Coralville Lake Climate Change Pilot Study

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Executive Summary

This study evaluates the use of future climate projections to assess the potential impacts of climate change on the operation of a USACE multipurpose reservoir in east-central Iowa. The Coralville Reservoir, on the Iowa River just above Iowa City, IA, has been in operation since 1958. The two largest floods during the period of operation have occurred in the last 20 years, with the largest merely four years ago.

Climate conditions in the Iowa River basin have changed significantly since the reservoir was placed into operation. Analysis of historical precipitation and flow data demonstrate increased reservoir inflow volumes compared to pre-project conditions upon which the project was originally designed. Observed changes in reservoir inflow has resulted in periodic modifications to the water control plan; however, the threat of continued climate change in the future, and the uncertainty associated with those changes, has the potential to result in increased future risks to meeting project purposes.

Using a calibrated hydrologic model of the Iowa River basin and dynamically-downscaled climate data, the risk to the reservoir system associated with future climate scenarios was analyzed. Reservoir operations for a number of future climate scenarios were simulated in order to test the robustness of the reservoir system to potential climate change effects and to identify potential adaptation strategies.

The study concludes that the numerous limitations associated with climate and hydrologic modeling makes it difficult to fully assess the risks for a project due to climate change using modeling tools alone. A project-based resilience-robustness approach that considers the vulnerabilities of the project to changes in climate, such as the approach by Brown et al. [2011], gives a better picture of the climatic risk for a project. Specific to reservoir management, this study concludes that long-term reservoir planning is not as valuable a tool to meeting the missions of a reservoir as short-term weather forecasting and a framework that allows for real-time, risk-based, decision making for reservoir operations.

Background

Study Area

Coralville Dam is a 1,400 ft long, 100 ft high rolled earthfill dam impounding Coralville Reservoir on the Iowa River located 83.3 miles above its confluence with the Mississippi River and 5 miles above Iowa City, IA. There are 3,115 mi^2 of mainly row-cropped agricultural land draining into the Iowa River above the dam [Water Control Manual]. An additional 9,400 mi^2 of uncontrolled drainage (below Coralville Reservoir) flows from the Iowa-Cedar watershed to the Mississippi River [USGS].

The primary purpose authorized by Congress (PL 75-761) is flood risk management for areas below the lake on the Iowa and Upper Mississippi Rivers. Other congressionally authorized purposes include low flow augmentation, fish and wildlife management (PL 85-624), and recreation (PL 78-534). Construction on the dam began in July 1949 but was delayed by the Korean Conflict. The reservoir began operation in September 1958 [Water Control Manual].

The reservoir is regulated by a gated conduit outlet with a discharge capacity of 20,000 cubic feet per second (cfs) at full flood control pool (712 ft NGVD). At pool elevations above full flood control pool the emergency spillway is activated and uncontrolled release begins. The 500 ft long uncontrolled concrete chute spillway has a discharge capacity of 244,000 cfs (peak of standard project flood) [Water

Control Manual]. The spillway has been activated twice in the history of the project, once each during the 1993 and 2008 floods.

During normal (non-flood or drought) operations the reservoir is regulated to maintain a seasonal conservation pool elevation (see table 1). During flood operations, the release schedule for the reservoir changes based upon forecasted pool elevations (i.e., storage utilized) and downstream constraints to control flooding. When the pool elevation is forecast to exceed elevation 707 ft (NGVD) major flood operations are initiated, and flows are regulated to maximize use of the remaining storage. During non-major flood operations, maximum releases are controlled by downstream constraints, including seasonal constraints due to agricultural production and river stage control points on the Iowa River (at Lone Tree, IA, and Wapello, IA) and the Mississippi River (at Burlington, IA). Additionally, releases are temporarily reduced in order to manage flash flood flows at Iowa City.

When reservoir inflows fall below minimum conservation releases, the reservoirs drought contingency plan is activated providing for low-flow augmentation of releases with the highest priority given to meeting downstream water supply requirements.

Table 1: Coralville Lake seasonal conservation pool elevations

Date	Regulation (Elevation ft NGVD)	Action Purpose
15 Feb – 20 Mar	Lower from 683 to 679	Increase storage for spring snowmelt
20 Mar – 20 May	Hold elevation 679	Duration of spring snowmelt period
20 May – 15 Sep	Hold 683	Storage for low-flow augmentation
15 Sep – 15 Dec	Hold 683-686	Increase in lake area for migratory waterfowl
15 Dec – 15 Feb	Hold 683	Storage for low-flow augmentation

Current Climate

Iowa City, just downstream of Coralville Dam, has a mean annual temperature of 10 °C (50 °F) and averages about 885 mm (34.9 in) of precipitation per year [cumulative data since 1893 from Iowa Environmental Mesonet AgClimate data]. Near the headwaters of the Iowa River basin is Northwood, IA, which has a mean annual temperature of 6.7 °C (44 °F) and averages about 820 mm (32.3 in) of rainfall per year [cumulative data since 1893 from Iowa Environmental Mesonet AgClimate data]. The climate across the basin is generally homogeneous as it lacks significant topography to affect precipitation and temperature patterns. The basin has a humid continental climate (Köppen classification 'Dfa'), which is characterized by large seasonal temperature differences including hot, humid summers and cold, sometimes frigid, winters.

Average annual temperature, total annual precipitation, and the number of days per year with precipitation have increased in Iowa from the late 19th to the early 21st century, and at the Iowa City gauge within the Iowa River basin, these trends are statistically significant at 95% confidence.

Since 1893, mean annual temperature has been rising at an average rate of 0.18°C (0.32°F) per decade at Iowa City. Figure 2 shows mean annual temperature since 1893 at Iowa City as well as the 30-year average and a linear trend line. Prior to 1960, only 6 years out of 67 (9%) measured a mean annual temperature at or over 52 °F (11 °C), but 1960 and later, 24 of 52 years (46%) have met or exceeded that threshold.

In Iowa, the biggest changes in temperature are due to wintertime and nighttime temperature increases. There are more frost-free days per year (about 5 more at the start of the 21st century than in the mid 20th century, and about 8-9 more than beginning of the 20th century). Warmer temperatures increase the length of the growing season, due to fewer days of frost. There is also earlier seasonal snowmelt, and lakes and streams remain frozen for less time. There has been a decrease in the number of extreme high temperature events (days above 100°F). Increased summer precipitation and soil moisture have suppressed surface heating and reduced daytime summer maximum daytime temperatures. From the Climate Change Impacts on Iowa 2010 report:

> *If Iowa were to experience a severe drought, as has occurred frequently in the past, the slow and steady rise in statewide annual mean temperature, now masked in summer by moist surface conditions, could lead to an abrupt switch to extreme summer heat comparable to the summers of 1983 or 1988.*

On average, annual total precipitation has been rising by 10.9 mm (0.43 in) per decade. Figure 3 shows annual total precipitation since 1893 at Iowa City, as well as the 30-year average and linear trend for those totals. Of note is the year 1993, which was an anomalously wet year across the whole Midwest (culminating in the Flood of 1993) and remains the wettest year on record by more than 350 mm (almost 15 in). There has been an increase in year-to-year variation in annual total precipitation as well. Visually this is represented by increasing noise in the annual total precipitation timeseries, and quantitatively it is an increase in 30-year coefficient of variation (CV) in annual precipitation from around 0.11-0.17 in the early 20th century to around 0.19-0.24 in the early 21st century.

On average there has been one more rainy day per year every 6.4 years. Figure 4 shows the number of days per year with greater than trace precipitation at the Iowa City gauge. While currently there are not as many rainy days as the late 1940s, total annual precipitation has increased steadily, which is due to a combination of more rainy days and increased frequency of moderate to intense rainfall.

Streamflow is largely driven by rainfall, although for any one event antecedent conditions play an important part in runoff-generating processes. Over time there has been an increase in average annual streamflow volume on the Iowa River as well as an increase in annual peak discharge. Figure 5 shows the annual average flow of the Iowa River past Marengo, IA. This average discharge mirrors the long-term trend in precipitation in both average and variability. The 15-day peak discharge past Marengo is an important metric for operations at Coralville Reservoir on the Iowa River, and its trend is shown in figure 6. There is a clear increase in the average annual 15-day maximum flow, as well as an increase in the interannual variation for that parameter.

Current Problem/Concern

Historical Iowa River flows into Coralville Lake show an increase in the mean and variance of annual 15-day peak discharge between the “design period” (pre-reservoir streamflow records) and the period over which the reservoir has been operation (1959-present). Of particular significance are the Floods of 1993 and 2008, whichboth exceeding the largest historical event upon which the original water control plan was developed. The largest historical floods available in the record at the time of project design were predominately spring snowmelt (or rain on snow) driven events, whereas the record flooding in 1993 and 2008 resulted from persistent late spring and summer thunderstorms occurring over a heavily saturated watershed. Increased total precipitation has led to higher soil moisture content, which has runoff implications both through affecting antecedent conditions preventing infiltration, and an increase in the installation of agricultural tile drains.

The Floods of 1993 and 2008, coupled with significant flooding in 2010, raised questions regarding the operation of Coralville Reservoir and (from the public's perspective) whether the reservoir was giving adequate weight to the risk of urban flooding from major flooding versus favoring protection to downstream agricultural areas during minor flood events. Public and community interest led the State of Iowa's Governor to formally request that the Corps of Engineers conduct a re-evaluation of the water regulation procedures at each of the four large flood risk management reservoirs within Iowa (Coralville, Red Rock, and Saylorville in MVR; Rathbun in NWK). Uncertainty in future climate conditions has the potential to be a major risk driver in the evaluation of alternative water management strategies to better management flood risks in the Iowa River Basin.

Purpose and Scope

Central Question

The study is concentrating on the following central question: How do we incorporate climate change considerations into reservoir operating policies that will be robust and adaptive to potential climate changes in the interest of long term risk management?

Previous Work

This pilot study is the first attempt at evaluating the potential effects of climate change on the operation of Coralville Lake or on hydrology in the Iowa River basin. However, other studies have been completed that evaluate the regulation plan for the lake in response to past floods. In 1997, a Section 216 (Review of Completed Works) study was completed for Coralville Lake and its regulation plan. Several alternative initiatives were proposed in order to enhance benefits at the lake, but none garnered a Federal interest. Additionally, a study to revise the water control plan was not initially funded. However, a 1999 regulation study resulted in implementation of two changes to the water control plan, resulting in the most recent (2001 version) water control plan.

Methodology and Approach

The approach to this study followed this general roadmap to achieve results:

1) Investigate original design assumptions for the dam and determine which metrics are sensitive to climate change
    a) Evaluate changes in meteorology from historical to potential future
    b) Examine possible bias or error in GCM/RCM results
2) Obtain downscaled climate data for the Iowa River basin, the area of interest
3) Run observed meteorology and downscaled climate scenarios through a calibrated hydrologic model to obtain flow information at critical locations for a variety of scenarios
4) Use post-processing tools to learn more about the effects of changes in climate and hydrology
    a) Reservoir sedimentation model – how is storage in the reservoir changing due to sedimentation?
    b) Flow routing model – how are the operational conditions for the dam changing?
    c) Reservoir operations model – how much influence does operation have on the possible changes at the reservoir?

The first step in evaluating the potential impacts of climate change for the reservoir was to understand the design parameters and assumptions upon which the original project design and water control plan were based. Using the design documentation and regulation manuals for the project, critical design parameters and assumptions were tabulated (see table 2). These parameters serve as guidance on whether or not the project is currently functioning as intended, and if these assumptions might be violated in the future due to climate change. Tools were developed to answer the question of whether or not these parameters might be sensitive to changes in climate in the future.

Climate change is highly visible in its impacts on hydrology. Changing climate conditions affect the water balance by directly changing the amount of evapotranspiration and precipitation, and timing and type of precipitation that occur. In order to assess these impacts quantitatively, the climate simulations were coupled with a hydrologic model of the study area.

Table 2: Design parameter matrix

Design parameter	Original design assumption	Observation during operations
Frequency of uncontrolled release over emergency spillway	Uncontrolled release would occur about once in 30 years	2 spillway events since 1958 (~54 years, about 27 year average interval)
Sedimentation/loss of storage space in reservoir	Loss of storage would occur at a rate of about 750-1200 ac-ft/yr	Average yearly loss of approximately 1700 ac-ft
Timing/mechanism of annual flood flows	Heaviest floods would occur due to spring snowmelt and flood magnitude would be related to amount of snowpack	Largest floods occurred during the late spring or early summer due to persistent and intense thunderstorm events (e.g. 1993, 2008)
Spillway Design Flood/Dam Safety	The dam was designed with freeboard above a probable maximum flood computed from the transposition of a historical storm during worst case operational conditions, with a peak inflow of 326,000 cfs (top of dam elevation NGVD 743’)	Dam has never been overtopped; max pool elevation ~717’ (~26’ freeboard)
Conservation pool storage volume	Maintain minimum discharge of 150 cfs at Iowa City and Lone Tree from 07/01 – 02/28 (243 days) with strong drought conditions; equating to a volume of 17,000 acre-ft	Due to sedimentation, the elevation of the conservation pool has been increased in order to maintain design volume

Hydrologic Model

The hydrologic analysis was performed using a quasi-distributed continuous hydrologic model, the Soil and Water Assessment Tool (SWAT) [Neitsch et al. 2009]. It was forced using observed meteorological data and RCM-downscaled results from GCMs. No land use change scenarios were tested for the future cases. The minimum inputs to run SWAT include a digital elevation model, landuse/land cover, soil type and meteorology.

Table 3: Iowa River SWAT model input sources

Input	Source
Land use/land cover	NLCD 2006 (MRLC)
DEM	1 Arc second NED (~30m resolution)
Soil coverage	STATSGO data for the United States included with SWAT model

Meteorology inputs for the model came from a variety of sources in order to have a long enough record of all required forcing variables to calibrate the model. Observed meteorology was necessary in order to calibrate the model to observed streamflow. Once the model was calibrated to match historical rainfall-runoff responses the model was run with downscaled climate data to evaluate the effect of climate change on hydrology.

USDA-ARS SWAT format meteorological data were used in calibration and "observed meteorology" runs. The data provided from this source were daily maximum and minimum temperature and daily total precipitation. These data span 1/1950-10/2009. Relative humidity, solar radiation and wind speed, in addition to temperature and precipitation, were from Iowa Environmental Mesonet data available over the time period 1/1998-12/2010.

The model was first calibrated for daily discharge at the Marengo, IA gauge using historical observed meteorological data. Observed flow and meteorological data are at a daily timestep, and thus the model was run at a daily timestep.

Table 4: SWAT model calibration results

Event	Location	Nash-Sutcliffe	Volume Error	R^2
Calibration (1999-2001)	Marengo	0.85	+5.7%	0.87
Validation (2006-2008)	Marengo	0.80	-7.9%	0.84
Validation (2003-2005)	Marengo	0.64	-0.51%	0.75

While achieving relatively good scores on the selected calibration metrics, one significant weakness of the model is in estimating the highest peak flow values. The model was unable to capture the most extreme flows and the relatively large variance in observed daily streamflow. Baseflow recession and the timing of peak flows were generally well-matched to observed hydrographs; however, the volume error grew with overestimation of baseflow contribution and underestimation of the most extreme peak flows. Additionally, some peak flow events were missed within the simulations (and some existed in model results without corresponding observed peaks) because of the coverage of precipitation gauges.

The daily discharge simulated by SWAT was used in three post-processing routines to gain information about dam sedimentation and reservoir operations.

Sediment accumulation in reservoir

Although SWAT has sediment modeling methods included in the model (based on the universal soil loss equation), sparse information for calibration and other factors made it difficult to set up and calibrate the model for sedimentation. An alternative, approximate approach was favored in order to estimate sedimentation rates in the reservoir. A power law relationship between sediment discharge and streamflow modified from USBR [1987] was established using observations at the Marshalltown gauge, upstream of Marengo on the Iowa River. The Marshalltown gauge recorded sediment loading for a short period (less than 10 years). The curve was applied to discharges at Marengo to compute a total sediment inflow to Coralville Lake. A sediment trap efficiency for the dam based on the reservoir capacity and the inflow [Brune 1953, Dendy 1974] was applied to the Coralville inflow hydrograph to compute the amount of sediment accumulating in the reservoir. The results of this method when compared to historical sediment survey results is acceptable for computing an estimate of annual average sediment accumulation.

Flow routing (inflow-pool elevation-release rate computation)

An Excel spreadsheet was created that routes reservoir inflow based on the water control plan in the current regulation manual (January 2001 revision). The model first attempts to discharge enough storage to achieve the seasonal conservation pool elevation, based on the pool elevation of the previous timestep and the inflow to the reservoir. The formal rules for maximum release are checked, including seasonal rules for maximum release (growing vs. non-growing season) and flow at control points downstream on the Iowa River. The action is first checked if informal rules regarding changes in pool elevation and release are being broken, but major flood and drought conditions override any informal rules.

The model gives good results for events where reservoir regulation stayed true to the manual. Aspects of the water control plan occur variably from year-to-year based on communication with project stakeholders. The spring drawdown and the fall pool raise are variable, so the model acted on the middle date of the available range of dates in the regulation manual. In other historical cases, the reservoir was operated under a temporary deviation to store more water and avoid downstream flooding. Additionally the model could not account for the downstream flow constraints on the Mississippi River, where river stages may dictate a short-term (seven day) reduction in releases from Coralville to reduce peak Mississippi River flooding.

Reservoir Operations Model

The Rock Island District's CorSim (Coralville Simulation) reservoir regulation model was used to evaluate the degree of regulation flexibility available without any structural modifications to the dam. Figure 6 shows the downstream discharge-frequency curves for three water management scenarios applied to historical reservoir inflows. The first scenario is based upon the current reservoir water control plan. The second scenario maximizes discharge to retain available storage for later use during a large magnitude flood (this approach would tend to favor urban protection) and is simulated by removal of downstream flow constraints such that the release is limited only by the size of the discharge conduit and reservoir elevation (head). The third scenario maximizes protection to low-lying areas downstream of the reservoir (typically agricultural) and is simulated by maintaining downstream limits until such time as the spillway crest elevation is exceeded and uncontrolled releases result. The resulting plot demonstrates the bounds of possible discharge-frequencies that could result from changes to the water control plan for the existing structure. By comparing how these bounds change in response to future climate scenarios, we can evaluate the degree to which climate change may limit or broaden management opportunities. As will be discussed in subsequent sections, the lack of extreme flood events in the regionally downscaled limited the effectiveness of this evaluation tool.

Climate Change Scenarios

The climate data used for the evaluations in this study came from the North American Regional Climate Change Assessment Program (NARCCAP) dataset [Mearns et al. 2007, updated 2012]. The data were processed and exported in SWAT format by Dr Christopher Anderson of Iowa State University.

Emissions scenario

The greenhouse gas emissions scenario used to force the GCMs in the NARCCAP datasets is the A2 scenario. The A2 emissions scenario is a high-emission Special Report on Emissions Scenarios [SRES; Nakicenovic and Swart 2000] greenhouse gas (GHG) scenario family. It projects vastly increased GHG emissions throughout the 21st century, fueled by continuously increasing human population, an economic (as opposed to environmental) policy focus, and independent, regionally-focused nations. Although the A2 scenario (along with the A1FI and A1B scenarios) is near the highest projected rate of GHG emissions for the early 21st century (according to the SRES), there is evidence that global GHG emissions exceed those scenarios thus far this century [Raupach et al. 2007] The emissions scenario makes up the foundational assumption about the rest of the future climate simulations. It is the driving force behind the GCM simulation and has the greatest influence on the resulting simulations. For this study, A2 is a reasonable "worst case" assumption going forward.

Global climate models

A General Circulation Model (GCM) is a model that simulates Earth systems, generally the coupled oceanic-atmospheric processes (AOGCM) that most characterize climate. The coupled circulation models for atmosphere, land, ocean, ice, etc. are referred to as Global Climate Models.

In this study two GCMs were used for projections, the CGCM and CCSM models. CGCM is the Meteorological Service of Canada of Environment Canada coupled atmosphere-ocean climate model from the Canadian Centre for Climate Modelling and Analysis (CCCma) Climate Research Branch. CCSM (Community Climate System Model) is the National Center for Atmospheric Research (NCAR) coupled climate model that incorporates four separate climatological models for atmosphere, ice, land and ocean. The version used for the runs in this study is CCSM3, which have since been superseded by CCSM4 as part of the Community Earth System Model.

GCMs are generally run at a coarse scale spatially (on the order of 2°-5° resolution) and temporally (monthly) because of computational limitations. These results are not as useful on a local scale, especially for investigations of climate change impacts on regional or local hydrology, so a method to disaggregate these results needs to be used. Thus the GCM results are downscaled to a finer resolution, in the case of this study ~50km resolution with a daily timestep.

Downscaling method

The downscaling method in use for the NARCCAP data is dynamic downscaling (not a delta or statistical downscaling method). Here regional climate models (RCMs) are forced by the GCMs to produce finer-scale results. RCMs are higher-resolution numerical weather prediction models that are nested within a GCM, so that the GCM acts as a boundary condition over a focused area. This allows a higher-resolution simulation of local weather process that are often of most interest in understanding regional climate.

For the NARCCAP data, RCM runs are also forced with NCEP reanalysis data for atmospheric conditions for the late 20th century which give an estimate of the best simulation that each RCM can produce. The reanalysis data have the same fluxes and states that GCMs would produce but are based on data assimilation and atmospheric modeling over the 20th century. The data incorporate observed historical data to make a best estimate simulation of atmospheric conditions. Thus the NCEP reanalysis data are a good proxy for actual atmospheric conditions that can be used to force the RCM, which in turn gives a good estimate of the performance of the RCM over the particular application area.

The RCM runs can also produce time series of other fluxes and states (other than temperature and precipitation) that are of interest for modeling. For example, to run the SWAT model, it additionally needs solar radiation, wind speed, and humidity (dew point or relative humidity), which are readily available outputs from many RCMs. The regional climate models used for downscaling the GCM outputs in this report are the WRFG and CRCM models.

WRFG (developed by NCAR) is the Weather Research and Forecasting model, using the Grell parameterization scheme (superseding the WRFP, PNNL scheme). CRCM is the Canadian Regional Climate Model developed at the Université du Québec en Montreal.

Downscaled climate simulation results are gridded, so for the purposes of hydrologic modeling the centers of the RCM grid cells were used as gauge stations. Because different RCMs have different grid schemes, the number of gauges used to cover the basin varied between RCMs but there were generally at least six gauges over the basin. The RCM grids are at about 50km resolution. All six forcing variables (T_{max}, T_{min}, P, RH, R_s, W) were read by the model from the downscaled RCM data.

It is important to keep in mind that the resulting downscaled climate data sets are highly experimental and come with their own major limitations and caveats. This study attempted to investigate the utility of these downscaled data as applied to the Coralville project.

Results

Physical system/climate findings

Climate Data and Observed Meteorology

The initial analysis of the downscaled climate outputs revealed some shortcomings in the regional climate model representation of local meteorology. Using the RCM-downscaled NCEP reanalysis data, the precipitation results were compared to observed precipitation using long-term averages. As the reanalysis data acts as a proxy for observed data in place of a GCM, this analysis demonstrates the RCM's best ability to generate local meteorology.

WRFG in general was getting a good picture of how precipitation occurs in the study region – the temporal distribution throughout the year was accurate (figure 8), and it produced storm events consistent with those in the region (figure 9). It was, however, very dry compared to observation, being low by about 7 in of rain per year while producing about the same number of rain events (see table 5). It appears that the model reduces the amount of moderate precipitation events that occur, resulting in frequent very light or heavy events, with few events of a more moderate intensity. (For the record, the problem with WRFG's water balance has been figured out and a paper will be published on the matter soon. New model runs are currently being completed.)

CRCM performed poorly at simulating local meteorology. CRCM precipitation results were more like Seattle, with most rain coming early in the year and the annual total precipitation coming as a result of a large number of small precipitation events. Intense events were very infrequent, and the annual maximum precipitation was close to constant between years of simulation (figure 9). CRCM split the precipitation over about 200 days of precipitation a year, where 100-120 is a more reasonable number (table 5). The total water balance for CRCM was much closer than WRFG, being slightly wet by about 1 inch per year on average. Brochu and Laprise [2007] similarly documented the observed precipitation biases of the CRCM model over the Mississippi River basin and show a wet bias, as well as a misdistribution of rainfall toward the earlier part of the year.

Table 5: Comparison of annual rainfall statistics for RCMs forced with reanalysis data

	Average Rainy Days Per Year	Annual Average Precipitation	Average Date of 50% Rainfall Accumulation
Observed	109	32.1 in	7/9
WRFG-NCEP	108	25.7 in	7/7
CRCM-NCEP	199	33.1 in	6/24

Future Climate Scenarios

In general, the shift from an RCM-GCM pair from historical emissions to future emissions scenario was not producing changes in extreme precipitation consistent with expectations of climate change in the Midwest. This is likely due to a combination of factors, namely the limitation of the RCMs noted above, as well as the short simulation periods. It is unreasonable to expect to sample events with average recurrence intervals longer than 50 or 100 years in a 25-30 year sample. The resulting data are heavily sampled out of the middle of the distribution of results, which results in very “vanilla” scenarios being given to the hydrologic model. Figure 10 shows the frequency-intensity plot for annual maximum daily precipitation for the four RCM-GCM pairs running future scenarios compared to observed precipitation. Two of the four pairs show slight intensification at the lower frequency events compared to observed precipitation, but the RCM biases are apparent. The CRCM runs are in general low, as they did not produce higher intensity rainfalls normally associated with Midwest convective thunderstorms.

The underlying biases in the RCMs heavily influence the output results. The WRFG-downscaled GCM results reflect the overall dryness of WRFG, and CRCM-downscaled results have the above noted wet bias and temporal misdistribution of precipitation. Overall the performance of WRFG was limited only by the dry bias; however, CRCM was producing results wholly inappropriate for the region.

The additional limitation of the hydrologic model in simulating the highest peak events meant that climate data representing the middle of the distribution of data was being processed by a model that under-predicted variance and extremes, resulting in rather average-looking flows. This limits the ability to test the operation of the reservoir under events of the most interest (extreme flood and drought). Figure 11 shows the flow-frequency curves for 15-day peak flows for the four future scenarios when compared to observed streamflow. The reduction in variance in the streamflow results creates the reduced frequency of events observed on the tails of the inflow frequency curves. The reduction in variance is due to the forcing climate data and the spatial and temporal resolution of the data used in the hydrologic model.

Table 6 summarizes the output from the sediment post-processing (annual average sedimentation rate) and the reservoir routing post-processing (amount of time in flood, amount of time in drought, number of spillway events.) Spillway events are classified as being any event where water goes over the spillway, even if this amount is trivial. (This designation has the habit of including some events where the elevation of the pool would likely be very close to going over without any flow being passed by the spillway.)

Table 6: Full table of post-processed hydrologic model results

RCM	Forcing	Time Period	Years	Average Daily Discharge (cfs)	Average Sed Rate (ac-ft/yr)	% Major Flood	% Drought	Spillway Events	Years With Major Flood
Observed Operations		09/17/1958-12/31/2010	52.3	2055	~1200			2	
Observed Meteorology		01/01/1999-10/30/2009	10.8	2171	1350	0.76%	0.00%	1	1
CRCM	NCEP	01/01/1981-11/30/2003	22.9	2641	1561	2.77%	0.00%	0	5
CRCM	CCSM	01/01/1969-11/16/1999	30.9	1825	909	0.24%	0.00%	0	2
CRCM	CCSM	01/01/2039-11/16/2070	31.9	1856	947	0.00%	0.01%	0	0
CRCM	CGCM	01/01/1969-11/16/1999	30.9	2737	1887	1.15%	0.02%	1	11
CRCM	CGCM	01/01/2039-11/16/2070	31.9	2700	1745	1.83%	0.03%	1	12
WRFG	NCEP	01/01/1981-12/25/2004	24.0	1318	596	0.45%	0.00%	0	2
WRFG	CCSM	01/01/1969-11/16/1999	30.9	1289	663	0.55%	0.00%	0	4
WRFG	CCSM	01/01/2039-11/16/2070	31.9	1282	711	0.34%	0.05%	1	4
WRFG	CGCM	01/01/1969-11/16/1999	30.9	1146	455	0.00%	0.03%	0	0
WRFG	CGCM	01/01/2039-11/16/2069	31.9	1813	991	1.26%	0.00%	0	5

The resulting simulations did not point toward one clear consensus for the future of inflows to Coralville Lake. When examining the difference between the mid-21st century and 20th century simulations for an RCM-GCM pair (Table 7), there is no clear picture of the future for the system. The results for the same GCM but different RCM agreed somewhat; the CGCM results forecast an increased flood risk (increase in percent of time in major flood, and total years entering major flood operations) while the CCSM results show a slight decrease in time in major flood but also an additional spillway event.

Table 7: Changes in hydrologic modeling results due to GCM-RCM pair

Model pair	Mean discharge	% Major flood	% Drought	Spillway events	Years with major flood
CRCM-CCSM	+31cfs	-0.24%	+0.01%	NC*	-2
CRCM-CGCM	-37cfs	+0.68%	+0.01%	NC	+1
WRFG-CCSM	-7cfs	-0.21%	+0.05%	+1	NC
WRFG-CGCM	+667cfs	+1.26%	-0.03%	NC	+5

NC=No Change

If we consider the result of the simulations without taking into account the limitations in the data and the hydrologic model it would appear that modifications to the regulation plan would be sufficient to handle projected climate change. This is not a prudent lesson to take from the study, as the limitations associated with the climate data and the hydrologic model drive the overall results so much as to say the climate data offer us very little with which to try to test adaptation strategies. Thus, caution in the approach of data with such limitations is very important.

Method or process used

The methodology used in the study was based largely on what we viewed as a "traditional" type of climate change impacts analysis for hydrology, in which downscaled climate data were run through a calibrated hydrologic model for a watershed. These runs were done under existing basin conditions, and the resulting climate change scenario results were compared to historical runs and observed hydrology in order to assess the impacts that climate change could potentially have on the hydrology of a watershed. The resulting climate change scenario runs were not as useful for testing the reservoir system's response as we had hoped initially.

We did not observe any emergent processes in the climate change simulations. The streamflow results show about what is expected in terms of increased winter rainfall resulting in streamflow, and reduced spring snowmelt floods (figure 12). Snowmelt flooding, which dominated the early period of record, has become less prevalent in the Iowa River basin with the largest flood on record (1993 and 2008) resulting from later spring and early summer rains. The simulated increase in flow due to spring and summer storms is consistent with observations during the operational period of the reservoir.

Implications for future reservoir management

Large Flood Operations. The current water control plan for Coralville Lake is similar to other reservoir projects within the Rock Island District in that the release schedule limits downstream flows to "safe" discharges (no or minimal damage with limits tied to seasonal agricultural production) until such time that a significant portion of the flood control storage has been utilized. At this point, releases are quickly ramped up to reduce the likelihood of higher, uncontrolled releases that would result when the unregulated spillway is overtopped. The major flood release schedule contained in the water control plan is based upon an optimization of available reservoir storage to the largest flood that had occurred prior to construction of Coralville Dam.

As observed during the 1993 and 2008 major flood events, flood volumes in excess of the historically observed maximum can and will occur again in the future. The current water control plan, which emphasized optimization of flood volumes to historic events, does not necessarily optimized flood risk reduction during future major floods. In evaluating future climate change scenarios, it was anticipated that additional major flood events would be represented in the model simulations to evaluate alternative water control plans that would improve the risk performance of the reservoir across a wide range of large flood events. As discussed above, the future climate scenarios evaluated failed to produce events at the extremes of the inflow volume-duration-frequency distribution. As a result, the mid-century future climate scenarios evaluated do not provide a basis for defining a new optimized release schedule for future major flood events.

The inability of the future climate scenarios to provide such a basis points to the importance of short term climate forecasts and the need to develop tools capable of informing water managers with risk-based decision criteria to evaluate operational scenarios during major flood events. The required decision support tool needs to be capable of incorporating modern forecast information into a risk-based decision tool. Such a system requires a clear set of risk-based criteria, consistent with project authorities, upon which water management decisions will ultimately be made. Further required are tools capable of incorporating the hydrologic, hydraulic, economic, and public health and safety factors into the decision process. The proposed CWMS National Implementation Plan would substantially develop many of these critical tools.

Drought/Low Flow Augmentation. Consistent with the major flood operations discussion, the future climate scenarios evaluated failed to produce events at the extremes of the inflow volume-duration-frequency distribution such that a range of severe drought conditions could be evaluated to identify improvements to the water control plan to improve the robustness of the project to meet future drought conditions. Historically, the greatest threat to being able to meet future conservation needs has been sedimentation of the reservoir. The future climate scenarios indicate (with one exception) that sedimentation rates are likely to increase over historical rates consistent with projected increases in precipitation and stream flow. Historically, the Rock Island District has conducted pool raises to offset anticipated sedimentation and periodically conducts surveys to re-evaluate reservoir storage. Increases in future sedimentation will force decisions regarding future conservation pool raises (and the corresponding reduction in available flood storage) earlier than anticipated based upon historical sedimentation rates.

Dam Safety. Increases in temperatures and precipitation patterns from future climate change has the potential to increase maximum probable extreme event precipitation. This has major implications for dam safety if climate change results in increased probable maximum precipitation estimates. Due to the extreme nature of these design events (having an expected recurrence of approximately once every 10,000 to 100,000 years), it was not unexpected that the 30-year blocks of future climate information do not support a direct analysis of climate change on the adequacy of the project's spillway design flood to meet future climate conditions. Continued monitoring of the trends in extreme precipitation is important in order to detect changes in the intensity and frequency of heavy rainfall events.

Directions for future study

This pilot is being used as a stepping-off point for another study being performed under contract with IWR by Dr Casey Brown at the University of Massachusetts. Dr Brown's study will use Coralville Lake as a testbed to develop methods for vulnerability assessment and risk evaluation that can be applied to assist in water management risk-informed decision making. The vulnerability assessment part of this study will develop "bottom-up" methods for water management that identify what type of climate changes or variability cause problems for a system, by identifying thresholds where system performance begins to degrade. The assessment process is done irrespective of the results of downscaled climate data, reducing the dependence of these vulnerability studies on downscaled climate data. It instead addresses the specific vulnerabilities of the system to climatic variability. Additionally, Dr Brown's study will attempt to evaluate potential ways to evaluate the likelihood of future climate conditions in order to assess risk.

Lessons Learned

Physical system/climate findings

Lesson: The dynamically-downscaled NARCCAP dataset was limited in its representation of hydrologic extremes (major flood or drought). This may be due to sampling error (limitation of using 30 years blocks of future climate data to evaluate extreme events having a frequency of significantly greater than once every 30 years), or limitations in the datasets resulting from climate model biases that under represent precipitation variability. The expectation of this kind of climatic shift comes from literature and observed changes in the Midwest; however, we found that the NARCCAP dataset was insufficient for us to test these shifts in our system.

Lesson: It was observed that regional climate models may not adequately represent the local meteorology. The WRFG model performed better in terms of timing and frequency of precipitation, but overall the results were biased on the dry side. The results from CRCM were not at all similar to local weather. We found that screening the RCMs prior to use would have helped guide dataset selection and allowed us to use RCMs more "in tune" with local meteorology if they were available.

Method or process used

Lesson: The original plan for the study was based on this expectation and so the analysis was designed to answer questions related to it. We found our questions regarding climate vulnerabilities were too specific, and that more broad questions about these vulnerabilities are warranted. Asking "How do I deal with greater and more frequent extremes" is too specific and is biased by expectations about what the climate data will indicate; a broader question to ask is "What vulnerabilities exist with my project related to future climate variability and how can those vulnerabilities be managed".

Lesson: Understanding the limitations and biases of downscaled climate data would have changed the path of our study. In addition to broadening the questions that are asked of the climate data, we discovered that the approach to analyzing the climate data would be determined best by first understanding the project's sensitivity and vulnerability to climatic variation and then formulating alternatives to reduce the climate sensitivity (increase robustness) of the project.

Lesson: Hydrologic models as tools for assessing climate change impacts have significant weaknesses, even if calibrated to the system being analyzed. The inability for the hydrologic model used in this study to simulate high peak flows made even the largest precipitation events result in moderate or moderately-high flows. However, a hydrologic model calibrated to simulating peak discharge events will not be able to capture long-term flow parameters important for other reservoir management considerations, such as sedimentation and drought.

Lesson: The inability of the dynamically downscaled climate data to provide a basis for developing regulation procedures to reduce risk in future major flood events emphasizes the importance of short term climate forecasts and the need to develop tools capable of informing water managers with risk-based decision criteria to evaluate operational scenarios during an event. While this implies a level of flexibility in future water management operations that traditionally has not been built into water control plans, any such implementation would need to clearly establish the criteria by which water management decisions will be made. This is consistent with the current national effort to fully develop and deploy the CWMS National Implementation Plan.

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Appendices

Figures

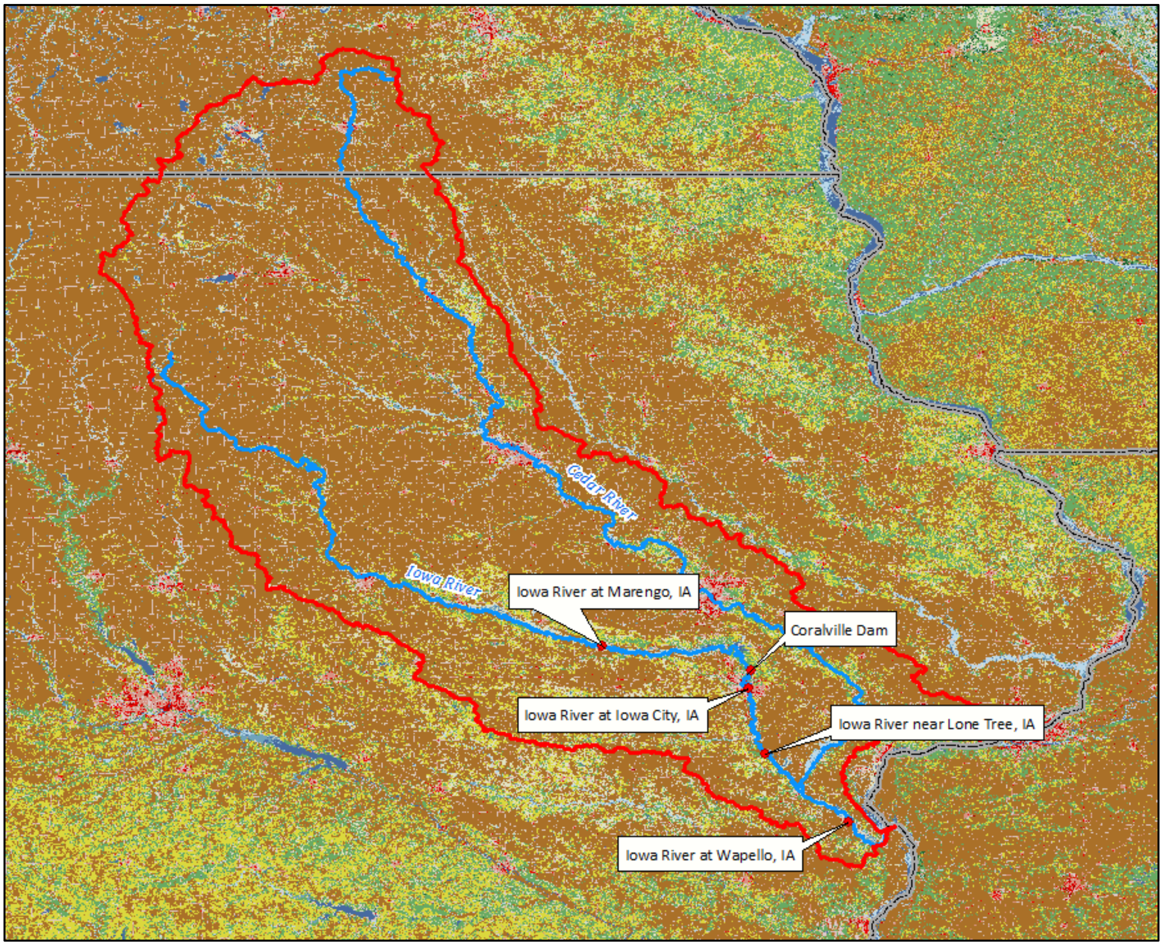

Figure 1: Iowa River basin (red) with NLCD 2006 landuse coverage and key operational constraint locations for Coralville Reservoir

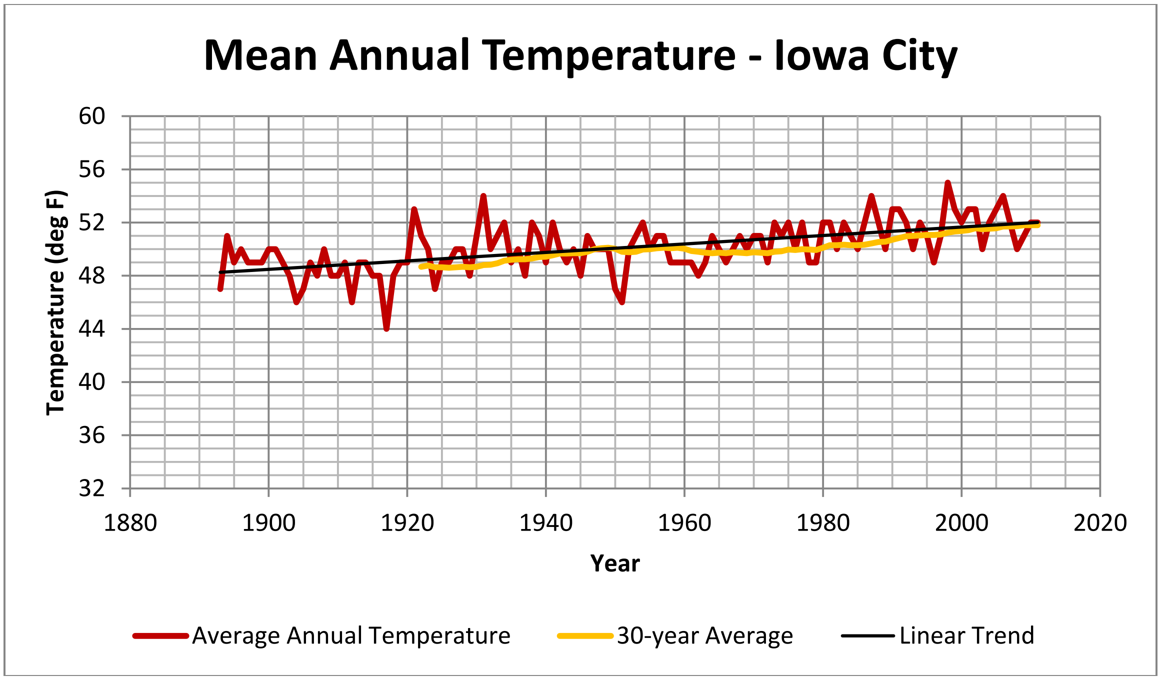

Figure 2: Mean annual temperature, Iowa City, IA gauge [IEM Climodat]

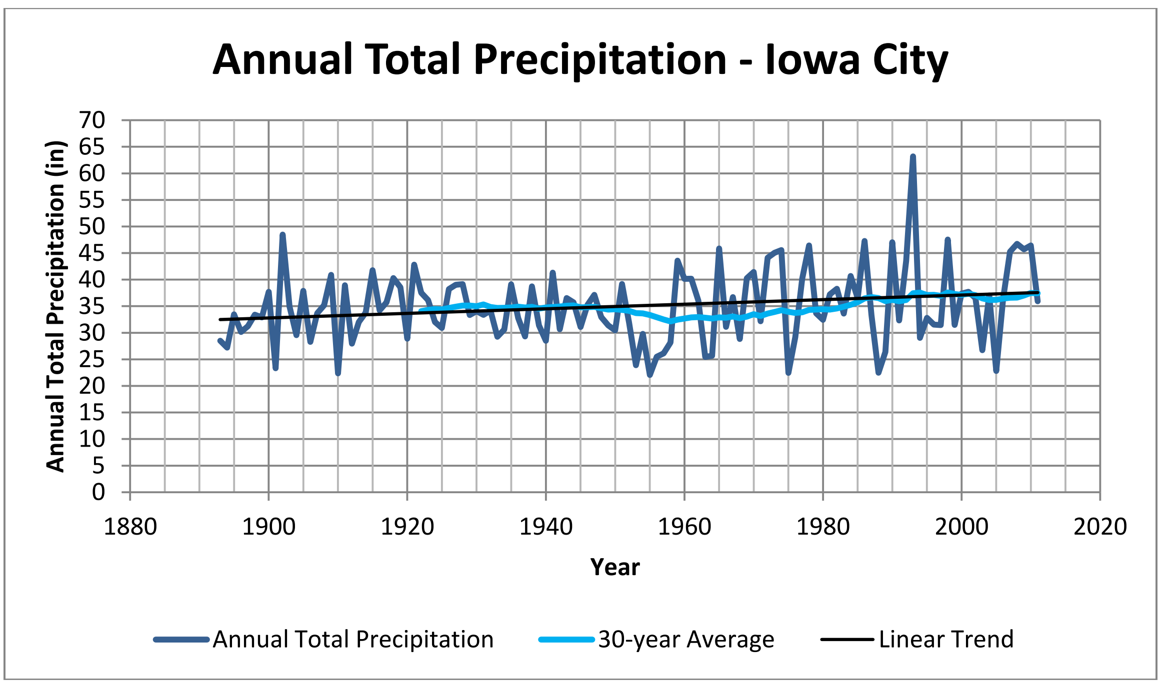

Figure 3: Total annual precipitation, Iowa City, IA gauge [IEM Climodat]

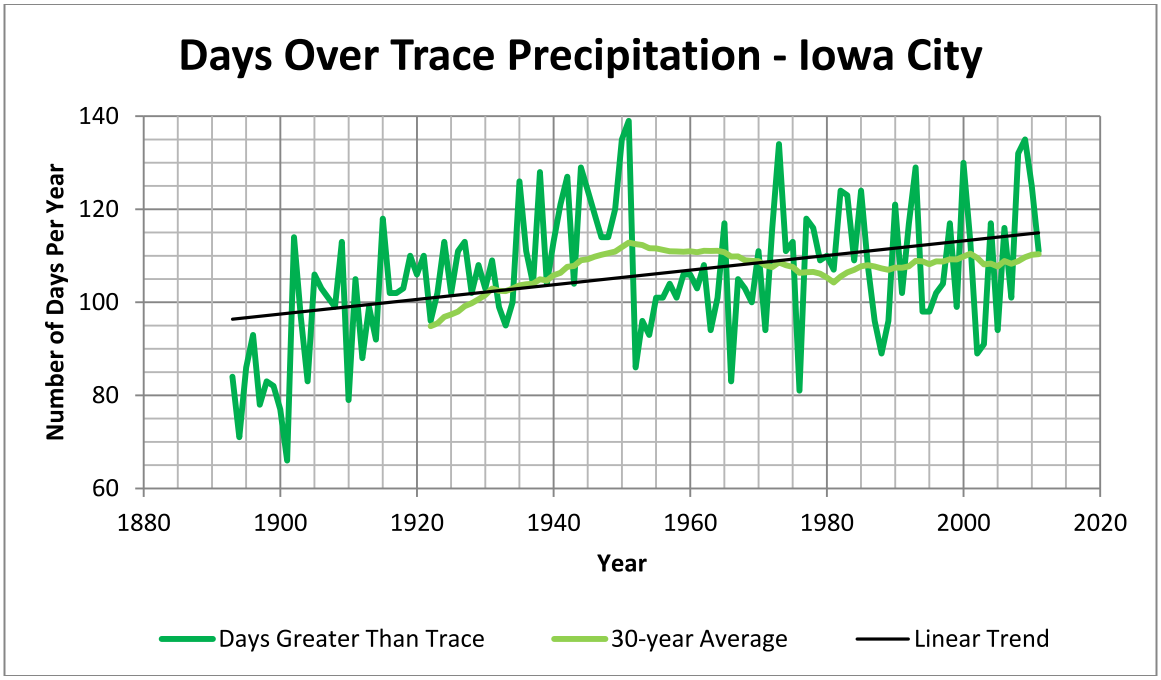

Figure 4: Number of days greater trace precipitation, Iowa City, IA gauge [IEM Climodat]

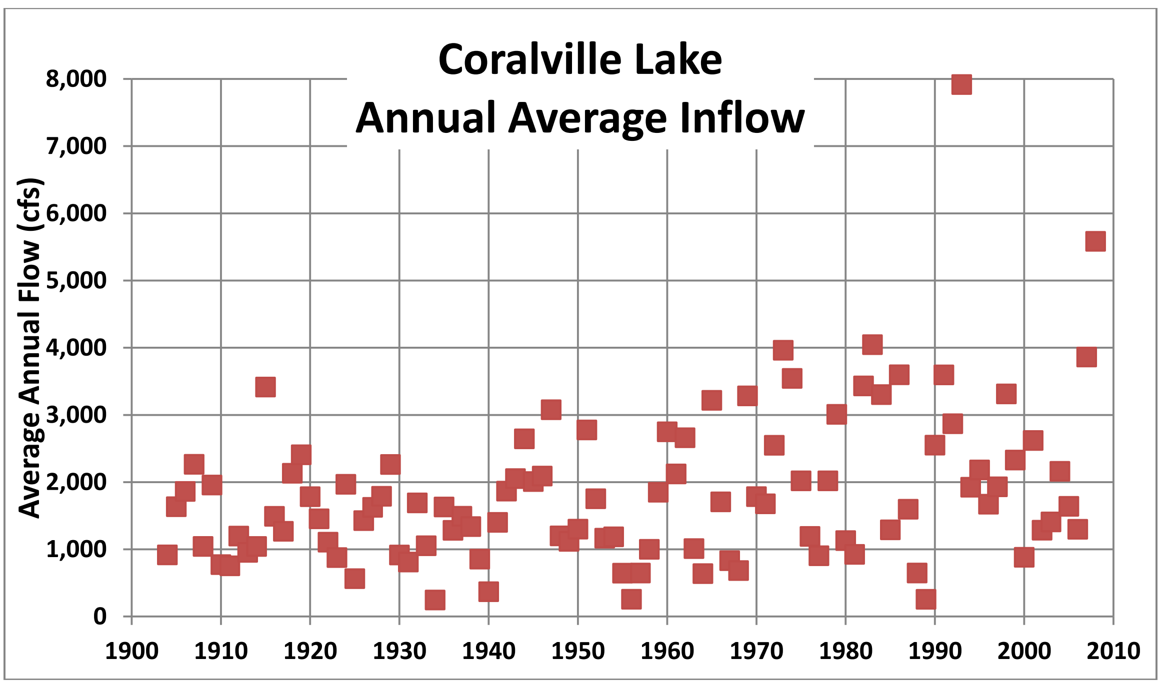

Figure 5: Annual Average discharge, Iowa River at Marengo

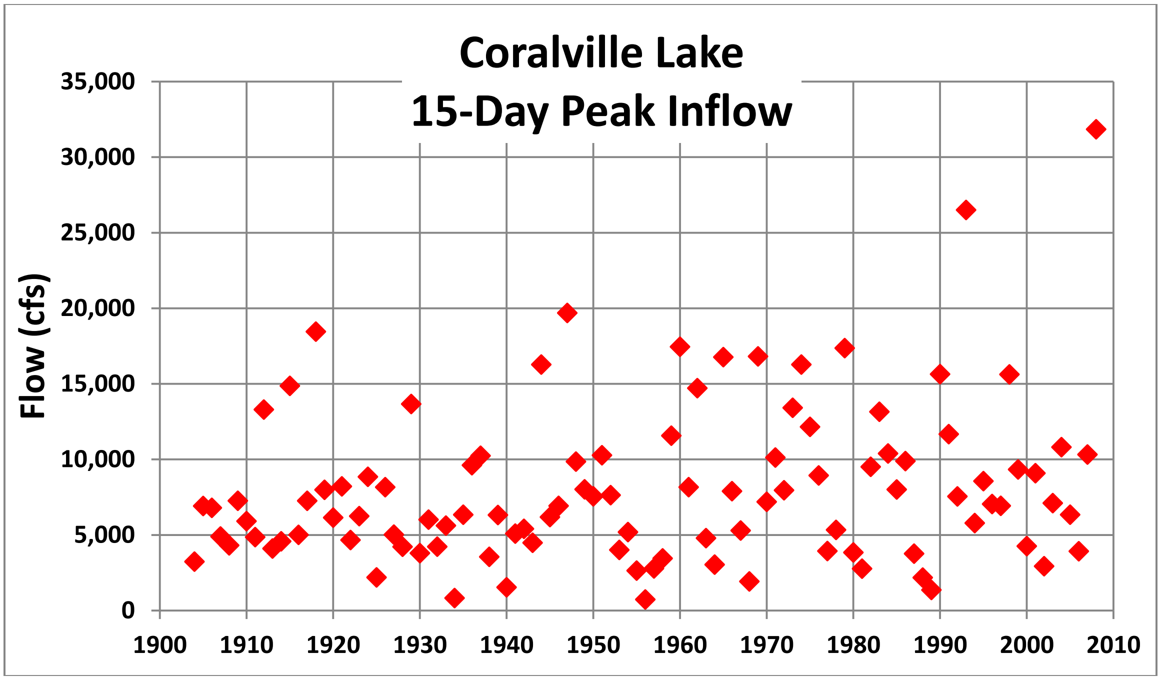

Figure 6: 15-day Peak Discharge, Iowa River at Marengo

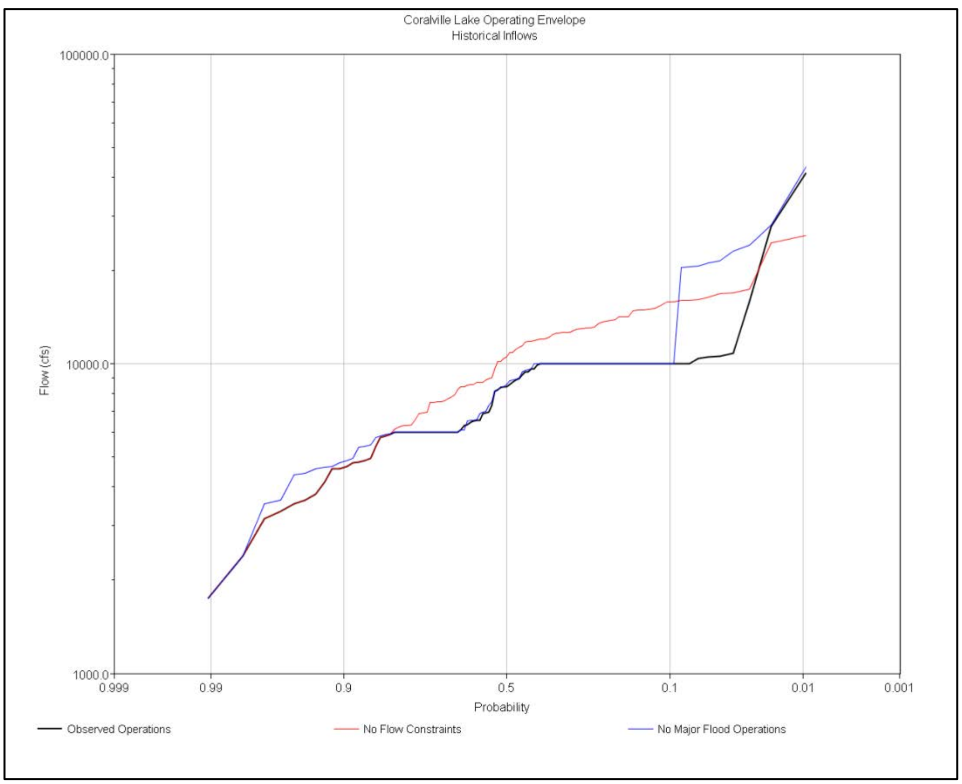

Figure 7: Coralville Lake operational envelope for releases. Black = observed operation, blue = releases held back, red = no flow constraints observed

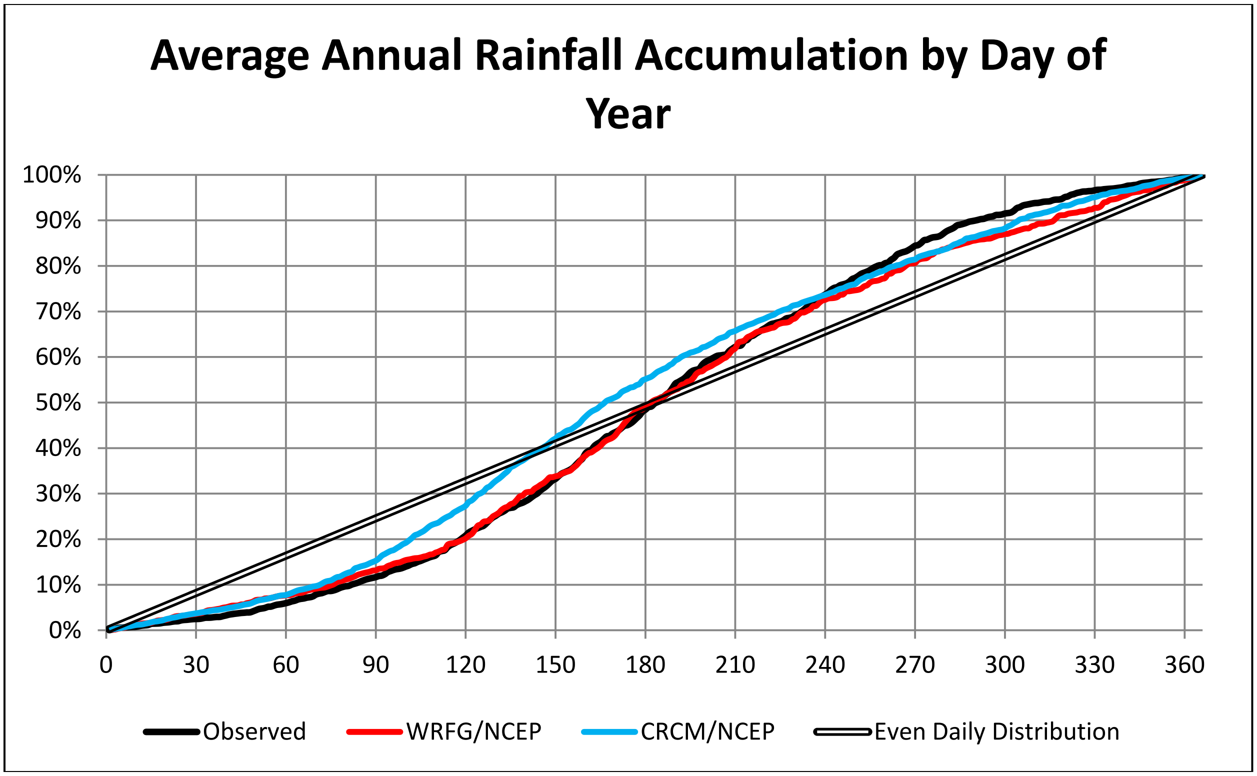

Figure 8: Average annual rainfall accumulation by day of year for RCMs forced with reanalysis data

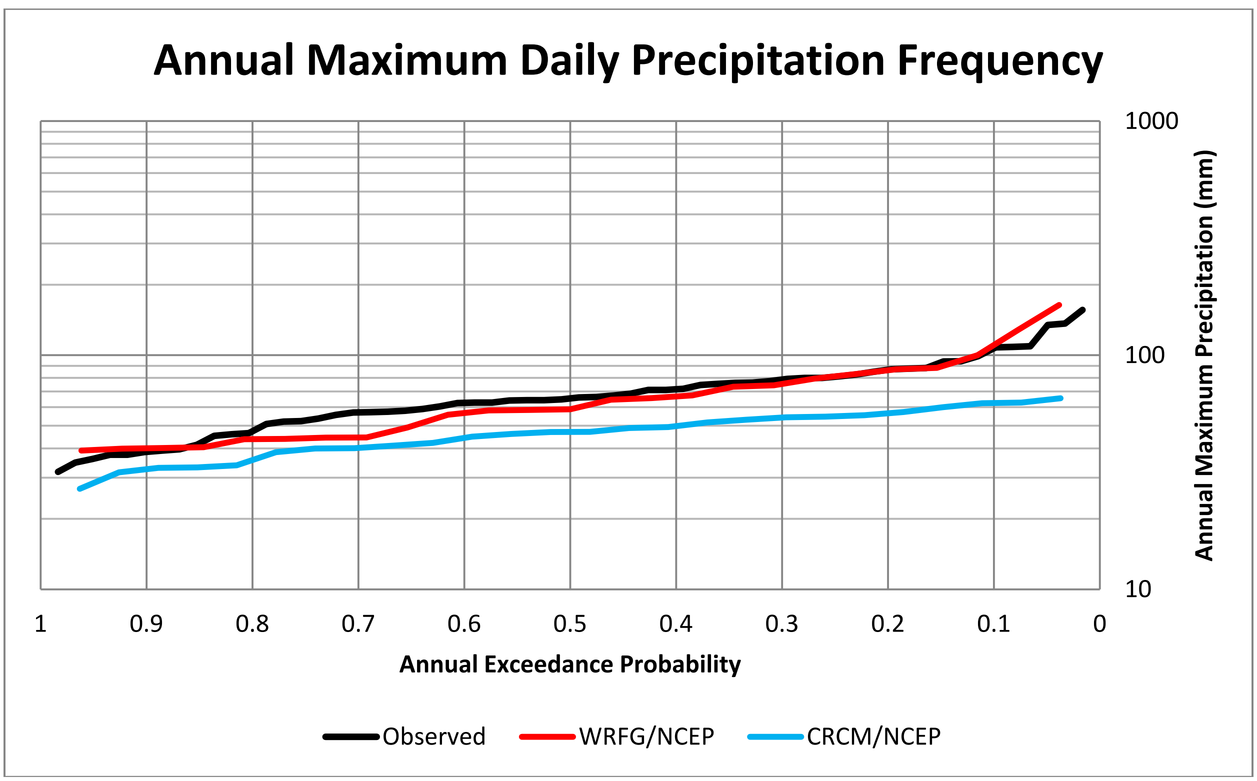

Figure 9: Annual maximum daily precipitation frequency plot for historical data

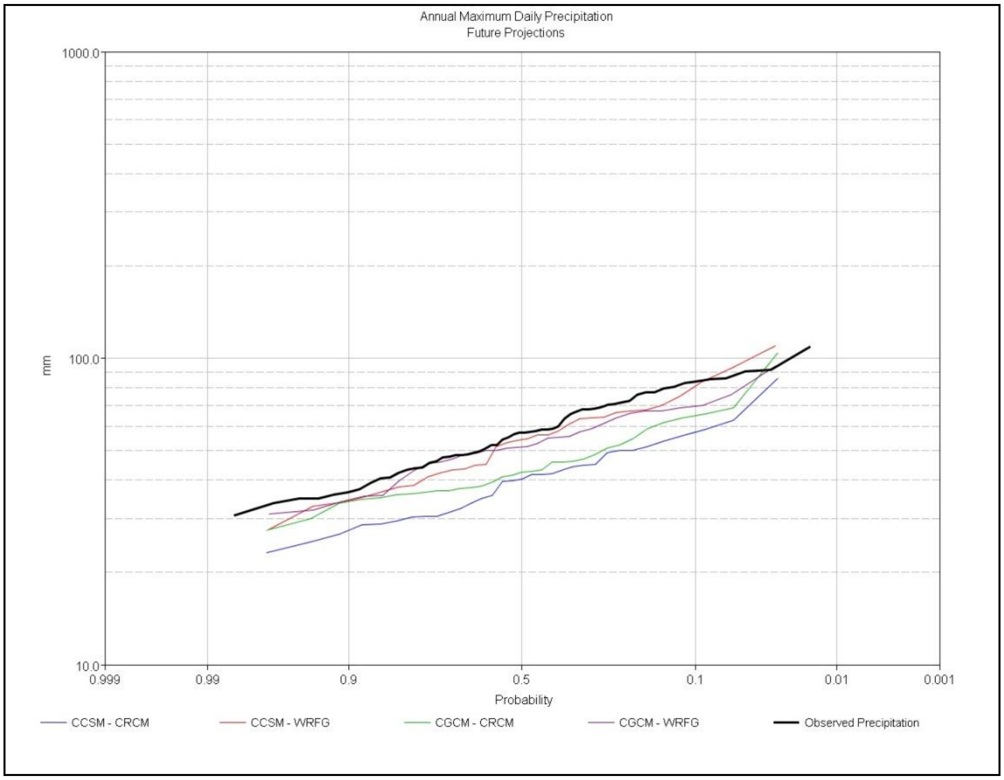

Figure 10: Annual maximum daily precipitation for future projections (annual exceedance probability vs. annual maximum daily precipitation)

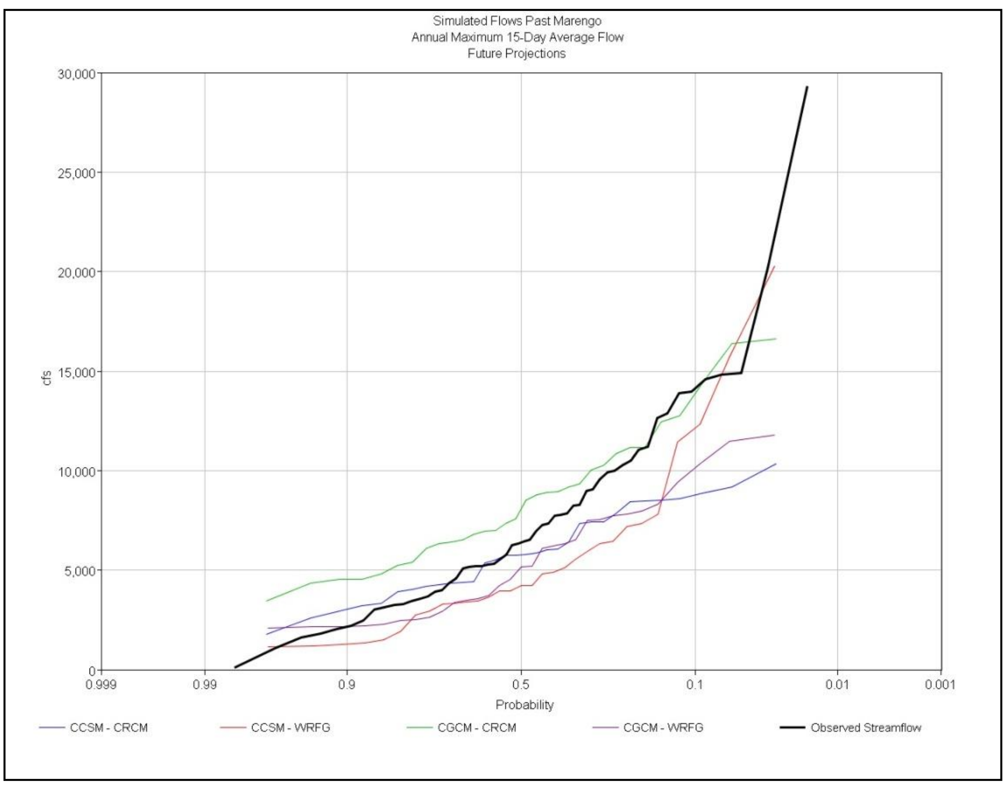

Figure 11: Annual maximum 15-day average flow past Marengo for future projections (annual exceedance probability vs. annual maximum 15-day average flow)

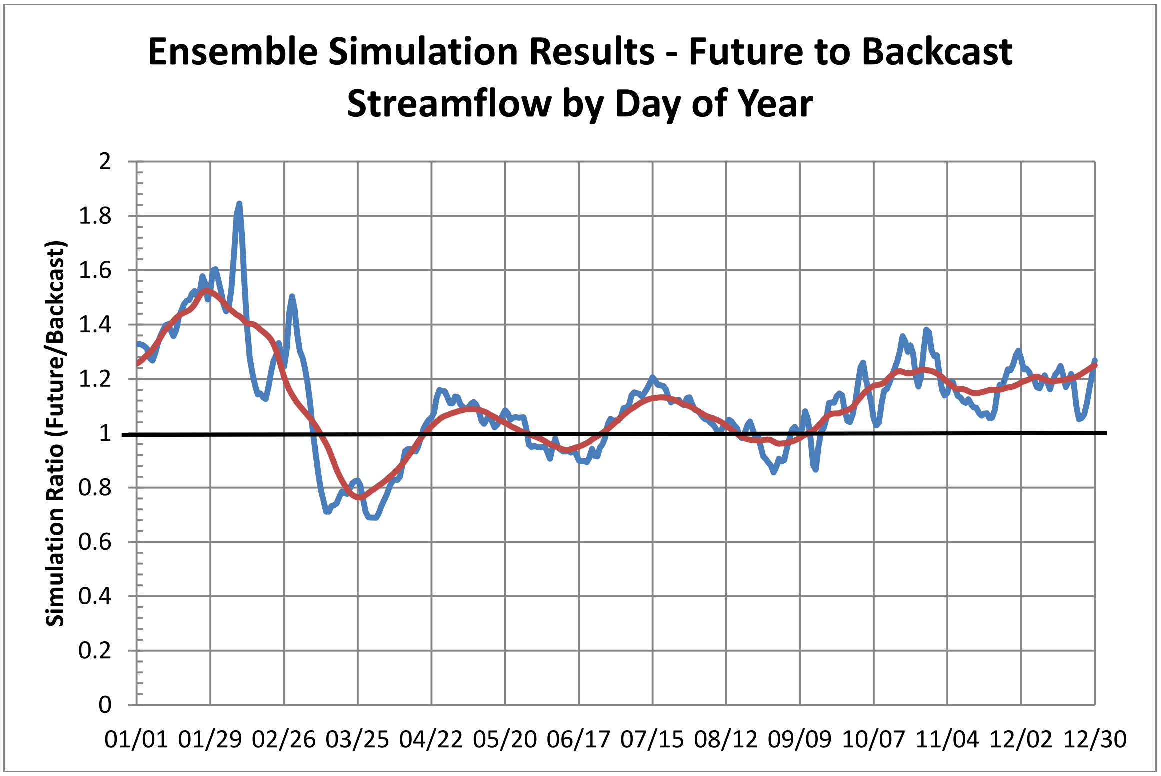

Figure 12: Ratio of discharge by day of year for ensemble future and historical simulations