P2.3 MODELLING HYDROLOGIC CONDITIONS IN PRESENT AND FUTURE CLIMATES – MODEL PERFORMANCE FOR RECENT CONDITIONS IN COASTAL BRITISH COLUMBIA

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1. INTRODUCTION

Streamflows modelled from climatic inputs for six mountain watersheds in the Georgia Basin of British Columbia, Canada are compared and contrasted for the period 1973-1993. Our ability to predict the hydrology of streams in future climates depends in part in our ability to model present circumstances. The comparison of observed streamflow data to modelled streamflows provides insight into model performance and the ability to reproduce hydrologic attributes that might be of interest in predictions of future scenarios.

For mountainous areas such as Georgia Basin, some general circulation models (GCMs) have suggested that higher air temperatures will increase the ratio of rain to snow, accelerate the rate of spring snowmelt, reduce the duration of the snow on ground period and enhance the spring freshet (Frederick and Gleick, 1999). Coulson (1997) suggests that freshet volumes will increase and occur up to one month earlier when the atmospheric CO_2 concentration doubles. Whitfield and Taylor (1998) found streams in coastal areas of British Columbia have already shown decreases in stream discharge during late spring and summer, an overall lengthening of the summer dry period, and increases in winter runoff.

Variations in temperature and precipitation exert tremendous influence on the amount and form of water that reaches the surface of Georgia Basin, British Columbia. The form in which precipitation occurs in winter, either snow or rain is the primary factor controlling the hydrology of the region (Wade *et al*., 2001). Watersheds were separated into three types: rainfall-driven streams, snow melt-driven streams, and hybrid (mixed rain and snow melt-driven) streams. A hydrologic model was used to simulate streamflows from each of these types for the period 1973-1993.

The assessment considers hydrologic model performance with respect to both central tendency measures and extreme events, namely floods. This investigation of biases between observed streamflows, modelled streamflows based on data downscaled from reanalyzed climate fields, and modelled streamflows based on data downscaled from the GCM provides insight to interpreting forecasts of hydrologic conditions for future climate scenarios. To assess how a GCM driven hydrologic simulation might perform for future periods we evaluate model performance for a recent historical period by analyzing differences between observations and model outputs.

2. METHODS

The Georgia Basin includes the drainages that surround the Strait of Georgia: Southern Vancouver Island, the Southern British Columbia mainland, and the waters flowing into Puget Sound in the USA. The physical and hydrological characteristics of the watersheds are listed in Table 1, and represent the three hydrological types present in the basin (Wade *et al*., 2001).

Table 1. Some attributes of the study watersheds.

Watershed	Basin Area (km^2)	Mean Basin Elevation (m)	System Driver
Englishman	324	695	Rainfall
Capilano	172	976	Rain/Snow
Coquitlam	54.7	1154	Rain/Snow
Cheakamus	285	1740	Snowmelt
Elaho	1250	1614	Snowmelt
Lillooet	2160	1678	Snowmelt

Local temperature and precipitation data used to calibrate the hydrologic model were selected from the dataset described by Danard and Galbraith (1997). This dataset is the result of a hybrid statistical-meteorological interpolation of daily maximum temperatures, minimum temperatures, and precipitation amounts in the Georgia Basin. The meteorological component of the analysis involved the application of a simple high-resolution boundary-layer model to data from the National Centers for Environmental Prediction (NCEP) Limited-area Fine Mesh model. Outputs from the boundary-layer model were combined with point observations using an objective analysis procedure. Results are available on a grid with a resolution of 1’ latitude by 1.5’ longitude (~1.9 km × 1.8 km). Kite and Haberlandt

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(1999) compared fields from the high-resolution analysis model with those from more complicated numerical weather prediction (NWP) models. They found data from the high-resolution boundary-layer model to be competitive with data from NWP models when used as inputs to macroscale hydrological models. Due to the complete spatial coverage offered by this approach, analyzed data may be better suited to drive hydrological simulations than actual observed point data. Stations selected for use in the current study are from six watersheds within the Georgia Basin. For each station, daily time series of maximum temperatures, minimum temperatures, and precipitation amounts from 1973-1993 were extracted from the database.

To assess the ability of GCM downscaling to yield local-scale climate information usable as inputs to watershed models, temperature and precipitation conditions in each watershed were estimated using analog downscaling models (Barnett and Preisendorfer, 1978). The analog modelling approach was chosen 1) for its simplicity and its competitive performance versus other more complicated models (Zorita and von Storch, 1999), and 2) because it offers a simple method for controlling model fit and the time structure of the simulated series. The latter point was a key consideration as the downscaling results were to be used in a watershed model that is sensitive to the time structure of the climate inputs (Huth *et al.,* 2001).

Large-scale climate variables used to define analogs with GCM variables were taken from the NCEP/NCAR Reanalysis model database (Kalnay *et al*., 1996). Atmospheric fields were chosen to represent surface circulation, boundary-layer moisture, average atmospheric temperature, and mid-tropospheric circulation conditions. Sea-level pressure (SLP), 850-hPa specific humidity, 850-500 hPa thickness, and 500-hPa geopotential height fields were extracted for a spatial domain spanning 30ºN-70ºN and 200ºE-250ºE. To match the GCM, reanalysis data defined on a 2.5º × 2.5º grid were regridded to a T32 Gaussian grid (~3.75º × 3.75º) using bicubic spline interpolation. The dimension of the large-scale climate dataset was further reduced using principal component analysis (PCA). Twenty principal components were retained to represent the atmospheric circulation data. A *k*-nearest neighbor analog model was used to link principal component scores of the climate fields with the maximum temperature, minimum temperature, and precipitation series from Danard and Galbraith's dataset. Values of *k* were chosen to be a compromise between maximizing model fit and maintaining the structure of the predicted time-series. Based on results from the cross-validation, *k* was set equal to 3 for maximum and minimum temperature series. For precipitation amounts, *k* was set to equal to 2. Prior to comparison, modelled temperature series were rescaled so that the modelled and observed means and standard deviations were. For precipitation, model outputs were inflated by multiplying by the ratio of the observed and predicted means. This preserved total precipitation amounts but lead to a slight underestimation of precipitation variance.

Atmospheric circulation data used in the GCM downscaling were from the IPCC IS92a greenhouse gas plus aerosol run of the first Canadian Global Coupled Model (CGCM1) (Flato *et al*., 2000). Daily time-series of climate fields for simulated years 1973-1993 were obtained for the area spanning 30ºN-70ºN and 200ºE-250ºE. CGCM1 climate variables were standardized to zero mean and unit standard deviation. The standardized climate variables were then projected onto principal components derived from the NCEP/NCAR Reanalysis data. Scores for the first 20 components were retained as inputs to the analog downscaling models. Daily time-series of maximum temperature, minimum temperature, and precipitation amounts for the 1973-1993 period were downscaled using analog models and the CGCM1 principal component scores. NCEP/NCAR reanalysis principal component scores and the surface climate variables from Danard and Galbraith's dataset were used as historical analogs. Following downscaling, simulated time-series of maximum and minimum temperature were rescaled so that their means and standard deviations matched those of the observed series for the baseline period. Simulated time-series of precipitation amounts were inflated to match observed mean values.

Using Danard and Galbraith's data as inputs, the UBC Watershed Model was calibrated to fit observed discharge records obtained from the Water Survey of Canada. The UBC Watershed Model was chosen because of its suitability for use in simulating the hydrology of mountain watersheds. The model uses elevation bands to capture orographic effects (Quick, 1995). The mean elevation, area, forested fraction, canopy density, orientation, permeability, etc. of elevation bands were obtained from a 25-m DEM and 1:250,000 thematic mapping (Whitfield *et al*., in press). Following calibration, temperature and precipitation series downscaled from the NCEP/NCAR Reanalysis and CGCM1 were used as inputs to drive the UBC Watershed Model.

The assessment of model results consists of four parts. First, we performed statistical tests on the differences in five-day average temperature, precipitation, and streamflow between the model outputs and observations using the non-parametric Mann-Whitney test (Leith and Whitfield, 1998). Second, we compared the model performance in terms of accumulated hydrological attributes such as runoff, snow water equivalent, and April snow cover. Third, we considered the statistical properties of the entire series of daily streamflows via the mean, maximum, skewness and kurtosis to determine if the model reproduces the observed streamflow distribution. Last, we estimated the magnitude of the 10 year flood using standard methods and the series of annual peaks for the observed series and each of the three modelled series using the Gumbel and Log-Pearson Type 3 statistical distributions.

3. RESULTS AND DISCUSSION

The results presented here are for observations and modelled outputs for the period 1973-1993 for six watersheds. There was generally good agreement between the maximum and minimum temperatures from Danard and Galbraith's dataset and those downscaled from the NCEP/NCAR Reanalysis. Figure 1 shows one such comparison from the Coquitlam watershed, where the NCEP/NCAR downscaled temperatures are significantly lower in the spring (starting with 5-day period 14). This feature is present in all of the downscaled maximum temperature series (Table 2). Few significant differences were noted between the observed and modelled minimum temperature series (Table 2). All CGCM1 downscaled input data revealed an underestimation of temperature in the late winter and early spring periods and an overestimation of temperature in the late summer and again in late fall and early winter periods (Figure 1). These differences are reflected in Table 2, which shows large numbers of statistically significant differences in five-day average temperatures between Danard and Galbraith's dataset and those downscaled from CGCM1 climate fields; in most watersheds nearly one-half of the time periods show statistically significant differences.

All downscaled CGCM1 data underestimated temperature in the late winter and early spring periods and overestimated temperature in the late fall and early winter periods (Figure 3). Significant differences were noted between observed temperature and precipitation and those downscaled from the GCM simulated climate fields (Table 2). These differences indicate the bias that exists between observations and simulated climate for present conditions. Wilby *et al.* (1999) showed that downscaled climate scenarios are sensitive to many factors, including the choice of predictor variables, downscaling domains, season definitions, the chosen mathematical transfer functions, calibration periods, and elevation biases. Palutikof *et al*. (1997) and Winkler *et al*. (1997) investigated the impact that biases between GCM and observed climate variables can have on downscaling models. It was concluded that standardization of predictor variables, as was done in the current study, can compensate for some of the differences between simulated and observed climate conditions. Still, differences between higher-order moments of the GCM predictors and the observed predictors can lead to biases in the downscaled climate series.

The precipitation input series were very similar between watersheds, and captured the seasonal variability of rainfall in Georgia Basin quite well (Figure 2). There were effectively no statistically significant differences between Danard and Galbraith's precipitation series and downscaled NCEP/NCAR precipitation series (Table 2). There were significant differences in precipitation between Danard and Galbraith's dataset and the series downscaled from CGCM1 climate fields (Table 2), with significant positive differences tending to occur in the winter, and significant negative differences tending to occur in the summer (e.g. Figure 2).

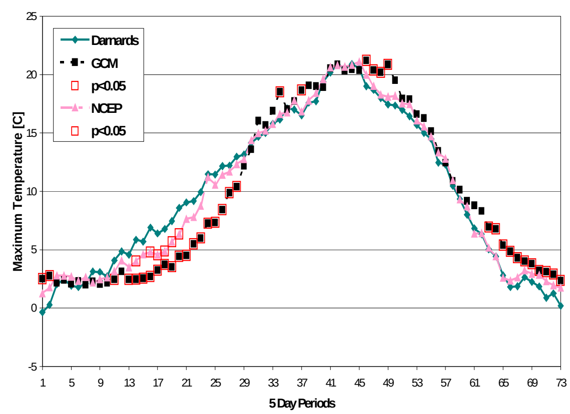

Figure 1. Five-day maximum temperatures from Danard and Galbraith's dataset, downscaled from NCEP/NCAR, and downscaled from CGCM1 for one of the Coquitlam River climate sites (1973-1993).

Table 2. Distribution of significant differences for maximum temperatures, minimum temperatures, and precipitation from each watershed between Danard and Galbraith's dataset and the downscaled NCEP/NCAR dataset, and Danard and Galbraith's dataset and the downscaled CGCM1 dataset. The values are the number of five-day periods showing statistically significant increases (+) and decreases (-) for the simulated 1973-1993 period.

	Maximum Temperature				**Minimum Temperature**				**Precipitation**			
	NCEP/NCAR		**CGCM1**		**NCEP/NCAR**		**CGCM1**		**NCEP/NCAR**		**CGCM1**	
	+	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+**	**-**
Englishman	1	7	18	16	2	1	15	17	0	0	2	7
Capilano	0	6	18	16	1	0	14	17	0	0	3	5
Coquitlam	0	6	19	17	2	1	14	18	0	0	4	6
Cheakamus	0	5	16	16	2	1	14	17	1	0	3	6
Elaho	0	4	16	16	3	1	15	16	0	0	4	5
Lillooet	0	4	16	15	2	1	16	16	1	0	3	6

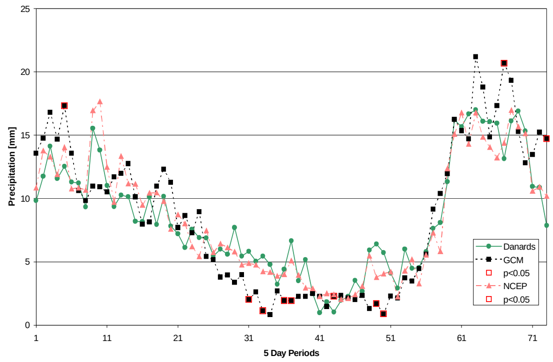

Figure 2. Five-day precipitation amounts from Danard and Galbraith's dataset, downscaled from NCEP/NCAR, and downscaled from CGCM1 for one of the Coquitlam River climate sites (1973-1993).

Measures of central tendency from the three models show good agreement with observations in most cases. For example, Table 3 shows the actual and modelled runoff for the 1973-1993 period. Observed runoff tends to be slightly higher than the modelled runoff for the six rivers. This difference is generally less than 10%, with the exception of the Elaho where the difference in on the order of 30%; however, amongst the modelled results there is little difference. There was general agreement amongst the models with respect to snow water equivalent (Table 3) and for the amount of snow-cover during the last 10 days in April (Table 3). The one notable exception was April snow cover in the Capilano ranging from a minimum of 37% for Danard and Galbraith's inputs to 79% for downscaled CGCM1 inputs. This difference reflects the slower warming of spring temperatures (Figure 1) in this particular watershed. In general, we find good agreement between observations and the models when the measure of interest is averaged temporally over long periods or spatially across the extent of the watershed.

Important differences between observations and model results were found for measures that consider seasonality of the streamflow regime and aspects of the statistical streamflow distribution. The modelled hydrograph for the Coquitlam River (Figure 3) and the Elaho River (Figure 4) demonstrate the differences in observed and modelled seasonal patterns. These figures show the agreement between discharges modelled using climate inputs from Danard and Galbraith's dataset and those using inputs downscaled from the NCEP/NCAR Reanalysis, a result that confirms the similarity of the climatic inputs in these two cases. This similarity exists across all the study watersheds, with the Elaho being the watershed with the greatest number of statistically significant differences (Table 4).

When discharge is modelled using downscaled CGCM1 inputs there is a definite temporal shift in timing of hydrologic events. This shift is characterized by a much delayed snowmelt peak, particularly noticeable in the timing of the onset of freshet. This pattern was observed in all six watersheds, but to a lesser extent in watersheds where snowmelt is not as important, e.g. Englishman and Capilano Rivers (Table 4). Furthermore, seasonal runoff timing and snowmelt runoff peaks exhibit marked differences between the two models (see Figure 3 and Figure 4). The delay in the spring snowmelt in the CGGM1 case reflects lower temperatures downscaled using climate fields from the GCM. Wilby *et al.* (1999) identified in their study that downscaling of GCM model control run data yielded significantly lower estimates of daily mean maximum and minimum temperatures than were observed during the recent normal period. From the two examples, it is evident that a bias exists between streamflow outputs from the watershed model when using CGCM1 downscaled inputs and outputs when using the inputs from Danard and Galbraith's dataset and those downscaled from the NCEP/NCAR Reanalysis project. In Figure 3 and 4 we see examples of this bias in the inability of the watershed model to simulate a close representation of the observed baseline period when using downscaled inputs from CGCM1. Simulated GCM climate fields used as inputs to the downscaling are sufficiently different from those represented in the NCEP/NCAR Reanalysis to cause significant biases in simulated streamflows from the UBC watershed model.

Statistical properties of central tendency such as the mean discharge are similar between the observed series and the modelled series (Table 5). However, there are frequently large differences between observed and modelled maximum values, as well as between higher order attributes such as skewness and kurtosis. In all six watersheds the maximum observed discharge was much larger than the maximum discharge generated from any of the three simulations. Skewness and kurtosis (Table 5) between observed and simulated streamflows can be quite similar (e.g. Lillooet and Elaho). However, the degree of correspondence between observations and model outputs is lessened as rainfall increases in importance as the flow generating process. Attributes such as skewness and kurtosis suggest that the effect of rainfall on the streamflow distribution is not being captured. It is possible that an alternate hydrology model might deal with this effect.

We estimated the magnitude of the 10-year flood from the observed and modelled series using Gumbel and Log-Pearson Type 3 distributions. The magnitude of the estimates was similar; only the Gumbel results are presented here. The relative magnitude of the estimated floods are shown in Figure 5; each estimate for each river was divided by the estimate of the mean 10-year flood from observed records. This allows us to compare the results from the three modelled series to the observed series.

Table 3. Comparison of observed and modelled runoffs (mm), annual snow water equivalent (mm), and percent of basin snow cover during the last 10 days in April for 1973-1993.

	Runoff (mm)				Snow Water Equivalent (mm)			Percent Snow Cover April 21-30		
	Observed	Danard & Galbraith	NCEP/ NCAR	CGCM1	Danard & Galbraith	NCEP/ NCAR	CGCM1	Danard & Galbraith	NCEP/ NCAR	CGCM1
Englishman	1344.1	1222	1212	1271	576	529	388	20	34	30
Capilano	3706.2	3568	3487	3392	4559	5224	5867	37	54	79
Coquitlam	3830.8	3691	3426	3690	11379	13254	14099	92	91	89
Cheakamus	2126.0	2022	1984	1887	6056	5984	6218	92	97	97
Elaho	3559.7	2648	2569	2474	9154	9153	10451	86	94	99
Lillooet	1826.3	1796	1860	1874	7913	7996	8148	65	66	69

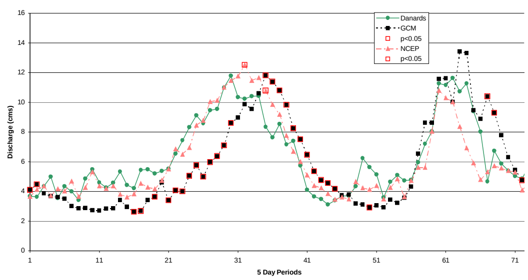

Figure 3. Modelled five-day discharges in Coquitlam River using Danard and Galbraith's data, downscaled NCEP/NCAR data and downscaled CGCM1 data for 1973-1993.

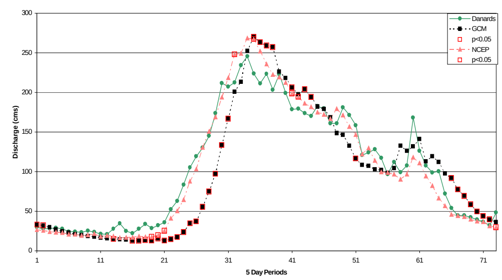

Figure 4. Modelled five-day discharges in Elaho River using Danard and Galbraith's data, downscaled NCEP/NCAR data and downscaled CGCM1 data for 1973-1993.

In each river both the magnitude and variability of the 10-year flood much is greater in the observed dataset than in any of the three modelled streamflow series. Between the modelled outputs, the estimates using Danard and Galbraith's dataset are generally slightly higher than those using the downscaled NCEP/NCAR and downscaled CGCM1 datasets. As rainfall decreases in influence between the six rivers, the modelled and observed results converge. In Figure 5, the rivers on the left show a larger difference between the observed and modelled results than those on the right. Resulting from the local nature of precipitation generating processes, statistical downscaling models can have difficulty modelling streamflow peaks driven by rainfall events (Cannon and Whitfield, 2002). In addition, the choice to inflate the precipitation series to preserve total rainfall amounts (but not the variance) likely contributed to the discrepancy. These factors account for much of the bias in flood estimates between watershed model outputs based on Danard and Galbraith's dataset and those from downscaled NCEP/NCAR and CGCM1 datasets. However, they do not explain the much larger discrepancy between observed streamflows and those obtained from the watershed model. This large bias could result from deficiencies in handling of extreme events in Danard and Galbraith's dataset, or from the watershed model being unable to accurately account for rain and rain on snow processes. In addition, calibration of the watershed model may have been conducted to try and match average flow conditions rather than extreme events. Further investigation is needed to determine the source and relative contribution of errors leading to the bias between observed and modelled flood estimates.

Table 4. Significant differences in discharges between models using Danard and Galbraith's data and those using downscaled NCEP/NCAR and downscaled CGCM1 data. The values are the number of five-day periods showing statistically significant increases (+) and decreases (-) for the simulated 1973-1993 period.

	NCEP/NCAR		**CGCM1**	
	+	**-**	**+**	**-**
Englishman	0	0	6	1
Capilano	0	0	4	9
Coquitlam	2	0	15	15
Cheakamus	0	1	12	21
Elaho	4	4	16	18
Lillooet	3	0	12	6

4. CONCLUSION

Discrepancies between GCM representations of climate fields and observations are well know (e.g. Palutikof et al. 1997; Wilby et al. 1999, Loukas et al. 2002). To assess the extent of these biases and their effects on subsequent hydrologic simulations we compared downscaled climate data from a GCM, downscaled climate data from the NCEP/NCAR dataset, and observed climate data using the

Table 5. Statistical attributes of observed and modelled daily streamflow in the study watersheds.

	Kurtosis				**Maximum Discharge** (cms)			
	Obs.	*Danard/ Galbraith*	*NCEP/ NCAR*	*CGCM1*	*Obs.*	*Danard/ Galbraith*	*NCEP/ NCAR*	*CGCM1*
Englishman	60.2	8.5	3.6	3.5	393.0	138.7	111.5	102.8
Capilano	32.5	12.7	5.6	10.1	393.0	239.1	155.3	183.6
Coquitlam	29.8	13.9	5.1	7.8	107.0	76.7	40.9	40.6
Cheakamus	17.8	4.2	0.4	0.5	260.0	184.2	98.3	111.5
Elaho	9.9	2.8	0.2	0.5	1040.0	751.7	547.6	709.5
Lillooet	3.9	2.5	2.4	2.5	1260.0	756.7	862.5	769.6
	Skewness				**Mean Discharge** (cms)			
	Obs.	*Danard/ Galbraith*	*NCEP/ NCAR*	*CGCM1*	*Obs.*	*Danard/ Galbraith*	*NCEP/ NCAR*	*CGCM1*
Englishman	6.4	2.5	1.7	1.6	13.1	12.4	12.7	13.0
Capilano	4.6	2.9	2.1	2.7	19.5	19.3	18.9	18.3
Coquitlam	4.4	3.0	2.0	2.4	6.4	6.4	6.1	5.9
Cheakamus	2.5	1.6	1.0	1.1	18.6	18.2	17.9	17.1
Elaho	2.4	1.4	0.9	1.0	60.1	101.3	101.8	98.2
Lillooet	1.5	1.7	1.6	1.7	120.9	123.5	127.6	129.2

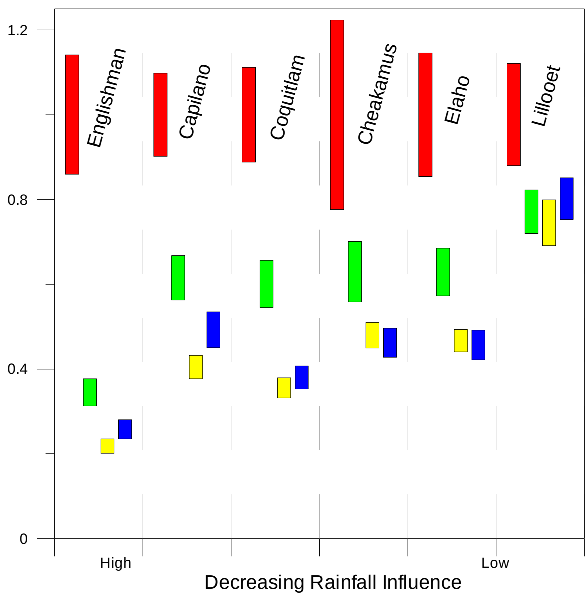

Figure 5. 95% confidence intervals for 10-yr flood estimates obtained for the six study watersheds via the Gumbel distribution; results are ordered from left to right by watershed according to rainfall influence. For each watershed, bars from left to right show estimates for 1) observed streamflows, 2) modelled streamflows using Danard and Galbraith's dataset, 3) modelled streamflows using the downscaled NCEP/NCAR dataset, and 4) modelled streamflows using the downscaled CGCM1 dataset. Magnitudes have been scaled so that the the flood estimate for the observed streamflows is equal to one.

statistical methodology suggested by Leith and Whitfield (1998). In addition, statistical attributes of simulated streamflow and derivatives of daily streamflow using each of the three climate datasets as inputs were also compared and contrasted for six rivers in Georgia Basin.

Downscaled climate series from CGCM1 were significantly different from Danard and Galbraith's series and those downscaled from the NCEP/NCAR Reanalysis. Downscaled temperatures from the CGCM1 rise earlier in the spring, peak later in the summer, and are higher during the winter. For precipitation, significant positive differences tended to occur in the winter, and significant negative differences tended to occur during the summer.

The bias between simulated results from the hydrologic model and observations is small for measures that are averaged over space and time, such as runoff and snow water equivalence. There are substantial differences in the time structure of modelled results, especially noticeable for series generated from the GCM where the bias in temperature is reflected in delayed spring snowmelt. The bias between observations and model results is much larger for measures that are sensitive to the tails of the streamflow distribution. This is particularly noticeable in watersheds where rainfall is an important streamflow generating process. When compared against observations, models significantly underpredict maximum discharge, and the skewness and kurtosis of the streamflow distribution. Similarly, the magnitudes of flows with a 10-year return period are underpredicted by all models. This effect is greatest in rivers where rainfall is the dominant hydrologic process.

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