Mapping Climate Risks in an Interconnected System

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Abstract

Infrastructure spending for climate change adaptation in complex water management systems is an ongoing challenge. While some approaches allow for risk assessment of individual components, they struggle to address risks for interconnected systems with feedback effects. Water budget models can be used to assess designs, but forecasting of future climate using adjusted historical records is limitative when considering rare extreme events. In order to model an integrated water management system at a smelter in Sudbury, Ontario, Golder Associated Ltd. developed a coupled water balance model and climate generator tool. The tool used statistics for historic weather (rather than simply shifting historic records) and a range of potential climate change scenarios to generate thousands of 'potential' climate records and system response, defining risk based on occurrence across multiple realizations. The tool was provided to the client (with options to modify the system) so that they could assess best direct future infrastructure spending.

1. Introduction

In 2004, Golder developed a water management model for a smelter site near Sudbury, Ontario. This tool was created so that site operators could simulate effects of weather events (such as larger rainfalls, significant spring melts, or dry summers) on operations at the site. The model was created using the GoldSim modelling environment, and included natural runoff and pumping flows to and from a smelter site, and between the various tailings and treatment ponds at the site. The user entered basic design parameters for the system, and the model was run with historic 1956-2011 daily climate data from the Sudbury Airport meteorological station (#6068153). The strength of this approach was that once it had been calibrated to measured data it could be used to accurately model the range of historic events in what is a large interconnected system (where modelling single elements in isolation would not be adequate).

One acknowledged limitation of the original model however was that it only used historic data; potential events not captured in the historic data could not be simulated. This led to the development of the Golder Climate Generator; a code within the GoldSim model that could generate synthetic climate records based on historic climate statistics (Davidson and MacKenzie, 2011). The code was used to generate synthetic climate records at two test locations. Results generally compared well with the seed data, with longer synthetic records showing a proportional increase in the number of extreme events generated.

Discussions with the client following the development of the Golder Climate Generator resulted in additional features for the tool, designed to allow operators to assess impacts of proposed changes to the system (including capital expenditures and changes to processes). One of the most significant of these was the addition of Climate Change to the generator, allowing the operators to assess not just the potential range of climate events based on historical climate statistics, but to create multiple simulated scenarios, or realizations of multi-year synthetic climate records based on high level Global Climate Model (GCM) results. This final step allowed for modelling of the complex system under changing climate conditions.

2. Program Description

2.1 Original Code

The original Golder Climate Generator used the Monte Carlo simulation capabilities of the GoldSim software to generate synthetic climate records given historic climate statistics (Davidson and Mackenzie, 2011). This synthetic record included daily mean temperature and daily mean precipitation, with corresponding calculations for snowfall, snowmelt, and evaporation. Climate statistics entered into the generator included annual, monthly, and daily means and standard deviations for average temperatures and precipitations, as well as likelihood of daily precipitation. Tests showed the resulting synthetic records generally matched the averages for the historical records, while at the same time including additional 'extreme' events that were not present in the limited historical records.

2.2 Accounting for Climate Change

In order to add climate change accounting to the synthetic output from the generator, additional parameters were added that would gradually shift the governing climate statistics. The shift was assumed to be linear over the 40 year period. The total change over the duration of the synthetic record would depend on the start and end points of the climate data.

Based on discussions with climate specialists at Golder, the annual and monthly average precipitation and temperature results from the GCMs were used to estimate the annual change, using the 2011 baseline as the starting position and the GCM results for 2050 as the final statistics and dividing the difference over the 40-year period. The use of these GCM results was based in part on the availability of monthly temperature and precipitation results from the multi-model GCMs, and in part the desire to avoid costly downscaling given the desired level of analysis. Based on the range selected, the generator was set to produce 40-year realizations of synthetic daily precipitation and mean temperature data.

While the shift over time based on the GCM results modifies the annual and monthly mean statistics for temperature and precipitation, there remains several statistical parameters in the model for which the GCMs do not provide guidance. Generating the future climate realizations therefore included the following assumptions:

- Standard deviations for most values were assumed not to change from levels in the 50-year historic record, with only the means for those values shifting based on the GCM results; and,
- Future changes in daily precipitation distribution (mean and standard deviation) were assumed from extrapolating trends from the historic data. The mean and standard deviation for daily precipitation for each month was taken from the historic record, and plotted by year. A linear regression line through the resulting points was used to estimate the annual rate of change (i.e. the slope of the regression line).

2.3 Uncertainties and Scenarios

In addition to the assumptions, uncertainties around the daily chance of precipitation (information which is not provided in the GCMs) and the results from the GCMs themselves (which produce a range of results for both temperature and precipitation) led to a total of five (5) scenarios being used to generate synthetic records. The scenarios are outlined below, and summarized in Table 1.

- **Average Conditions**: Using the average 2050 monthly temperature and precipitation distributions across all selected GCMs with no change to daily chance of precipitation;

- **+30% Conditions**: Average Conditions (as above) with a 30% increase in daily chance of precipitation by 2050 (resulting in increasingly frequent but smaller precipitation events);

- **-30% Conditions**: Average Conditions (as above) with a 30% decrease in daily chance of precipitation by 2050 (resulting in decreasingly frequent but larger precipitation events);

- **High GCM Conditions**: the 2050 monthly precipitation distribution which produced the highest annual precipitation of all examined GCM results coupled with 2050 monthly temperature distribution which produced the coldest annual temperature of all examined GCMs;
- **Low GCM Conditions**: the 2050 monthly precipitation distribution which produced the lowest annual precipitation of all examined GCM results coupled with 2050 monthly temperature distribution which produced the warmest annual temperature of all examined GCMs.

Table 1: Scenario Descriptions

Scenario	Mean Annual Temperature (ºC)	Mean Annual Precipitation (mm/yr)	12-Month Average Daily Chance of Precipitation
Historic Climate (2011)	*3.7*	*889.7*	*0.56*
Average Conditions (2050)	6.2	954.4	0.59
+30% Conditions (2050)	6.2	954.4	0.89
-30% Conditions (2050)	6.2	954.4	0.26
High GCM Conditions (2050)	4.6	985.7	0.59
Low GCM Conditions (2050)	6.1	955.0	0.59

Note:
°C – degrees Celsius
mm/yr – millimetre per year

A total of 1,000 realizations (each with a 40-year synthetic record of daily data) were created for each of the above scenarios, which in turn were used in the water management model. The use of 1,000 realizations was intended to limit the bias from single events and to map out as fully as possible the 'expected' risks associated with certain events occurring (assumed as 5^{th} and 95^{th} percentile results for each year). The results were evaluated at key points in the model.

3. Results Evaluation and Discussion

Tables 2 through 4 provide selected results for water levels at three site ponds. Statistics for each scenario were estimated for the first and last years (2011 and 2050, respectively) from the 1,000 realizations run for each scenario.

The results generally show that, based on the water management at this particular site, both the expected low (5^{th} Percentile) and high (95^{th} Percentile) water level results are expected to decrease between 2011 and 2050. This included the scenario with the largest expected increase in precipitation and smallest increase in temperature ('High GCM'); this scenario had been expected to produce higher water levels due to increased precipitation and decreased evaporation. Likewise, the "-30%" scenario had been expected to produce higher expected water levels resulting from relatively larger single rainfall events (given similar monthly precipitation and less frequent rainfall), but in fact it was the more frequent rainfalls produced in the "+30%" scenario that tended to produce the higher expected water levels. Low water results are generally similar as they are tied to outflow invert levels.

Table 2: 5th and 95th Percentile Results – Tailings Pond A

Scenario	Tailings Pond A Water Level (masl)				
	Average Conditions	+30% Conditions	-30% Conditions	High GCM Conditions	Low GCM Conditions
2011 5th Percentile	308.28	308.27	308.28	308.28	308.28
2011 95th Percentile	310.55	310.54	310.57	310.52	310.51
2050 5th Percentile	308.27	308.27	308.27	308.27	308.27
2050 95th Percentile	309.94	309.96	309.84	310.27	309.52

Note:
masl – metres above sea level

Table 3: 5th and 95th Percentile Results – Tailings Pond B

Scenario	Tailings Pond B Water Level (masl)				
	Average Conditions	+30% Conditions	-30% Conditions	High GCM Conditions	Low GCM Conditions
2011 5th Percentile	292.95	292.96	292.96	292.96	292.96
2011 95th Percentile	294.11	294.11	294.10	294.09	294.10
2050 5th Percentile	292.85	292.83	292.85	292.95	292.82
2050 95th Percentile	293.81	293.83	293.77	293.93	293.65

Note:
masl – metres above sea level

Table 4: 5th and 95th Percentile Results – Quality Pond C

Scenario	Quality Pond C Water Level (masl)				
	Average Conditions	+30% Conditions	-30% Conditions	High GCM Conditions	Low GCM Conditions
2011 5th Percentile	290.72	290.72	290.72	290.72	290.72
2011 95th Percentile	292.02	292.03	292.02	292.02	292.02
2050 5th Percentile	290.69	290.69	290.69	290.73	290.69
2050 95th Percentile	291.79	291.82	291.74	291.92	291.66

Note:
masl – metres above sea level

Table 5 shows the change in total flow at the final discharge from the site. The results generally show a decrease in flows leaving the site for most scenarios between 2011 and 2050, with the exception of the 'High GCM' scenario. This suggest that, given reasonable assumptions for the site (an average of GCM results) that there will be somewhat less outflow from the site in the 2050 future.

Table 5: 5th and 95th Percentile Results - Final Discharge Point

	Final Discharge Annual Flow (m^3/yr)				
Scenario	**Average Conditions**	**+30% Conditions**	**-30% Conditions**	**High GCM Conditions**	**Low GCM Conditions**
2011 5th Percentile	4,620,000	4,790,000	4,800,000	4,680,000	4,700,000
2011 95th Percentile	8,150,000	8,100,000	8,170,000	8,210,000	8,290,000
2050 5th Percentile	4,020,000	4,230,000	4,180,000	4,910,000	3,840,000
2050 95th Percentile	7,650,000	7,680,000	7,760,000	8,640,000	7,500,000
	Final Effluent Point Daily Flow (m^3/day)				
Scenario	**Average Conditions**	**+30% Conditions**	**-30% Conditions**	**High GCM Conditions**	**Low GCM Conditions**
Overall Maximum	130,000	130,000	150,000	150,000	140,000
Overall Minimum	300	300	300	1,800	200

Note:
m^3/yr – cubic metres per year
m^3/day – cubic metres per day

4. Conclusions

Based on the previous sections, the following conclusions can be drawn:

- The Golder Climate Generator may be modified to include basic assumptions of climate change shifts from readily available GCM results.
- The resulting synthetic climate records can be used as input to complex water management models.
- Multiple scenarios may be required to assess the potential effects of variables for which GCM results do not provide guidance.
- Analysis of a large number of results may be used to estimate the probable effects of climate change on modeled systems.
- It is possible to evaluate the effects of a range of proposed site changes to water management into the future using this approach.

5. References

Davidson, Christopher and Mackenzie, Kevin, "*Golder Daily Climate Generator*", Canadian Society of Civil Engineering, 20th Canadian Hydrotechnical Conference, June 2011.