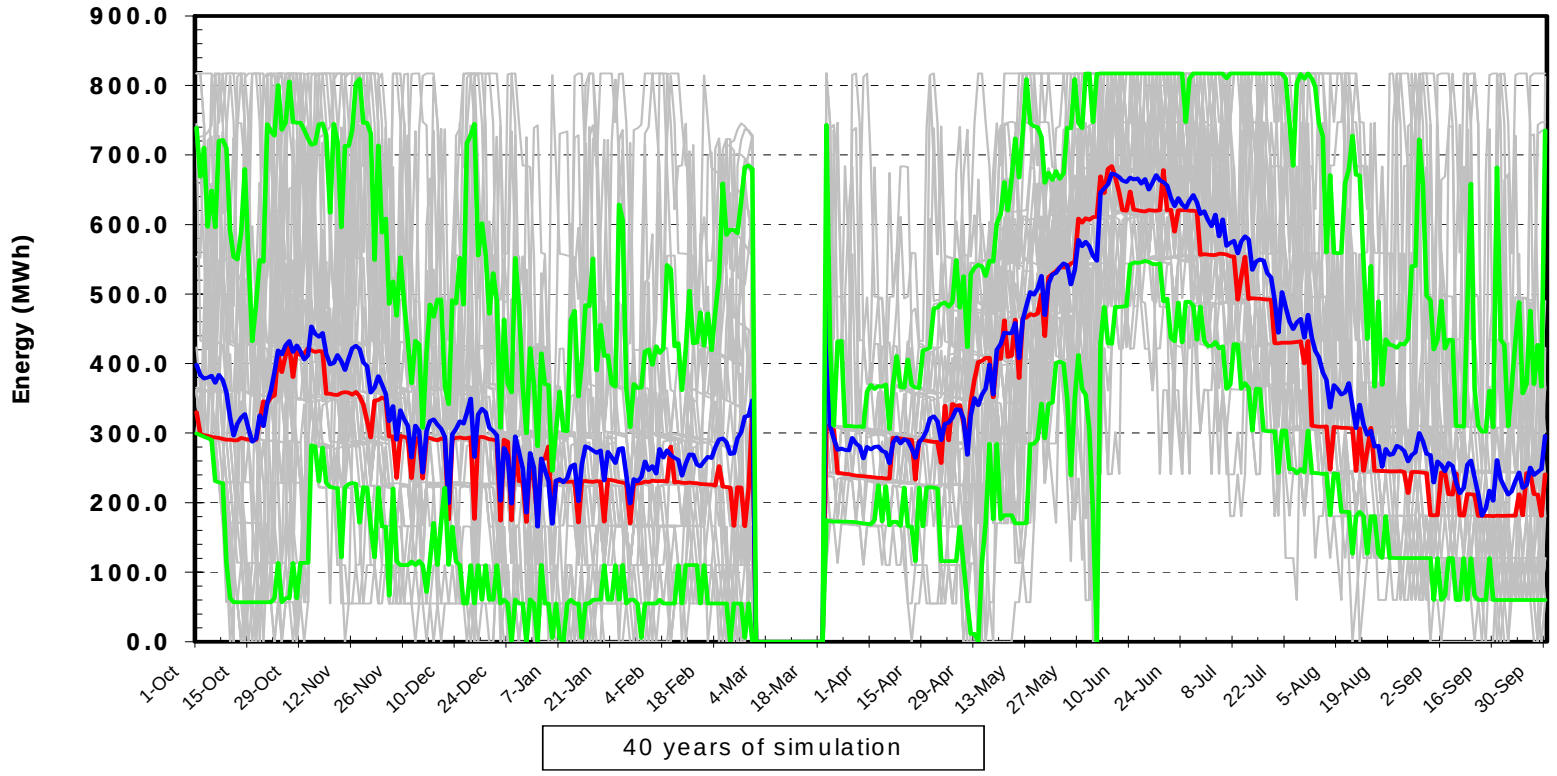
Graphical Output - Energy Production

Alt-G

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Energy



Results

- **Current base operation is relatively unconstrained**
- **Most popular constraints to apply:**
  - **Reservoir elevation**
  - **Turbine discharge**
  - **Timing of annual maintenance outage**

Results

- **17 different elevation and outage timing constraint alternatives were modeled (Alt-A to Alt-Q)**
- **13 of these were modeled with increased turbine discharge (Alt-AA to Alt-QQ)**
- **6 alternatives modeled before tradeoff meeting**
- **final tradeoff narrowed to 6 final alternatives**

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Results - 6 Trial Alternatives

Alternative Name	Goal	Timing and elevation of reservoir operating limits	Timing and depth of maintenance draw down*	Instantaneous diversion through turbine
Alternative A	To represent current operations	Year round Minimum 45 meters Maximum 53.34 meters	Draw down allowed (e.g., for annual maintenance) Gate test: September	Per existing license
Alternative B	Maximize effective littoral zone. Note: by maximizing effective littoral zone, recreation objectives are also maximized.	Year Round Minimum 52 meters Maximum 53.34 meters	No drawdown for annual gate test	Per existing license
Alternative C	Remove spill gate testing from Alternative A	Year round Minimum 45 meters Maximum 53.34 meters	No drawdown for annual gate test	Per existing license
Alternative D	Meet recreation objective for peak recreation period and constrain operation flexibility to promote effective littoral zone for remainder of year	May-October Minimum 52 meters Maximum 53.34 meters November-April Minimum 48 meters Maximum 53.34 meters	Annual maintenance drawdown to minimum in March No drawdown for annual gate test	Per existing license
Alternative E	Meet recreation objective for peak recreation period and constrain operation flexibility to promote effective littoral zone for remainder of year	May-October Minimum 52 meters Maximum 53.34 meters November-April Minimum 49 meters Maximum 53.34 meters	Annual maintenance drawdown to minimum in March No drawdown for annual gate test	Per existing license
Alternative F	Test increased allowable turbine discharge to 95 m^3/s relative to Alternative E**	May-October Minimum 52m Maximum 53.34m November-April Minimum 49m Maximum 53.34m	Annual maintenance drawdown to minimum in March No drawdown for annual gate test	Allowable turbine discharge increased to 95 m^3/s (5 m^3/s less than turbine capacity to stay within a 100 m^3/s license

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Results - 6 Trial Alternatives

Objective	Fish	Fish	Power	Power	Power	Recreation	Spills	Spills
	Effective littoral zone (hectares)	Annual Entrainment (Spill-Days)	Annual Energy (MWh)	Annual Revenue ($CDN millions)	Annual Capacity (MW)	Annual Recreation (Weighted Recreation -Days)	Log boom impacts (Return Period > 200 m^3/s)	Bridge impacts (Return Period > 600 m^3/s)
Alt-A	0	7	125,975	$6.70	30.80	179	0.6	4.1
Alt-B	20.35	25	124,036	$6.54	31.69	274	0.4	3.7
Alt-C	0	8	126,117	$6.74	30.84	181	0.7	5.1
Alt-D	5.54	15	124,744	$6.64	31.26	221	0.5	4.6
Alt-E	10.03	17	124,018	$6.61	31.29	231	0.5	4.6
Alt-F	10.03	13	125,834	$6.67	35.93	231	0.5	4.6

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Results - 6 Final Alternatives

Alternative Name	Goal	Timing and elevation of reservoir operating limits	Timing and depth of maintenance draw down*	Instantaneous diversion through turbine
Alternative A	To represent current operations	Year round Minimum 45 m Maximum 53.34 m	Draw down allowed (e.g., for annual maintenance) Gate test: September	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)
Alternative G	Revise Alternative F to generate gains in Fish and Power	*May & October* • Minimum 50 m • Maximum 53.34 m *November-April* • Minimum 49 m • Maximum 53.34 m *June-September* • Minimum 52 m • Maximum 53.34 m	Annual maintenance draw down to minimum in March No draw down for annual gate test	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)
Alternative I	Revise Alternative G to generate gains in Fish while not significantly impacting and perhaps benefiting Power and other objectives	*October-September* Year round • Minimum 49 m • Maximum 53.34 m	Annual maintenance draw down to minimum in March No draw down for annual gate test	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)
Alternative J	Provide an alternative that is clearly distinct from Alternative I and Alternative G	A 48.5 m hard minimum and a 52 m soft maximum year round.*	Annual maintenance draw down to minimum in March No draw down for annual gate test	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)
Alternative M	Provide an alternative that is clearly distinct from Alternative I and Alternative G	A 47.0 m hard minimum and a 53 m soft maximum year round.*	Annual maintenance draw down to minimum in March No draw down for annual gate test	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)
Alternative N	Provide an alternative that is clearly distinct from Alternative I and Alternative G	A 48.0 m hard minimum and a 53 m soft maximum year round.*	Annual maintenance draw down to minimum in March No draw down for annual gate test	Two scenarios** 1. Per existing license (82.18 m^3/s) 2. with an increase in the instantaneous diversion limit (100 m^3/s)

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Results - 6 Final Alternatives

Objective	Power*	Fish	Recreation	Spill	Spill	Power*	Power*	Power* *+	Fish
	Annual Revenue ($CDN)	Effective littoral zone (hectares)	Annual Weighted Recreation Days (days)	Bridge (Spill Return Period > 600 m^3/s in years)	Log boom (Spill Return Period > 100 m^3/s in years))	Annual Capacity (MW)^	Annual Total Energy (MWh)^	Annual Increased Green-house Gas (tCO_2e)	Annual Spill Days (days)
Alt-A	$7,980,517	5.87	146	3.4	0.5	30.4	125,953	0	10
Alt-G	$7,978,748	13.69	213	4.6	0.5	31.23	126,533	(177)	18
Alt-M	$8,027,856	15.98	153	5.1	0.6	30.57	126,243	(89)	13
Alt-I	$8,014,959	19.96	192	4.6	0.5	30.984	126,525	(175)	17
Alt N	$8,000,298	20.26	162	4.6	0.6	30.733	126,484	(162)	14
Alt-J	$7,898,537	23.52	152	4.6	0.6	30.608	126,790	(256)	13

BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

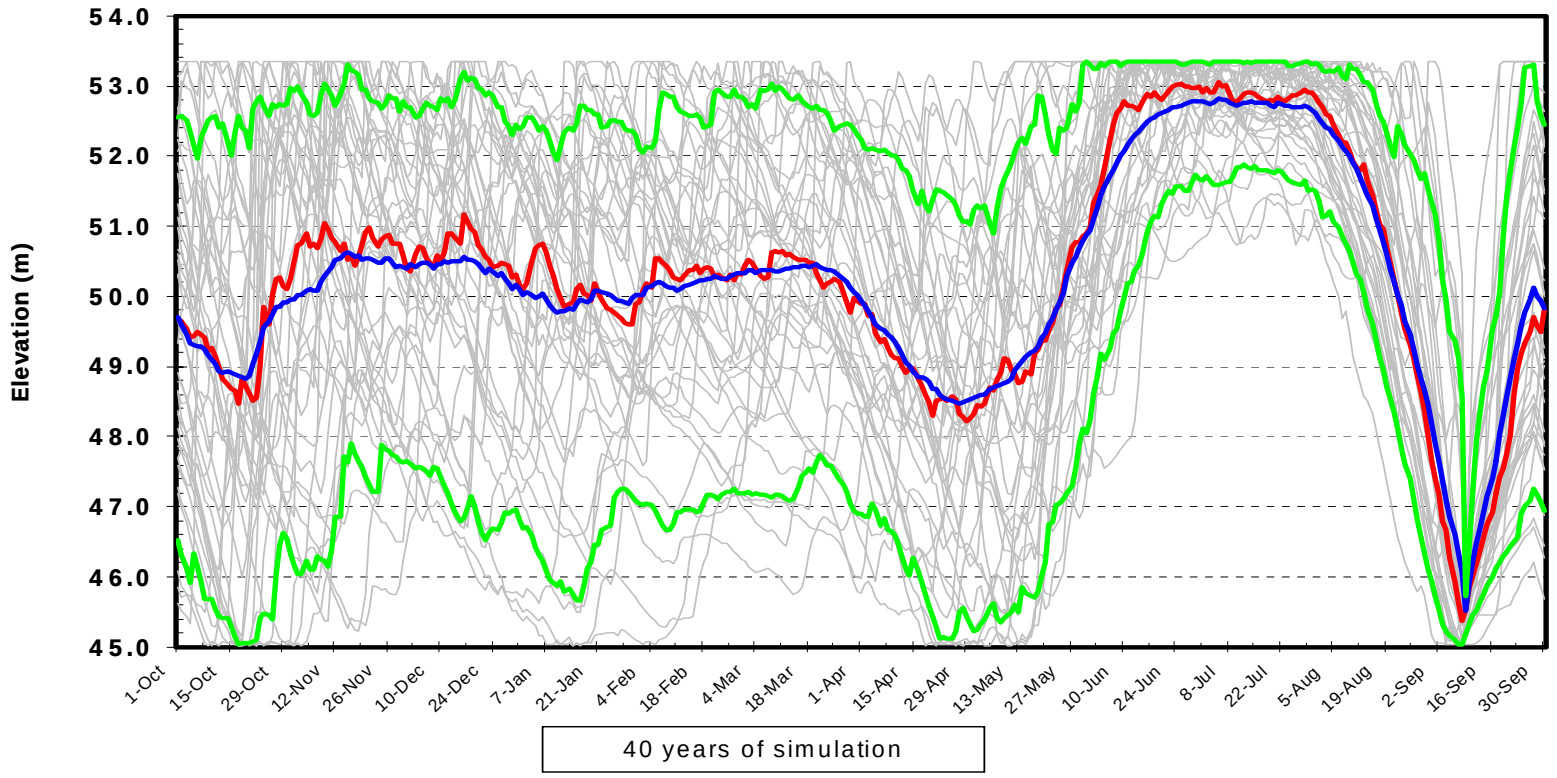
Graphical Output - Reservoir Elevation

Alt-A

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Elevation



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

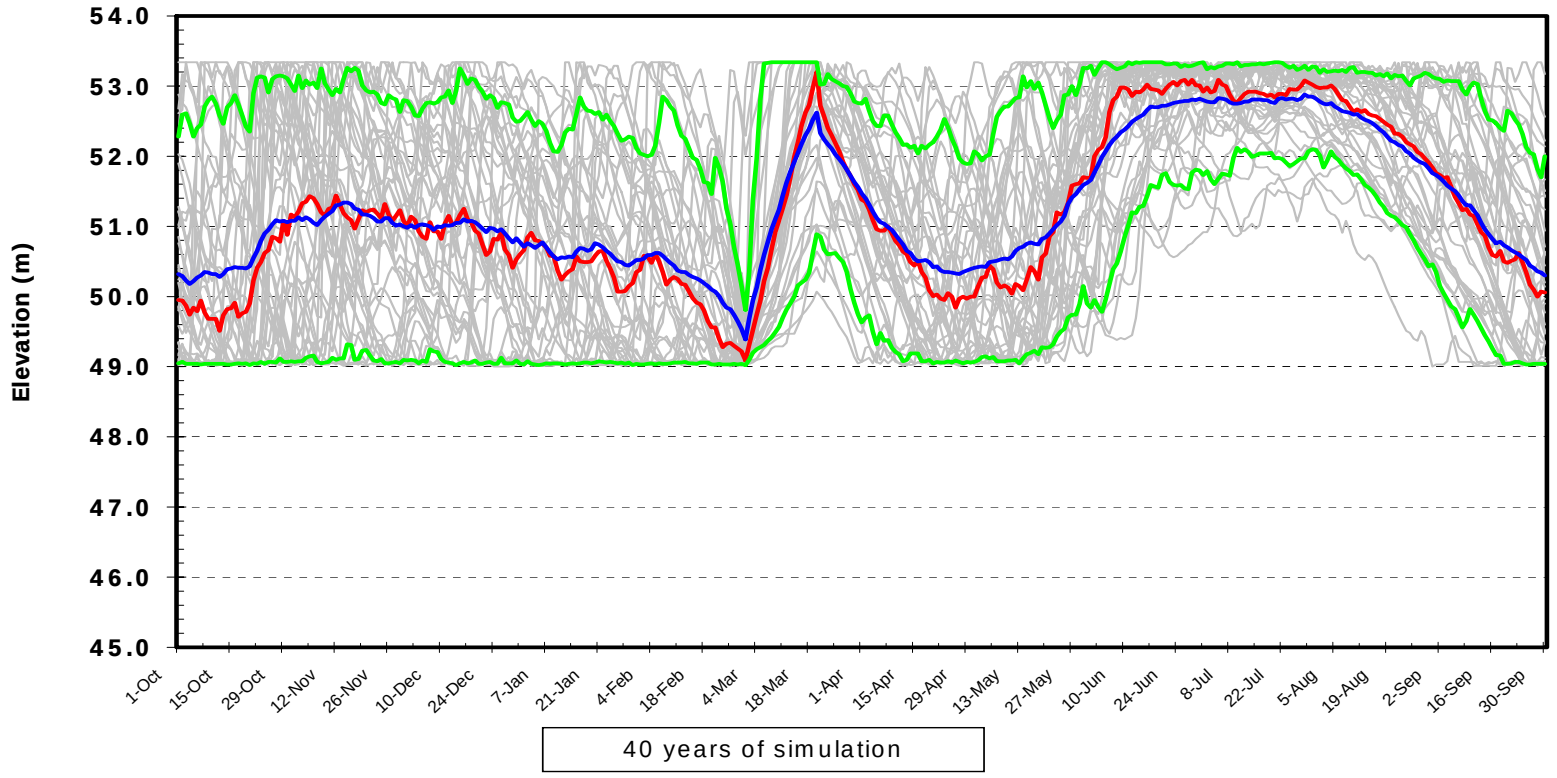
Graphical Output - Reservoir Elevation

Alt-II

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Elevation



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

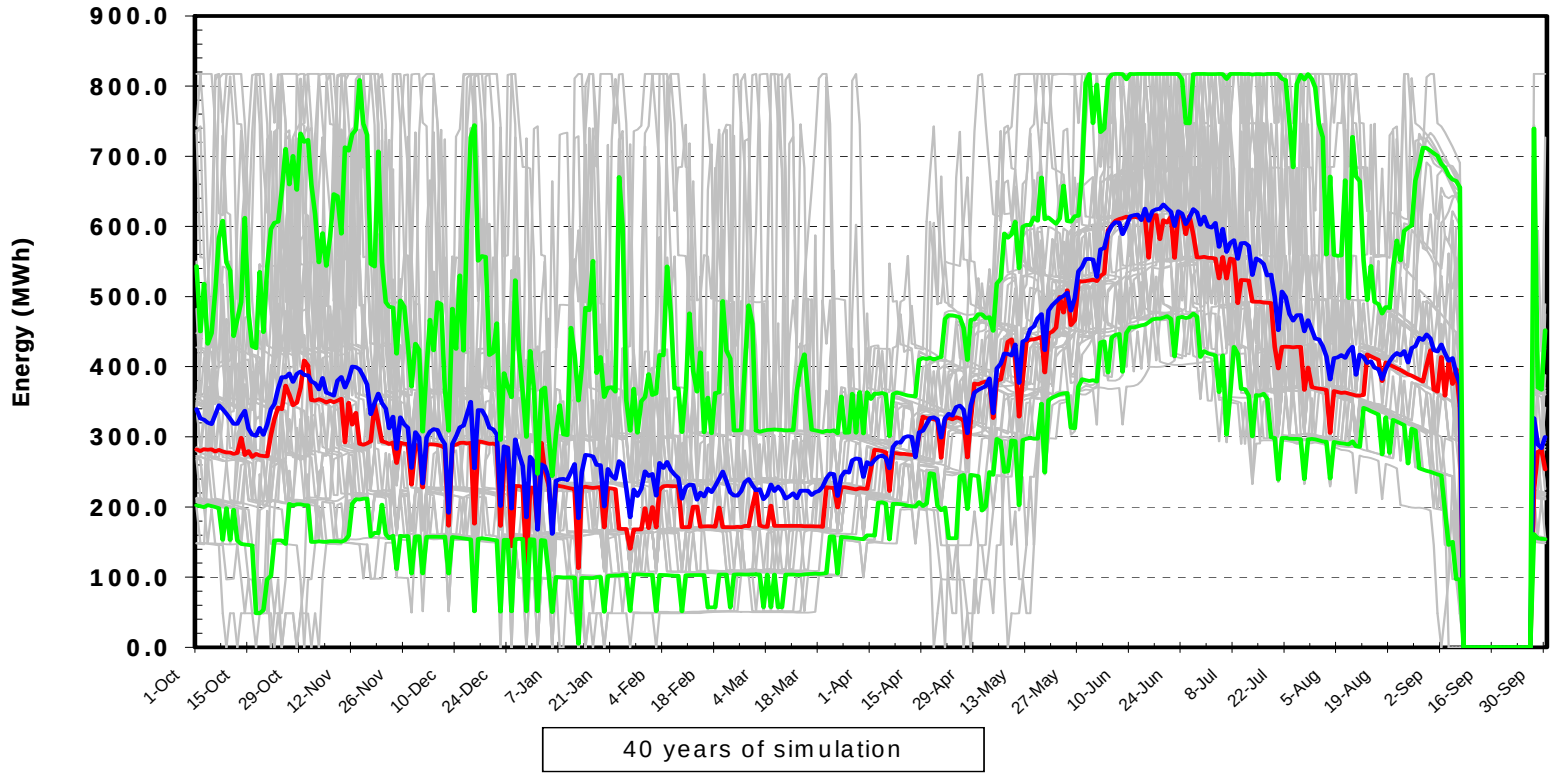
Graphical Output - Energy Production

Alt-A

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Energy

Graphic View of Results



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

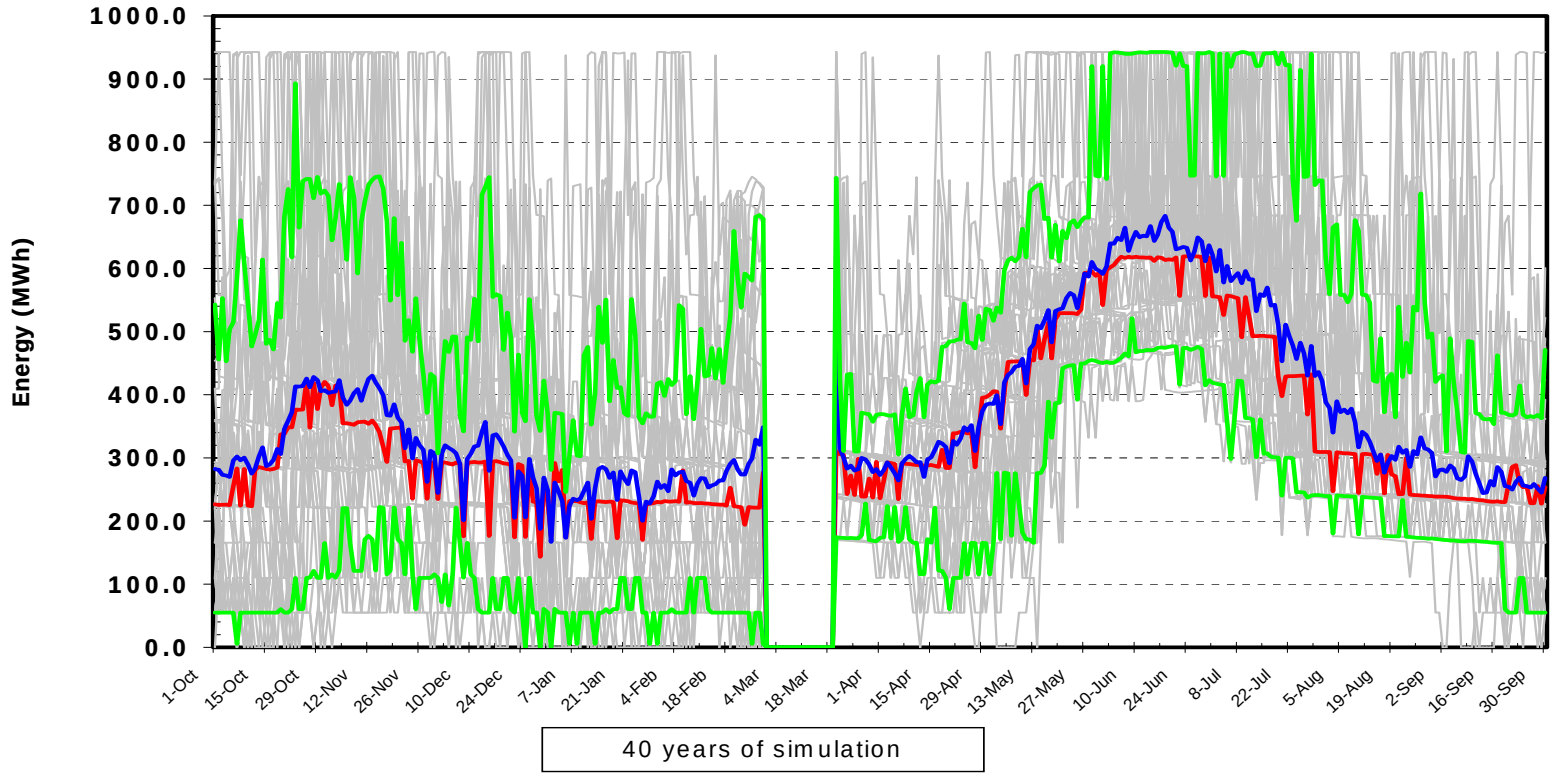
Graphical Output - Energy Production

Alt-II

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Energy



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

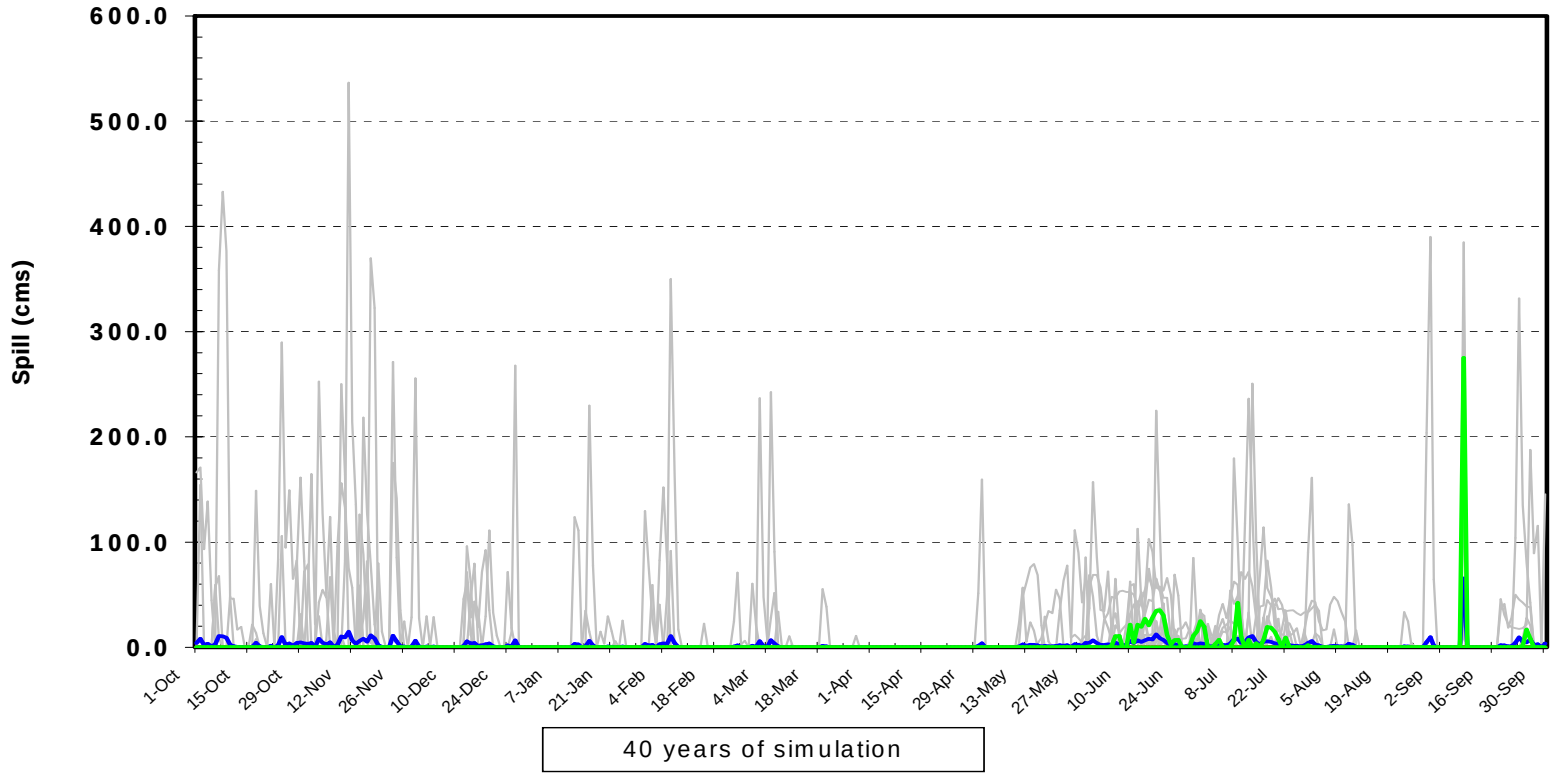
Graphical Output - Spill

Alt-A

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Spill



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

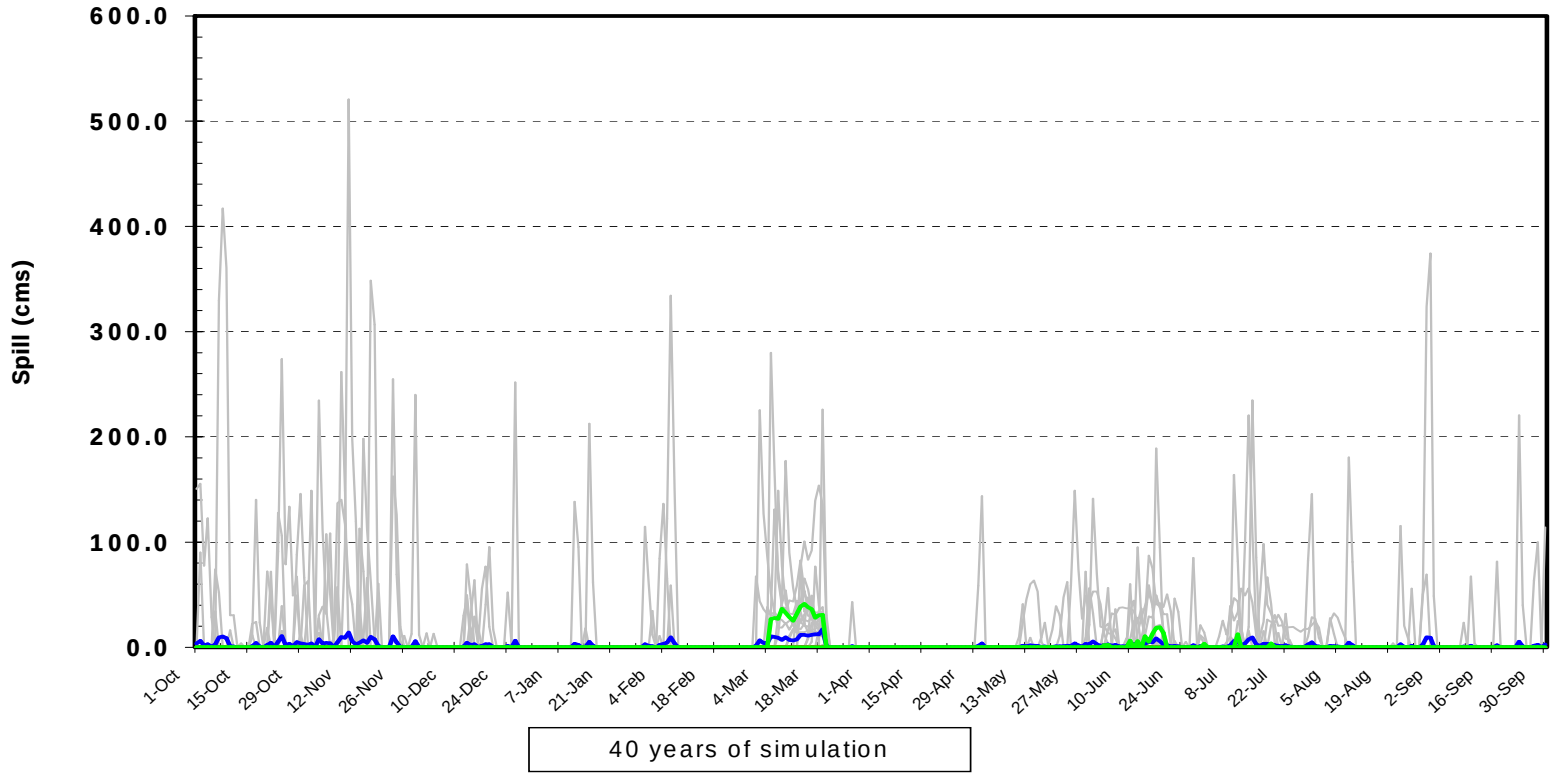
Graphical Output - Spill

Alt-II

☑ Plot Median Line
☑ Plot Mean Line
☑ Plot 10/90 Percentile Lines

Graphic View of Results

Spill



BC Hydro Generation Integrated Operations & Risk Management
Interactive Modeling for Assessing Tradeoffs in Water Use Planning

Summary

- **SOPHOS dynamic programming model with Excel PM Calculator and Graphics front end used to provide interactive model within Water Use Planning trade-off process**
- **Allowed WUP stakeholders to try out different constraints within the meeting environment, and shortened the Clowhom WUP process**

Credits

- **James Bruce, BC Hydro biologist, developed Excel front end**
- **John Kelly, BC Hydro project manager, approved use of this alternative approach despite the inherent process risk**

BC Hydro Generation Operations
Stochastic Optimization Program for Hydro Operations Studies (SOPHOS)

Application in Operations Planning

- **Model currently set up to run for:**
  - **a) Clowhom**
  - **b) Whatshan**
  - **c) Wahleach**
- **In use for Clowhom operations planning for three years**

BC Hydro Generation Operations
Stochastic Optimization Program for Hydro Operations Studies (SOPHOS)

Operations Planning