NASA AMES RESEARCH CENTER CLIMATE CHANGE EFFECTS AND ADAPTATION RESEARCH: HIND- AND FORECASTING FLOOD RISK OF NASA AMES RESEARCH CENTER USING THE BASINS MODEL

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ABSTRACT

NASA Ames Research Center (ARC), located at the southern end of San Francisco Bay, CA is at increased risk of flooding under future climate change scenarios. Sea level rise, accompanied with tidal action, storm surges, and local erosion, may cause inundation at current levee heights. Also, possible changes in storm frequency and intensity, as well as land use changes, could cause inland flooding by fresh water. This analysis uses the BASINS (Better Assessment Science Integrating point & Non-point Sources) model to simulate hydrologic conditions at NASA ARC during selected past El Niño events and possible future precipitation scenarios. The 1997/98 storm event caused flooding on the Center, while the 1977/78 and the 1992/93 events, which were similar in precipitation amount and frequency, did not. BASINS modeled these past heavy precipitation events and other future storm events under projected climate conditions to assess flood risk at NASA ARC. These preliminary results will assist master planners in adapting new procedures for NASA ARC future developments with awareness of anticipated climate change effects.

KEYWORDS: climate modeling, NASA Ames, flood risk, BASINS, sea-level rise

INTRODUCTION

The effects of climate change are expressed especially near coastal areas. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, "present-day sea level change is of considerable interest because of its potential impact on human populations located in coastal regions and on islands" (Solomon, *et al*., 2007). Sea levels vary normally on a daily, monthly, and seasonal basis. The highest tides occur in winter and summer, and during new and full moons. Sea levels also rise during El Niño winters. Coastal flooding in the San Francisco Bay occurs during winter storms, when strong winds raise water levels, and high waves pound the coast. If this coincides with high tides as well, the risk of damage to coastal areas, including levees, is increased greatly (Luers, *et al*., 2006).

NASA Ames Research Center (ARC) is located at 37.4°N, 122.05°W in the Stevens Creek watershed, at the south end of San Francisco Bay, CA. This location leaves NASA ARC vulnerable to flooding from the effects of sea level rise, changes in storm intensity and frequency, and other precipitation patterns. Located on the site are the Moffett Federal Airfield, the Ames Research Center campus, the NASA Research Park, and wetlands along the northern boundary of ARC. NASA ARC daily operations include the fields of aeronautics, reentry physics, space science, space research, technology development, astrobiology, life sciences, human factors, earth sciences, and information systems. ARC is also home to the 20 G centrifuge, the Columbia Supercomputer, a vertical motion simulator and the world's largest wind tunnel, with a test section measuring at 80 feet by 120 feet (24.384 m to 36.576 m). These daily operations and assets could be greatly affected by sea level rise.

NASA ARC is hydrologically divided into western and eastern drainage systems, as shown in Figure 1. The water accumulated in the western drainage area flows into the Storm Water Retention Pond (SWRP). The SWRP has a holding capacity of 960 acre-ft (41,817,600 cubic feet or 1,184,142.56 cubic meters), and because it is a superfund site, evaporation is the only removal mechanism under normal conditions. However, if the SWRP is going to overflow and cause inland flooding, permission can be granted from the Mid-Peninsular Regional Open Space District (MROSD) to pump water into Stevens Creek (Philip Williams & Associates, LTD, *et al*., 2005), which then flows out into the bay. This western drainage pump capacity is 10 cfs (0.2832 cms). The water in the eastern drainage area flows toward the Northern channel, where it is pumped out at a rate of 49 cfs (1.3875 cms) (Philip Williams & Associates, LTD, *et al*., 2005).

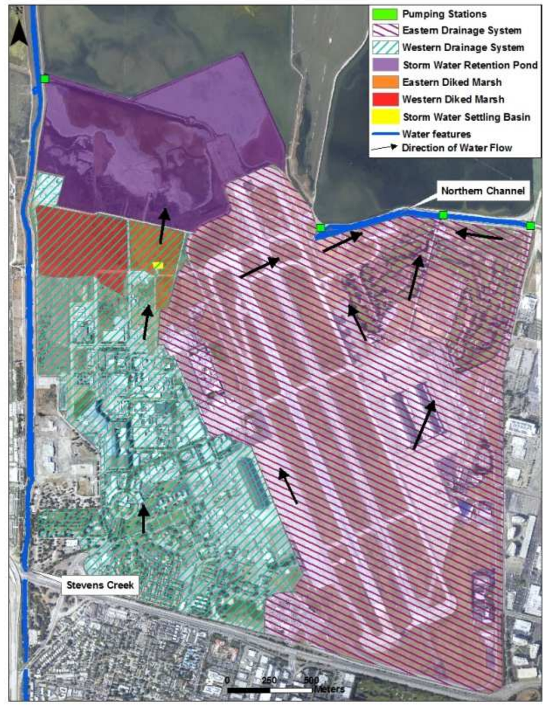


Figure1. Major hydrology features of NASA Ames Research Center.

The 1997/98 winter storm season has been recognized as a particularly strong El Niño event as part of the El Niño Southern Oscillation (ENSO) (McPhaden, 2009). El Niño is characterized by warmer than normal sea surface temperatures in the equatorial eastern Pacific which brings heavy rainfall to the study area (Pacific Marine Environmental Laboratory, 2010). At least 19 stations in California had record breaking precipitation amounts in February 1998. The flooding from this heavy precipitation caused 35 counties to be declared as federal disaster areas, including Santa Clara County, the location of ARC (Ross, *et al*., 1998).

Figure 2. Potential inundation of study area by 2050 and 2100 if levees fail.

Between February 2nd-9th, a series of storms resulted in flooding on the NASA ARC campus. For the NASA ARC area, the total February 1998 rainfall was 10.25 inches (26.035 cm). This is about 350% of average February rainfall for this area (Western Regional Climate Center, 2010). With the rainfall and run off at such high levels relative to normal, the capacity of the storm water retention pond was met and exceeded. The NASA Disaster Assistance and Rescue Team (DART) worked with the MROSD to counteract the effects of the flood. Over 15,000 sand bags were used and emergency pumps at Stevens Creek and the Northern Channel (see Figure 1) were operated to expel the water from the storm water retention pond into Stevens Creek. Normal pumping capacity is 1.2 million gallons per hour (4,542,494.14 liters per hour), and at the height of the storm the pumping stations were pumping almost three million gallons per hour (11 356 235.4 liters per hour) (Dolci, 2009). It is thought that the levees between ARC and the bay prevented more serious damage from occurring.

Historical records show that sea level along the California coast has been rising at a rate of about 8 in/century (20.32 cm /century) (Cayan, *et al*., 2009). According to the IPCC 2007 report on global climate change (Solomon, *et al*., 2007), it is projected for the Bay Area that the sea level will increase between 11 and 18 inches (27.94 cm to 45.72 cm) by the year

2050, and 22 to 35 inches (55.88 cm to 88.9 cm) by the year 2100 (see Figure 2). These increases will put NASA ARC at a higher risk for damage resulting from erosion and flooding, especially when combined with the effect of ENSO (McPhaden, 1999).

The goal of this project is to assess flood risk to NASA ARC under projected future climate scenarios. This is first done by simulating hydrological conditions at NASA ARC through hindcasting of previous El Niño winters. These are the 1997/98 El Niño storm event, which caused flooding on the Center, and the 1977/78 and the 1992/93 El Niño events, which were similar in precipitation amount and frequency, but did not flood NASA ARC. These events will then be the basis to forecast hydrological conditions when parameters are changed under future climate scenarios, such as temperature increase, precipitation frequency and intensity changes, sea level rise, and land cover changes. Separately, these parameters will test the sensitivities of the mean flow of water through the NASA ARC watershed, and together the parameters can be used to forecast conditions under a projected future climate scenario.

METHODOLOGY

Better Assessment Science Integrating Point & Non-point Sources (BASINS)

In response to the need for past and future projections of hydrologic effects of climate change at ARC, hydrologic and watershed modeling and environmental analysis was conducted using the Better Assessment Integrating point and Non-point Sources (BASINS) model package. BASINS is a software product of the Environmental Protection Agency (EPA) and includes a data extractor, projector, project builder, Geographic Information Systems (GIS) interface, various GIS-based tools, a series of models, and custom databases from which to download meteorological and hydrological data. The GIS data and other databases are available through a web data extraction tool. The model allows users to specify a geographic area of interest and to download data from the EPA and United States Geological Survey (USGS) relating to land cover, meteorology and hydrology.

BASINS implements the Hydrological Simulation Program– FORTRAN (HSPF) model by using historical time series of rainfall, temperature, evaporation, and parameters of land use patterns, soil characteristics, and agricultural practices to simulate the hydrological processes that occur in a watershed. An HSPF simulation results in a time series of runoff, streamflow rate, sediment loads, and other hydrological factors.

Meteorological Data

Historical meteorological data were collected for the months November through April for the 1977/78, 1992/93, and 1997/98 winter rain seasons. These data sets were not available for the Moffett Field meteorological station KNUQ, through the BASINS database, so they were obtained from other sources such as the NCDC (National Climate Data Center), CIMIS (California Irrigation Management Information System), and the NSRDB (National Solar Radiation Database).

The only data required to generate streamflow from the BASINS model are hourly precipitation and potential evapotranspiration. However, a full meteorological data set will give more accurate model results. A full meteorological data set within BASINS requires hourly precipitation, temperature, wind speed, solar radiation, potential evapotranspiration, dewpoint, and cloud cover.

The meteorological data collected were formatted using Watershed Data Management (WDM) Utility to create data sets in the correct format for the HSPF hydrology model within BASINS. The data sets used in this project included all of the variables in the full meteorological data set, except for cloud cover.

Potential evapotranspiration (PET) was not an observation available from the Moffett Field meteorological station; the closest observation of PET was from the CIMIS data for San Jose, CA – a more urbanized area than NASA ARC. PET therefore had to be calculated within BASINS. The Jenson method (Bordue and McGuinness, 1973) was used to calculate PET, and this required the inputs of daily minimum and maximum temperatures, as well as daily solar radiation. Daily PET was generated, and then disaggregated into hourly PET for the required HSPF input.

Any missing or bad data points for temperature, dewpoint, or wind speed had to be interpolated between the nearest two observational points so that the data sets would have a constant interval between points. A constant interval time series is necessary to create a correctly formatted WDM file. Any precipitation value that was bad or missing was regarded as no precipitation. This too was to satisfy the constant interval requirement.

Moffett Field precipitation data for the 1977/98 and 1992/93 years were available in daily and 6-hour time interval measurements. The HSPF model, however, requires hourly precipitation input. Within BASINS, there is a method to disaggregate precipitation data based on daily and hourly precipitation of nearby stations. For this project, the aforementioned years had hourly precipitation computed for Moffett Field by disaggregating daily Moffett Field precipitation data along with hourly San Jose, CA precipitation data. The San Jose meteorological station is the closest station to the Moffett Field location that has hourly precipitation data.

Geographic Information Systems Data

To gain an understanding of NASA ARC's hydrologic features, GIS data layers specific to our study area were obtained. These data were used to compile maps and to learn more about the boundaries and hydrologic features at ARC. Digital elevation models (DEM) at 3 meter resolution and LiDAR (Light Detection and Ranging) information at 1 meter resolution were obtained from USGS Seamless Server (http://seamless.usgs.gov) and USGS LiDAR viewer (http://lidar.cr.usgs.gov/Lidar_viewer). Other high resolution GIS data were obtained from NASA staff and the Santa Clara Valley Water District. Data for this study area were downloaded, extracted and projected to the Universal Trans Mercator Zone 10 North map projection.

Some preliminary data-processing was executed using the GIS, such as selecting data points for field work, calculating slope of the study area, and calculating area and other inputs for the HSPF model. Boundaries were digitized based on physical maps provided by NASA and combined with the GIS layers to select the study area. GIS data such as the DEM and boundary polygons were used in BASINS in place of existing layers so that we could run the model with more accurate and higher resolution data. A DEM and a stream file were used to delineate the larger watershed into a smaller watershed/basin that encompasses ARC. Several maps were produced using the Environmental Systems Research Institute's (ESRI) mapping software: ArcGIS 9.3.1, ArcMap and ArcCatalog.

This report has delineated a watershed that encompasses the entire study area, and does not distinguish between the eastern and western drainage systems. To simplify, this report will consider a total center pump capacity of 59 cfs (1.6707 cms).

BASINS Climate Assessment Tool (CAT)

The BASINS CAT is used to assess the effects of climate variability and change on watershed systems. This tool allows users to create climate change scenarios and to answer several "what-if" questions. The CAT can make single changes to a parameter, or iterate changes over a specified interval. The parameters that can be changed are temperature (which also requires a recalculation of PET), precipitation, frequency of storm events, and intensity of storm events. These changes can be applied individually to test sensitivity, or together to test a climate scenario.

On a technical note, the May 2010 release of BASINS 4 has a conflict between two install files that prevents HSPF from running within the CAT, which required a work-around. Other users of the May 2010 release of BASINS will need to download a future update package to get the CAT running.

Climate Scenarios

Precipitation by 2100 is expected to keep with the seasonal Mediterranean patterns, with most precipitation falling in the winter. However, models have not been able to produce statistically significant results about whether precipitation will increase or decrease in the study area. (Luers, *et al*., 2006; Karl *et al.*, 2009). On the other hand, the intensity of precipitation events has increased by 9% between 1958 and 2007 for the Southwest United States region, and models project that they will continue to increase (Karl *et al*., 2009).

Three scenarios were chosen from the Our Changing Climate 2006 report (Luers, *et al.*, 2006). The lower emissions scenario, B1, medium-high emissions scenario, A2, and higher emissions scenario, A1fi, describe a range of demographic, economic, and technological changes, as well as varying changes to greenhouse gas emissions in years to come. Further details to these scenarios are shown in Table 1. Based on the aforementioned projections, this report considers changes in temperature from 0 to 10°F (0°C to 5.56°C), changes in overall precipitation from 85% of normal to 115% of normal, and changes in storm intensity up to 10% above normal.

Table 1. IPCC projected emissions scenarios.

Emission Scenario	Projected Warming Range (°F)	Emissions Projections	Economic/Technologic Growth	**Population Growth**
B1	3-5.5	Decline by 2050	High economic growth	Decline by 2050
A2	5.5-8	Increase through 2100	Uneven growth	Continuous growth
A1fi	8-10.5	Increase three-fold through 2100	New and efficient technologies; fossil-fuel intensive	Decline by 2050

Field Work

Field work was conducted on July 13th and July 16th, 2010 at NASA Ames Research Center. Data were collected using a Garmin 60CSx GPS, a Garmin GPSmap76, and a Silva Ranger Compass 515 which had a built in clinometer. The purpose of the field work was to verify the heights of the levees north of NASA ARC using the built in altimeter on the GPS. To calibrate the GPS, several known benchmarks from National Geodetic Survey (NGS) markers, which were placed by USGS, were found, and then the GPS unit was used to calibrate the altimeter with the known elevation (see Figure 3).

On the levees and along Stevens Creek Trail, specified locations were marked with the GPS units to record the latitude, longitude, and elevation. At the same locations, levee heights were manually measured by pulling a meter measuring tape down to the water edge, and kept at the same angle of the slope of the levee. The other end of the measuring tape was pulled up to the eye height of the observer. There, the observer used the clinometer to measure the angle of the levee from the horizon. Knowing the total length from water edge to observer eye (T), angle of depression (α), and length from levee top to observer's eye height (h), the height of the levees (χ) could be calculated, as shown in Equations 1 to 3:

Figure 3. Area of fieldwork at NASA ARC. Images show (from top) levee heights being manually measured, a benchmark from NGS, and a NASA ARC medallion.

Equation (1) $$\chi = L\sin(\alpha)$$

Equation (2) $$L = T - y$$

Equation (3) $$y = h/\sin(\alpha)$$

Where:

- χ = levee height
- α = angle of depression
- L = length along slope of the levee
- T = total length from water edge to observer eye
- y = length along slope from levee edge to observer's eye height
- h = height from levee top to observer's eye height = 156 cm

RESULTS

Hindcast

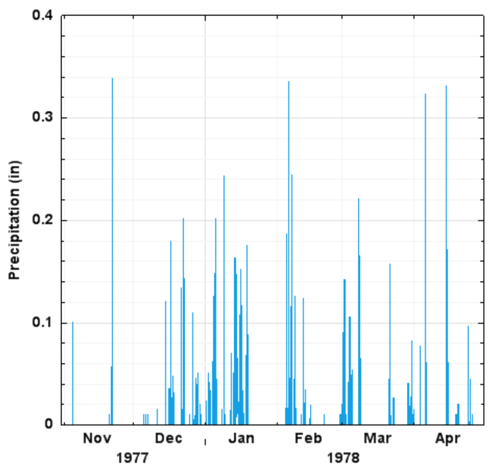
The observed precipitation and modeled streamflow for the years 1977/78, 1992/93, and 1997/98 are shown in Figure 4. During the 1997/98 storm season, there were 91 rain days, and a total of 24.51 inches (138.45 cm) of precipitation fell. The flooding event during February 1998 had a peak daily average flow over the defined watershed area of about 254 cfs (7.1925 cms), and the mean daily flow for the entire time period is about 13 cfs (0.3681 cms) (see Table 2).

The 1977/78 rain season had a total seasonal precipitation of 24.64 inches (62.59 cm), which is similar to the 1997/98 season. There were 71 rain days in this season, which is 20 days less than the 1997/98 season. The mean daily flow modeled for 1977/78 is about 8.6 cfs (0.2435 cms), and the maximum daily flow is 88.4 cfs (2.5032 cms).

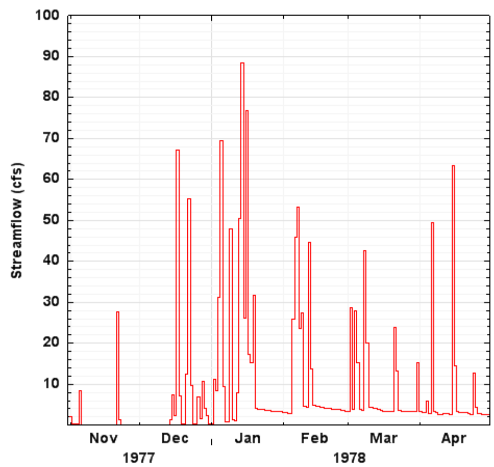
Table2. Summary of observed precipitation and modeled streamflow for hindcasted years.

Rain Season (Nov-Apr)	Total Season Precip (in)	Total Rain Days	Mean Hourly Precip (in)	Max Hourly Precip (in)	Mean Daily Flow (cfs)	Max Daily Flow (cfs)	Min Daily Flow (cfs)
1977/78	24.64	71	0.0044659	0.338	8.6133	88.434	0.0085922
1992/93	19.37	68	0.0043692	0.36	8.7864	84.816	0.005492
1997/98	24.51	91	0.005784	0.71	13.021	253.63	1.010767

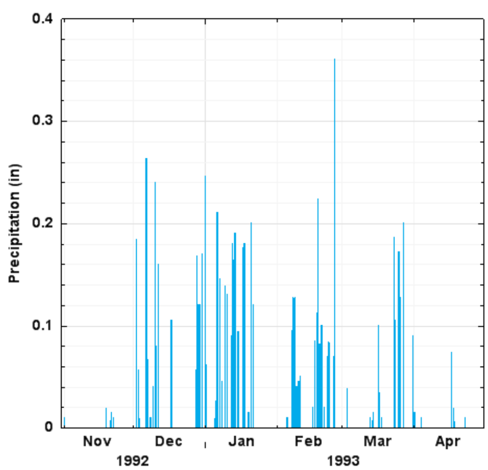
The 1992/93 season had 68 rain days, which is similar to the 1977/78 season. The total rainfall for 1992/93 was 19.37 inches (49.20 cm), which is about 4 inches (10.16 cm) less than both the 1997/98 and 1977/78 years. The mean daily flow modeled for 1992/93 is 8.79 cfs (0.2489 cms), which is similar to the flow modeled for 1977/78. The maximum daily flow for 1992/93 however was the least of all three study years at 84.82 cfs (2.4018 cms).



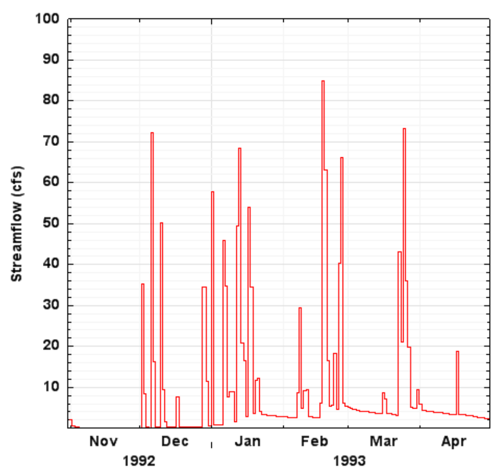
Interpolated hourly precipitation at Moffett Field 1977/78



Modeled daily streamflow within NASA ARC watershed 1977/78



Interpolated hourly precipitation at Moffett Field 1992/93



Modeled daily streamflow within NASA ARC watershed 1992/93

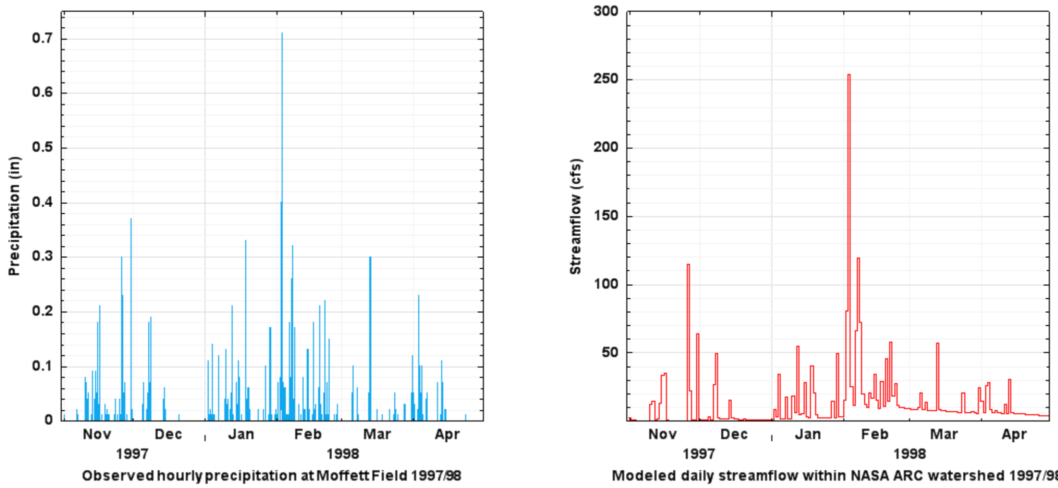


Figure 4. (Left) Observed or interpolated precipitation and (right) modeled mean daily flow for storm seasons (top) 1977/78, (center) 1992/93, and (bottom) 1997/98.

Forecast

To create sensitivity analyses, several meteorological and land cover changes were made to the three storm seasons of study. First, temperatures were increased by up to 10°F to simulate temperature changes up through the A1fi high emission scenario projected for 2100. Then, precipitation was both increased and decreased by 15%, because global climate models do not have statistically significant results for changes in precipitation trends for the study area. Next, simulations in land use changes were generated by taking 20% of each the agriculture and range land areas within the study area, and converting it into urban built up land. Lastly, to simulate a sea level rise of 18 inches (45.72 cm) under levee failure, the 307.5 acres (124.44 ha) that would be inundated within the study area by 2050 was converted from urban land into water area. Figures 5 and 6 show how these land use changes altered the flow.

To create a range of future climate scenario, a combination of temperature increase from 0 to 10°F (0°C to 5.56°C) and precipitation change from 85% to 115% of normal was modeled using the BASINS CAT. The results from this model run can be seen in Figure 7. Next, changes in storm intensity were generated by specifying that the top 10% of rain events over 0.1 inches (0.254 cm) would have up to a 10% increase in precipitation volume. This can be seen in Figure 8.

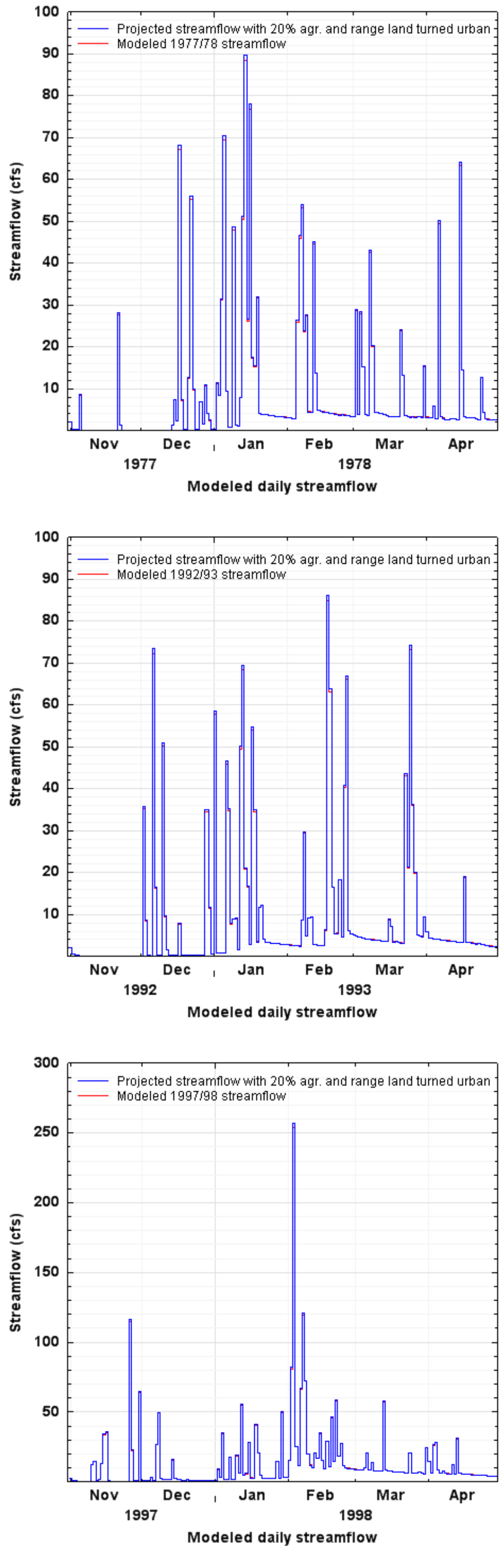


Figure 5. Modeled daily mean flow when land cover is changed by converting 20% of agriculture and range land into urban land for storm seasons (top) 1977/78, (center) 1992/93, and (bottom) 1997/98.

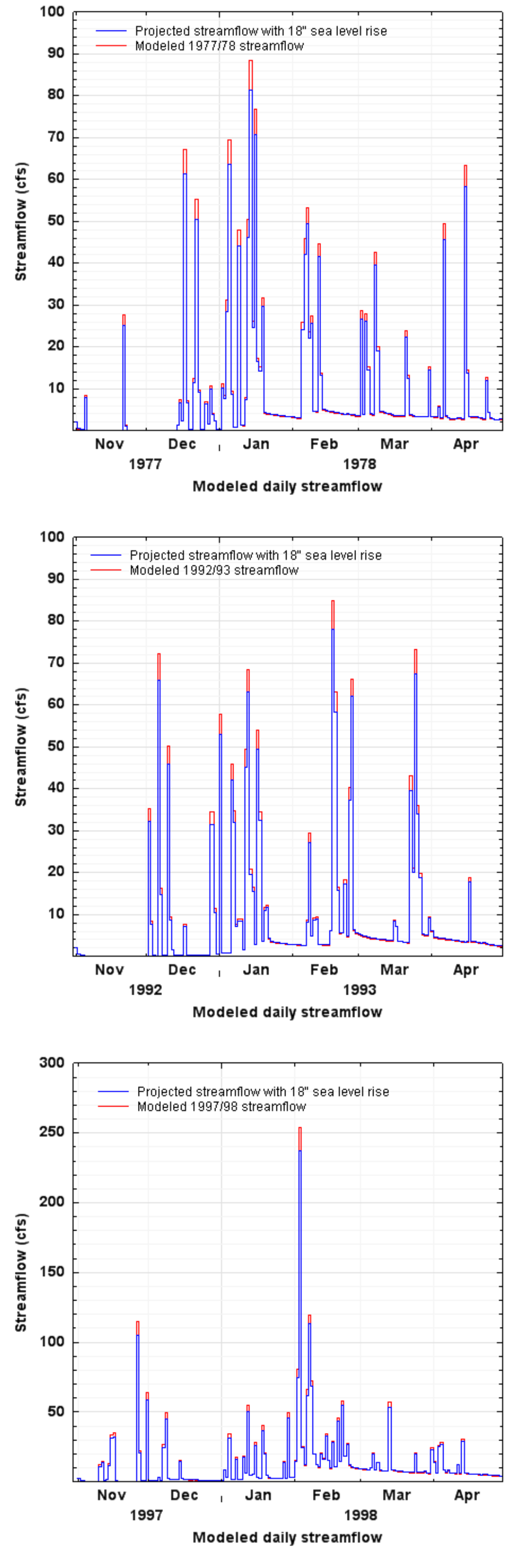


Figure 6. Modeled daily mean flow when land cover is changed to simulate a sea level rise of 18” by taking 307.5 acres from urban land and turning it into wetlands for storm seasons (top) 1977/78, (center) 1992/93, and (bottom) 1997/98.

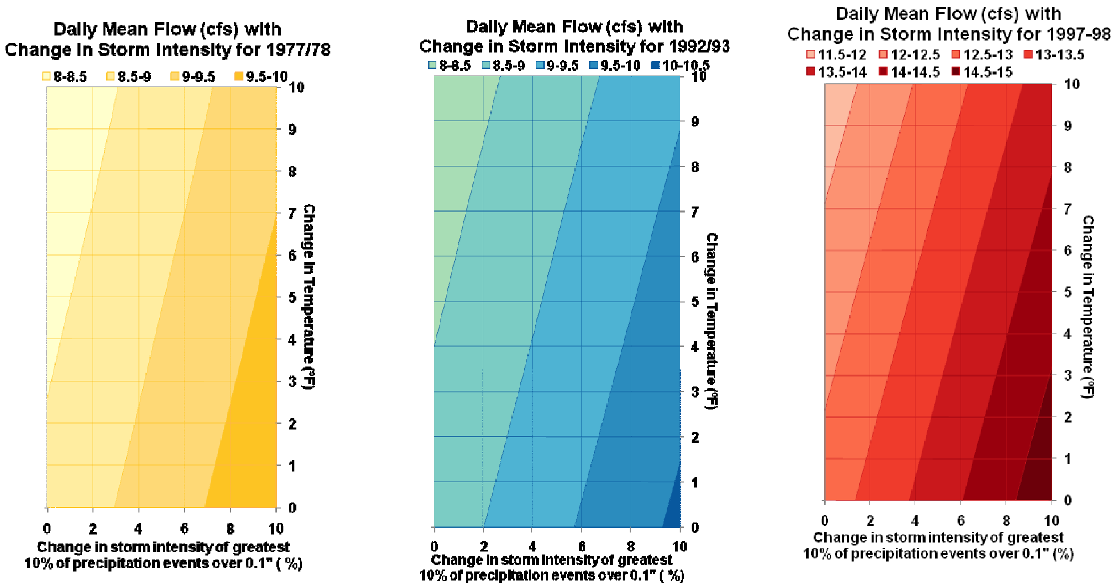


Figure 7. Modeled daily mean flow (cfs) when temperatures are increased from 0 to 10°F (0°C to 5.56°C) and precipitation is changed from 85% to 115% of normal for (left) 1977/78, (center) 1992/93, and (right) 1997/98.

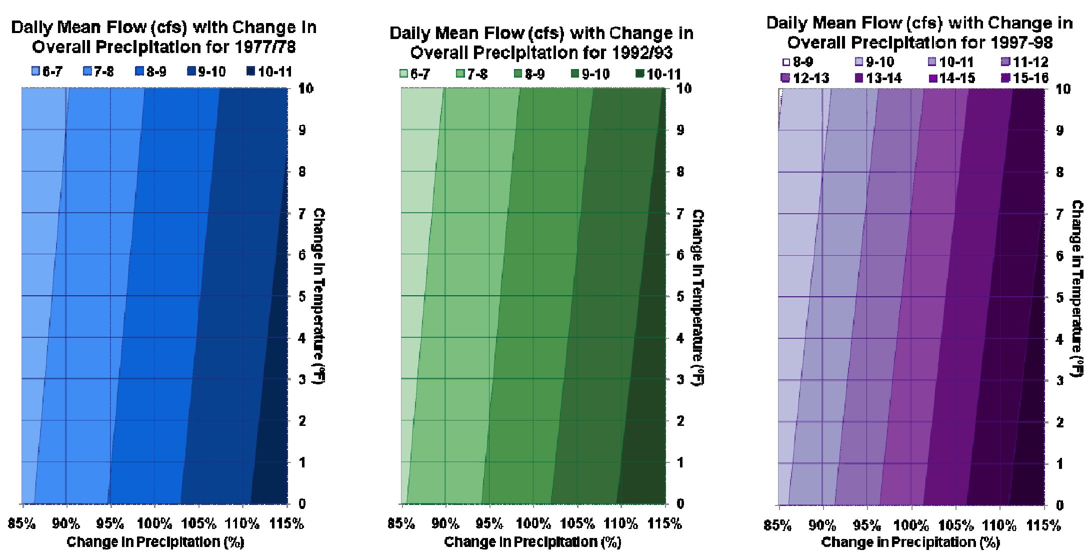


Figure 8. Modeled daily mean streamflow (cfs) when temperatures are increased from 0 to 10°F (0°C to 5.56°C) and storm intensities are increased by taking the top 10% of rain events over 0.1 inches (0.254 cm) and amplifying up to a 10% increase in precipitation volume.

Fieldwork

The heights of the levees as calculated from manual measurements were more accurate as compared to the DEM and the LiDAR data than the GPS readings (see Figure 9). The Garmin 60CSx had a constant altitude error range of ± 23 ft (7 m). The Garmin GPSmap76 (not shown) had varying altitude error ranges that were no more accurate than ± 56 ft (17 m). In the latitudinal and longitudinal directions, the Garmin 60CXs had 1 ft. (0.30 m) accuracy with nominal resolution, and the Garmin GPSmap76 had 10 ft. (3.05 m) accuracy with 1 ft. (0.30 m) resolution.

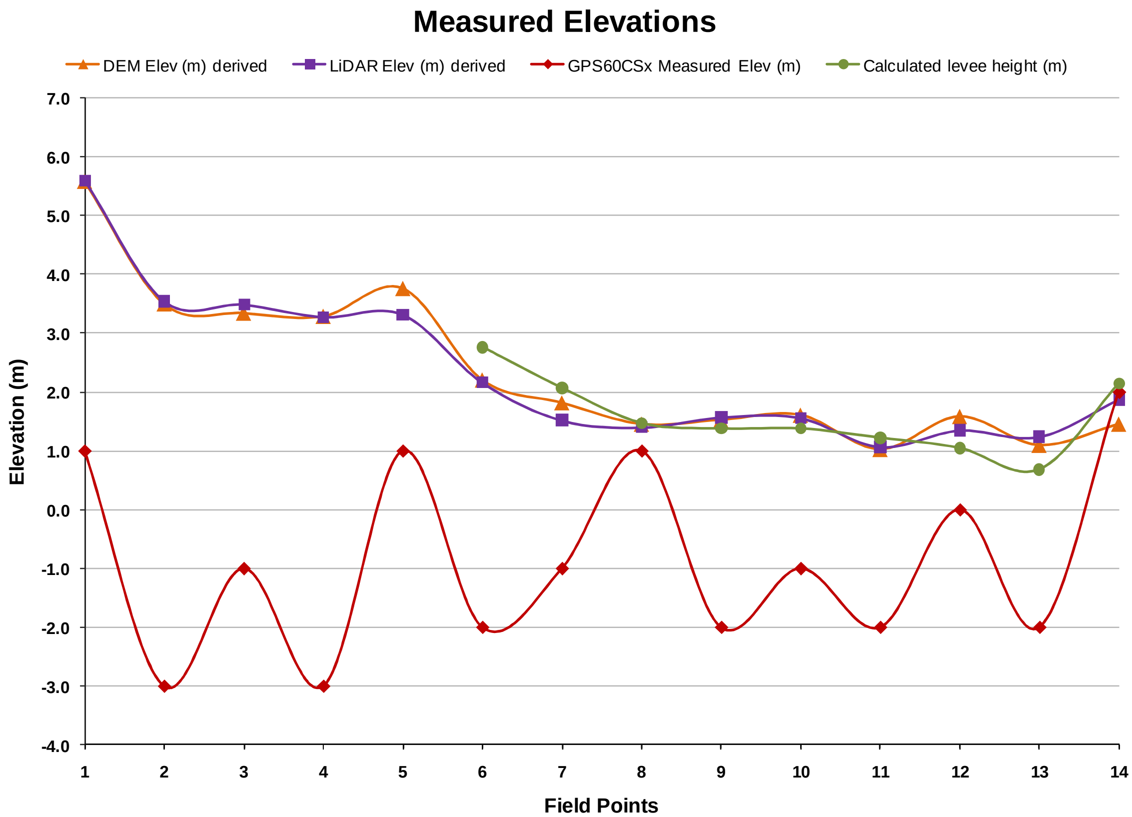


Figure 9. Comparison of levee height measurements with given values from DEM and LiDAR data

DISCUSSION AND CONCLUSIONS

Because this report does not distinguish between the western and eastern drainage areas, the pump capacity for the watershed area combines the western and eastern pump capacities for a total of 59 cfs (1.6707 cms).

The BASINS CAT results show that as temperature is increased, the mean daily flow decreases. This could be due to increased evapotranspiration, as that variable is recalculated when temperature is adjusted. When precipitation increases, the mean daily flow also increases. The contour plots show that together the changing precipitation with increased temperatures has an overall increasing linear effect on the mean daily flow. Original assumptions were that there would be more of a positive feedback process with increased temperatures. An example could be that increasing temperatures would allow the atmosphere to hold more liquid water, which could lead to more availability of precipitation to fall, which could therefore lead to increased flow.

The BASINS CAT results also show that as the top 10% of storms with a rainfall volume more than 0.1” (0.254 cm) intensify up to 10% above normal, the flow increases. The increased storm intensity scenario does not increase mean daily flow as much as the scenario where overall precipitation is increased up to 15% above normal. However, this does not mean that more intense storms are less of a threat than overall increased precipitation. If there is a comparison of overall precipitation increased by just 10%, and storm intensification increased by still 10%, the storm intensification scenario has modeled streamflow that is slightly increased (0.2% to 0.5%) from that of the overall precipitation increase. And in general, if an increased storm event has the volume of precipitation such that the SWRP is filled and starts to overflow, but the pumps cannot pump out water as fast as it is flowing in, then inland flooding can occur. This is what happened during the February 1998 flooding event. The storm had a peak hourly rainfall of 0.71 inches (1.80 cm), and this caused the mean daily flow to be 254 cfs (7.1925 cms). This inflow rate is about 430% more than the pumps combined can pump out of NASA ARC.

When modeling a change in land cover by converting 20% of the present-day agriculture and range land and turning it into urban land, the mean daily flow increases. This could be due to the increase in impervious surfaces that are associated with urban land and an increase in surface run-off. When simulating the 18” (45.72 cm) rise in sea level by changing 307.5 acres (124.44 ha) of urban land into wetlands, the mean daily flow decreases. This decrease is most likely due to a decrease in surface run-off.

The Garmin GPS units used in the field work were accurate in the latitudinal and longitudinal directions, but were inaccurate in the altitudinal direction even though they were calibrated using known benchmarks. The GPS elevation data for this project is therefore not valid to use for verifying levee heights. The clinometer measurements, however, were very close to DEM and LiDAR given elevations.

Future Work

This report covers the work accomplished in the first summer of a two-summer project. Below are possible directions this project could take during the next summer term.

It is suggested that the Terrestrial Observation and Prediction System (TOPS) model be used to give a more accurate and properly downscaled data set for the hydrology at ARC. The current limitation in using TOPS was because at this time, it does not include a distributed hydrological model (i.e. grid cells are not connected, which is required to properly simulate hydrology at high spatial resolution). Downscaled climate projections tailored for NASA ARC for use in the TOPS model will be provided by NASA Goddard Institute for Space Studies.

In use with the BASINS model, the watershed at ARC should be split into an eastern and western portion based on the drainage area delineations. In the BASINS model, the pipes and drainage system of NASA ARC should be included for more accurate flow direction and flow amount results.

The effects of sea level rise on the hydrology of NASA ARC aren’t fully understood with the BASINS model output. Perhaps more resources could be acquired to better understand these effects.

Another year of interest to hindcast could be the 1982/83 El Niño season, as it had 60 total rain days and 22.83 inches (57.99 cm) of total precipitation.

It would be advisable to team with the Environmental Management Division at ARC, who are working with the Army Corps of Engineers on a feasibility study to increase the height of the levees. It is also recommended that final results be given to NASA ARC master planners, who can then adapt new procedures for future developments with awareness of anticipated climate change effects on the center.

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