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SIMULATION OF HYDRO-ECOLOGICAL INDICES IN A LONG-TERM HYDROLOGIC MODEL USING DOWNSCALED CLIMATE DATA

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Abstract: The effects of climate change are likely to have a significant impact on environmental flows, which are often represented by hydrologic and ecological indices. Changes in flow regimes caused by climate change have implications for river ecology, and projections of future flow regimes must be reliable. Uncertainty must be quantified in order to determine strategies to maintain future environmental flow needs. To assess the potential impacts of climate change on important indices, downscaling of general circulation models (GCM) is required to use climate change projections in hydrologic models. This is due to the spatial mismatch between GCM output data and meteorological data required to drive hydrological models. There are a variety of downscaling methods and the choice of method depends on the scale of the hydrologic application. The objective of this research was to determine if hydro-ecological indices are preserved in downscaled climate data. This has applications to the preservation of environmental flows. Two New Jersey watersheds located within the Pinelands ecoregion, an ecologically sensitive area with many endangered and threatened species, were used in the analysis. Hydro-ecological indices were calculated for the Batsto River Watershed (an undeveloped watershed) and the Maurice River watershed (a developed watershed) and were analyzed using dynamical downscaling and various bias correction methods to determine which method best preserved historical ecological indices and determined future indices. Results indicated that accounting for the seasonal aspects of flow when dynamically downscaling will allow for more reliable values of hydro-ecological indices.

1 INTRODUCTION

Water resources planning and design includes the maintenance and regulation of environmental flows, which require long-term data and simulations for proper assessment. Environmental flows are necessary to maintain the healthy ecology of a river system. Ecologically relevant hydrologic indices (hydro-ecological indices) have been used to assess environmental flows and quantify long term patterns in stream flow. Hydro-ecological indices (also known as Ecologically Relevant Stream flow Statistics, ERSS) are a measure of the stream flow signal and represent the five major components of flow: frequency, magnitude, duration, timing and rate of change. These indices are expected to change due to climate change.

For instance, due to projected climate change impacts on ERSS, a minimum of 38 species were predicted to have significant declines in Missouri (USA). Mitigation measures can be created from future projections of ERSS. A full range of flow measures are important to estimate ERSS, particularly ERSS that represent extreme low and high flows which are crucial estimates for environmental flows and ecological function. The five major components of stream flow, particularly duration and magnitude of extreme events, are likely non-stationary in response to climate change. The research that has assessed the impact of climate change on hydro-ecological indices has focused primarily on multiple streams or regions, such as the continental United States and not looked at multiple GCMs, downscaling or bias correction methods. However, potential changes must be assessed using general circulation models, downscaling and hydrologic models.

Application of downscaled climate projections to assess changes in the flow regime have a high level of uncertainty. Statistical or dynamical downscaling of GCM model output is required to obtain climate conditions at the desired local scale. Dynamical downscaling uses higher resolution (smaller spatial grids) regional climate models (RCMs) that are driven by larger scale GCM grids (which contain climatic information) for a region of interest. Statistical downscaling uses model output from GCMs or RCMs to estimate climate conditions down to the scale of a single location. Dynamical downscaling is a large source of uncertainty and it is unknown if hydro-ecological indices are well represented by simulations driven by downscaled data.

Additionally, there is a need to more fully assess the ability of hydrologic models to simulate ERSS, and to assess models driven by dynamically downscaled climate projections in particular. Low flow indices were poorly predicted in a hydrologic model due to the choice of calibration criteria that focused on peak flows (Shrestha et al. 2014). Caldwell et al. (2015) found that the level of calibration had a greater impact on prediction of ERSS than the hydrologic model used. Uncertainties due to GCM downscaled data led to poorer prediction of ERSS using a hydrologic model (Shrestha et al. 2014).

The objectives of this research were to evaluate hydrologic model performance at representing several ERSS for (1) simulations driven by observed meteorological data and (2) simulations driven by dynamically downscaled data. Additionally, the effects of bias-correction of stream flows for simulations from (1) and (2) on estimates of ERSS were also examined.

2 METHODS

The Precipitation-Runoff modelling system (PRMS) was used in this analysis, which has been widely applied to assess potential climate change impacts on hydrologic responses (Daraio and Bales 2014; Koczot, et al. 2011; Hay and Clark 2003) and to assess hydro-ecological indices (Caldwell et al. 2015). PRMS is a distributed deterministic rainfall-runoff model that requires the meteorological data inputs of precipitation, maximum and minimum temperature and solar radiation at a daily time-scale. The CMIP5 multimodel ensemble data archive contains dynamically downscaled bias-corrected GCM meteorological output that can be used to drive the hydrologic models. ERSS were calculated from PRMS simulated stream flows using these inputs. An illustration of the modelling framework is in Figure *1*.

2.1 Site Description

Observed daily mean flows from two USGS gaging stations were used: the Batsto River at Batsto, NJ and the Maurice River at Norma, NJ (Figure *2*), both located in the Pinelands Ecoregion. The upper Maurice River watershed has a basin area of 290 km^2 and the Batsto River watershed has a basin area of 180 km^2. The upper Maurice River watershed is more urbanized compared to the Batsto. Both rivers were classified by the USGS as class B, which represents a stable stream with a high base flow, typically located on the coastal plain (Henriksen et al. 2006).

2.2 Simulations

Daraio (2017) used PRMS to simulate potential climate change impacts on stream flows in these two basins, and the calibrated models were used in this analysis. The models were driven by (1) observed historical meteorological data, and (2) dynamically downscaled bias corrected climate projections from 13 GCMs (available from the CMIP5 multimodel ensemble). Simulations for both watersheds were run for a historical period from water years 1956-2005. Stream flows were bias corrected by Daraio (Under review) using flow duration curves (FDC), which are cumulative distribution curves that show the relationship between flow magnitude and frequency. Quantile mapping was used for bias correction of the simulated stream flows based on observed historical data, and from simulations driven by dynamically downscaled data.

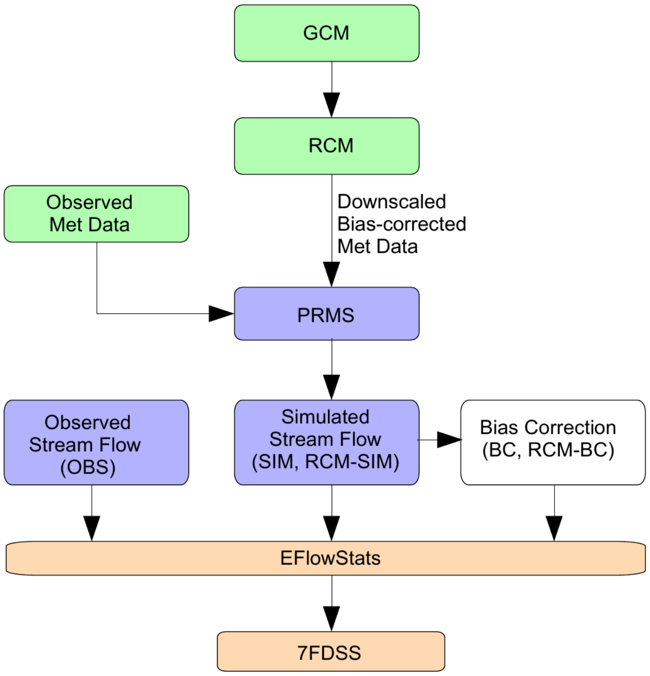

Figure 1: Diagram of Climate and Modelling Processes within the Study

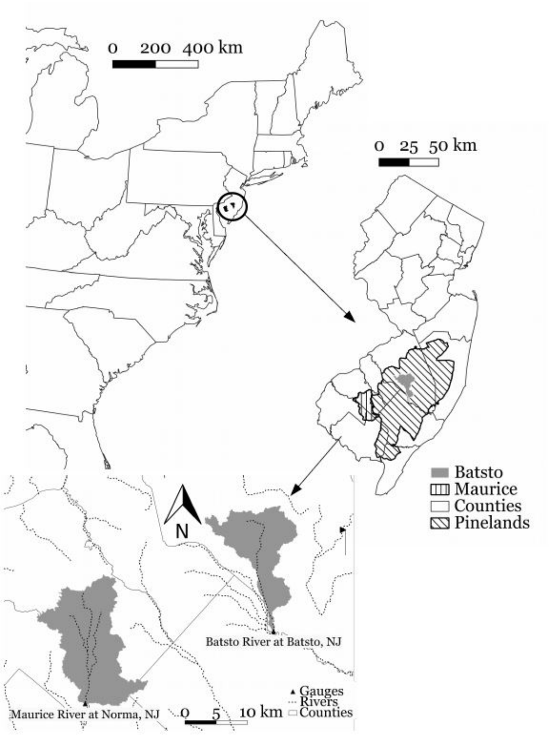

Figure 2: Site Map of the Study Areas, Batsto River Watershed (USGS Site 01409500) and Maurice River Watershed (USGS Site 01411500)

There were four sets of simulated stream flows for each basin, simulated stream flow driven by observed meteorological data (SIM), bias-corrected simulated stream flow driven by observed meteorological data (BC), simulated stream flow driven by dynamically downscaled meteorological data (RCM-SIM), and bias-corrected simulated stream flow driven by dynamically downscaled meteorological data (RCM-BC).

2.3 Hydro-ecological indices

There are a large number of hydro-ecological indices and frameworks in the available literature and there is no need to calculate all indices (Olden and Poff 2003). Indices were chosen based on the seven fundamental daily stream flow statistics (7FDSS) (Table *1*), identified by Archfield et al. (2014). These are mean (λ_1), coefficient of variation(τ_2), skewness(τ_3), kurtosis(τ_4), autoregressive lag-one correlation coefficient(r_1), amplitude(A) and phase(ω) of the seasonal record, which describe the stream flow time series and have minimal correlation between pairs (Archfield et al. 2014). These indices were calculated for observed stream flows and each of the stream flow sets using the package "EflowStats" (Thompson et al. 2013) in R (R Development Core Team 2008). Comparisons were made to the ERSS calculated from historical stream flow records for the two basins using percent error (simulated/historical-1) for each ERSS. A value of 0 indicated that the simulated ERSS equaled the ERSS calculated from observed stream flows.

To get a measure of the variation in these indices, and see if there were any apparent trends in the data, thirty year moving averages of the selected indices were calculated for the observed data, Figure *3*.

Table 1: 7FDSS and Ecological Significance (Archfield et al. 2014)

Indice	Ecological Significance
Mean (λ_1)	Distribution of Daily stream flow
Variation (τ_2)	Distribution of Daily stream flow
Skewness (τ_3)	Distribution of Daily stream flow
Kurtosis (τ_4)	Distribution of Daily stream flow
Autoregressive Lag-One(r_1)	Proxy for the duration and rate of change of stream flow
Amplitude (A)	Seasonal Signal
Phase (ω)	Seasonal Signal

3 RESULTS

3.1 Observed ERSS

Figure *3* shows the variability of the ERSS through time. The Maurice River Watershed has larger mean flows (λ_1) than the Batsto and lower skewness (τ_3) and kurtosis(τ_4). In recent years (post 1995) the watershed that had greater variability (τ_2) changed between the two basins. The seasonal ERSS (A and ω) is greater in the Maurice River Watershed than the Batsto. This may be due to the greater urbanization in the Maurice basin.

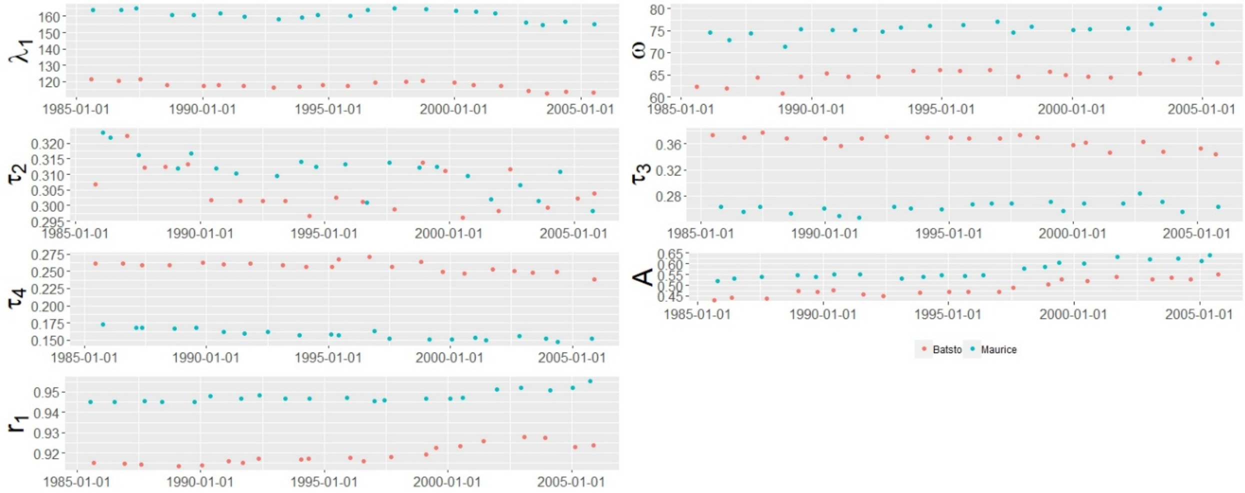

Figure 3: Historical 30 year moving averages for 7FDSS on the Batsto and Maurice River Watersheds

3.2 ERSS from Hydrological Model Simulations input with Observed Climate Data

There were differences between the ERSS calculated from observed stream flow and the ERSS with simulated flows (SIM). Without bias correction PRMS underestimated all calculated ERSS except for the autoregressive lag-one correlation coefficient (r_1) and variation (τ_2) in the Batsto River Watershed (Figure *4*). The Batsto River Watershed had the largest error on $\tau 3$, ω and A, with percent errors of -31%, -41% and -72% respectively. The model showed a greater degree of correlation between daily flows. Similar results were found in the Maurice River Watershed, where without bias correction, all indices were underestimated (λ_1 -7%, τ_2 -10%, τ_3 -8%, τ_4-6%, r_1-6%, A-47%), except for phase (ω) which had an error of 17%. The percent error was greater in the Batsto River Watershed compared to the Maurice River Watershed.

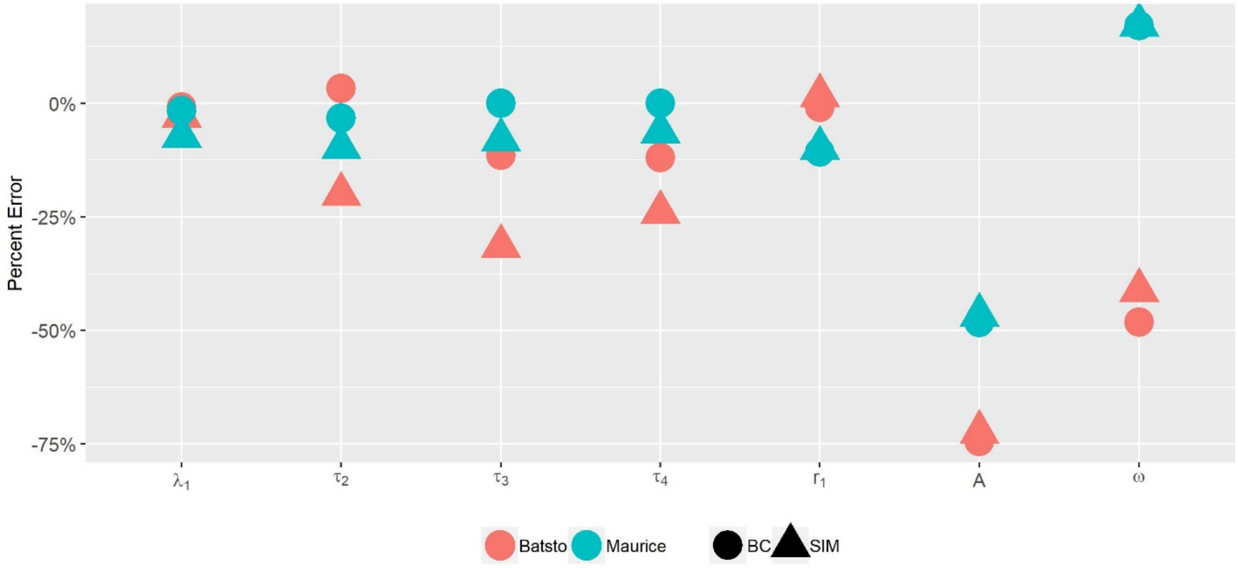

Figure 4: Percent Error from the 7FDSS calculated from historical climate simulations inputs into the PRMS (hydrological model) for the Batsto and Maurice River Watersheds

With bias correction, the error for most model simulated ERSS were reduced. While the skewness (τ_3) improved to have a reduced error from -31% to -11%, the percent error A and ω of the simulation decreased from -72% and -41% to -74% and -48% respectively. In the Maurice River Watershed the percent error of the phase and amplitude both stayed the same, at 17% and -47% error respectively. The remaining ERSS in the Maurice River Watershed stayed the same or got closer to a value of 0 (λ_1 -2%, τ_2 -3%, τ_3 0%, τ_4 0%, r_1-11%).

Figure *4* shows that the first four statistics, which represent the daily distribution of the stream flow, were better approximated by BC simulated stream flows in the Batsto and Maurice River Watershed. However, the more seasonal aspects of the flow (phase, and to a lesser extent, amplitude) were better approximated by uncorrected (SIM) stream flows.

3.3 ERSS from Downscaled Simulations

Estimated ERSS percent error values are shown for both watersheds in Figure *5* for RCM-SIM and RCM-BC. Forty RCM simulations were run from 13 GCMs that provided an ensemble of ERSS represented in boxplot format, Figure *5*. All hydro-ecological indices were underestimated except for ω (3% error) in the Maurice River Watershed and r_1 (4% error) in the Batsto River Watershed without bias correction (Table *2*). The Batsto River Watershed underestimated ERSS more than the Maurice River Watershed. For example, a -46% error in the Batsto River Watershed and a -18% error in the Maurice River Watershed for *A*. Without bias correction, there was an increase in percent error from the observed ERSS. Large errors were in the ERSS that simulated daily stream characteristics as well as the seasonal signal. In the Batsto River

Watershed τ_2, τ_3 and τ_4 had percent errors of -34%, -36%, -38% respectively. Similar results appeared in the Maurice River Watershed with the same τ values having percent errors of -27%, -19% and -4% respectively. However, with bias correction the results improved.

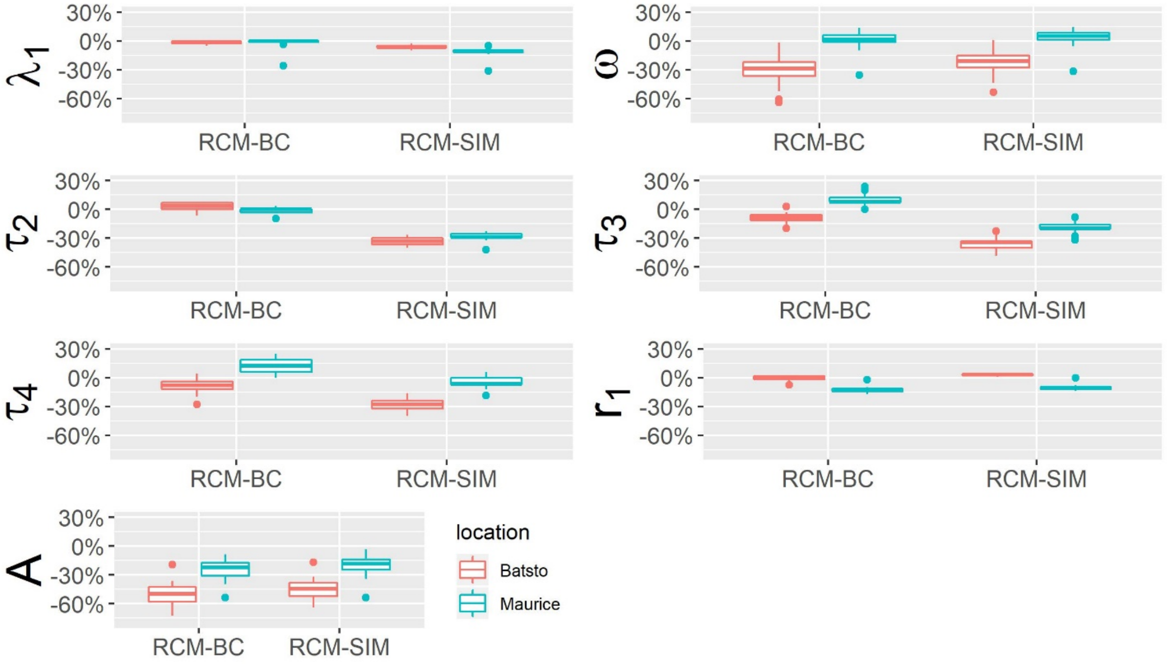

Figure 5: Error Ratios for the 7FDSS for Batsto and Maurice River Watershed with bias correction done on the RCM model driven stream flows

Bias correction improved the calculation of ERSS for the downscaled simulations. The first four ERSS improved with bias correction ($\lambda_1, \tau_2, \tau_3, \tau_4$). In the Batsto River Watershed the percent error of these first four statistics were -4%, -7%, -15%, -14% and in the Maurice River Watershed the same percent errors were -3%, -12%, -2% and 6%. However, the seasonal aspects of the flow (A and ω) did not improve in either watershed (Table 2). The Batsto River watershed had a -49% error on the amplitude of bias corrected stream flows (RCM-BC).

Table 2: Percent error for each of the 7FDSS for bias corrected (BC) and non-bias corrected (SIM) simulations for the Batsto and Maurice River Watersheds (D)

	Batsto		Maurice	
	RCM-SIM	RCM-BC	RCM-SIM	RCM-BC
λ_1	-6%	-4%	-10%	-3%
τ_2	-34%	-7%	-27%	-12%
τ_3	-36%	-15%	-19%	-2%
τ_4	-28%	-14%	-4%	6%
r_1	3%	1%	-10%	-12%
A	-46%	-49%	-18%	-22%
ω	-22%	-28%	4%	3%

4 DISCUSSION

The results indicated that the majority of ERSS calculated from simulations (SIM and BC) underestimated those determined from observed historical streams. This is consistent with PRMS simulations of ERSS done by Caldwell et al. (2015), though it is not likely that the cause of the underestimation is related in the different basins. The calibration criteria in both models may explain some of the similar results. Caldwell et al. (2015) was calibrated to annual, monthly, mean monthly and daily flow volumes, while Daraio (2017) was calibrated to daily and mean monthly flows. One variable well represented (without bias correction) was the mean (λ_1), with a maximum error of -10% in the RCM-SIM on the Maurice River Watershed. The average error for λ_1 is -5% across all watersheds and simulations. The lower error ratio on λ_1 and the larger percent error on the remaining 7FDSS may be due to the calibration criteria in the PRMS model being daily flow and mean monthly flows (Daraio 2017). This calibration criteria does not prioritize the seasonal signal or extreme high and low flows. It was expected that certain indices would respond better to different bias correction techniques that account for the seasonal aspects of flow, and this was found. Seasonal characteristics of flow are often more poorly represented by hydrologic models than magnitude and that was found in this study with the greater percent error found in A and ω (Vigiak et al. 2018). Overall, the hydrologic model was better able to capture ERSS that represented the daily distribution of flows. Simulating ERSS from observed meteorological data showed that bias correction improved the results and lowered error ratios. Similar results were found when ERSS were calculated from dynamically downscaled flows.

Both RCM-SIM and RCM-BC consistently underestimated the ERSS in both watersheds. Without bias correction (RCM-SIM), ERSS estimates for the Batsto Watershed had greater error than for the Maurice River Watershed. For simulations using observed meteorological data, the ERSS estimated with BC performed better than ERSS estimated using uncorrected simulations (SIM) with the exception of phase and amplitude. Bias correction did not improve the representation of the seasonal aspect of the stream flow signal for either simulations driven by observed meteorological data or RCM driven simulations. This points to a limitation in the PRMS model. While bias-correction did not improve these measures of seasonality, Daraio (Under review) was able to use bias-corrected stream flows to improve the models' ability to simulate seasonal cycles in flow.

As expected, the RCM driven models did not perform as well on ERSS estimation in comparison to simulations driven by historical meteorological data. The greater percent errors in RCM-SIM and RCM-BC suggests that the RCM introduces more error into the hydrological model. This is consistent with other analyses that downscaling and GCM structure are greater sources of uncertainty than hydrological parameters and model structure (Kay et al. 2009). Overall, bias correction improved the ERSS calculations. However, they did not adequately improve seasonal aspects of the flow, and in fact they increased error in these hydro-ecological indices (ω, A). Different bias correction techniques may have to be employed to improve upon these statistics.

One of the limitations of these results stems from the inclusion of a relatively small number of indices, even though they are considered representative of the primary aspects of the flow regime. The 7FDSS represent a preliminary set of hydro-ecological indices that may not best represent ecological conditions in the Pinelands. Additionally, natural variability of indices was not considered but will be in future analysis. Application of different calibration criteria more relevant to ERSS may improve the application of the models to estimates of hydro-ecological indices.

5 CONCLUSIONS AND FUTURE WORK

The importance of environmental flows and the natural flow regime has only been recognized in the past twenty years, and research projects to incorporate these topics into climate change research are even more recent (Poff et al. 1997). Hydro-ecological indices can be used to simulate environmental flows and estimates must be reliable for applications to water resources planning and management. Using GCM simulations compared to observed meteorological data increased uncertainty into the model framework which led to greater percent errors. ERSS that described daily stream flow were better simulated by bias corrected stream flows compared to ERSS that described seasonal aspects of flow.

We are continuing our research to include more indices, including a suite of indices based on the Spearman's correlation matrix. We are also further exploring the effectiveness of stream flow bias-correction at different temporal scales (Daraio, under review) at improving estimation of ERSS. In particular, indices related to the seasonal aspects of flow were not well-represented and future work will be done to better represent these seasonal ERSS. The long-term goal is to use this preliminary work toward development of more robust climate change impact studies. Additionally, a more thorough analysis of baseline variability will be done to fully quantify the uncertainty in indices estimated using observed stream flows. Future work will also include choosing statistics more relevant to the Pinelands region.

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