MODELING CURRENT AND FUTURE WATER USE IN UTAH WITH NASA'S TERRESTRIAL OBSERVATION AND PREDICTION SYSTEM

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ABSTRACT

Cache County is one of the biggest agricultural producers in Utah and over 70% of the county's water is used for irrigation. In this project, we use NASA's Terrestrial Observation and Prediction System (TOPS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data to gain an understanding of the water cycle in Cache County by comparing the precipitation, snowpack, and runoff amounts to the crop evapotranspiration (ET) requirements. By modeling ET, we evaluated the true demand for water and compare it to the amount of water supplied, determining the water efficiency. We found that the current irrigation practices have an efficiency of approximately 30%. Furthermore, we employed a climate change scenario to study the effects of temperature increase on Cache County's water cycle and agricultural production. As climate changes, snow cover will significantly decrease and crop evapotranspiration will increase, altering the current water supply.

INTRODUCTION

According to the IPCC Fourth Assessment (2007), "climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use change, including urbanization" any glacier and snow-fed rivers are currently experiencing increased runoff and earlier spring-peak discharge Higher temperatures yield higher evapotranspiration rates and earlier snowmelt, altering the hydrologic cycle and making it useful to model and predict the effect of climate change on water supply and demand.

The hydrologic cycle is an essential Earth process, providing a means for the circulation and conservation of water. The basic features of the hydrologic cycle include the evaporation of moisture from oceans and other sources, condensation and transportation in the atmosphere, and precipitation. Snow that collects in the mountains during the winter serves as water storage for the summer. As snow melts in the spring, rivers flow and the surrounding areas are provided with a plentiful freshwater supply. The western United States is highly dependent on this process since the area's water cycle is characterized by winter snowfall and summer drought.

Agricultural regions are especially sensitive to changes in the hydrological cycle. Evapotranspiration is the combination of water loss from the soil through evaporation and from the plant through transpiration. Evapotranspiration is affected by weather conditions and temperature, so more water is needed to replace the moisture lost during hot summer months than cooler winter months. In the western United States, crops are heavily irrigated to account for water loss due to evapotranspiration. Since the water used for irrigation is often supplied as runoff from snowpack, this area will be particularly affected if the area experiences decreased precipitation, earlier snowmelt, and increased evapotranspiration.

Cache Valley is a primary agricultural producer in the northern region of Utah. Located in the Wasatch Range between the Wellsville and Bear River Mountains, Cache Valley is like much of the western United States in that it receives most of its water in the form of spring runoff from winter snowpack. At least 60% of the land in Cache Valley is irrigated and over 75% is used for agriculture. The primary use for the county's water is irrigation, using both the flood and sprinkler methods of watering. The residents and farmers in the county depend on the snowmelt flows of Bear River, Logan River, and Little Bear River. The cost of water in Cache Valley is lower than the national average and much lower than that of other western states (Utah Division of Water Resources, 2001), making inefficient irrigation practices both easy and affordable. As climate changes, it is very likely that this area will suffer from water scarcity problems as crops will have higher evapotranspiration rates and spring runoff will occur earlier. For these reasons, we have chosen Cache Valley, Utah, as a case-study example to model and predict the effects of climate change on water supply and demand. The results of the study, however, are applicable across the globe.

METHODOLOGY

Water Cycle Data

In order to gain an understanding of the water balance in Cache Valley, we looked at snowpack, runoff, and water use data. Historical runoff data was obtained using USGS Water Data for the Nation, an online database for viewing daily discharge rates at many sites across the county. Snow water equivalent and snow depth data at snowpack telemetry (SNOTEL) sites were viewed using USDA's Natural Resources Conservation Service (NRCS). Irrigation and water use data comes from USGS Estimated Use of Water in the United States. We used county-level data from 2000 to calculate irrigation efficiency.

Terrestrial Observation and Prediction System (TOPS)

In response to the recognized need for improved simulations of water resources, we conducted ecosystem modeling and computer science research to implement the Terrestrial Observation and Prediction System (Nemani et al. 2003, White and Nemani 2004) for the state of Utah at a one kilometer resolution. TOPS (http://ecocast.arc.nasa.gov/) is a unique modeling system composed of two central real-time input data streams combined with ecosystem models. The two real-time data streams are: (1) descriptions of vegetation canopies based on satellite remote sensing of LAI (Leaf Area Index) from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice et al. 2002); and (2) gridded surfaces of temperature, radiation, precipitation, and humidity generated from a large variety of remotely-sensed and ground-based sources. The real-time inputs describing vegetation canopies and meteorology are then used as inputs for the TOPS ecosystem model.

To simulate the water cycle, TOPS implements the Biome-BGC (Thornton 1998, White et al. 2000) water flux model, based on a Penman-Monteith approach relying on LAI and meteorology. Daily water fluxes are: precipitation, snow, soil water, evapotranspiration, calculated as the sum of transpiration, soil evaporation, canopy evaporation, and snow sublimation, and runoff, calculated as soil water in excess of soil water holding capacity (calculated from equations in Clapp and Hornberger (1978)).

Water-Related Land Cover

We produced a new water-related land cover map of Cache County, generated from the USGS Water Use Census of 2000. By interactive data language (IDL) transformation processing, we converted this vector water-related land cover map to a raster map to match the gridded climate variables and other model inputs. Then we used the raster water-related land cover map to run TOPS.

Snow Model

The snow model in TOPS is based on empirical temperature index model with radiation-driven melting (e.g. Rango and Martinec, 1995). The model uses daily air temperature, precipitation, and solar radiation to simulate daily snow accumulation and melting processes (Thornton, 1998; Allen *et al.*, 1998). The model consists of one snow pool with fluxes of snowfall, snow melting, and snow sublimation. At temperatures below 0 ◦C, predicted precipitation is in the form of snowfall. Snowmelt and sublimation are predicted by:

$$S_{\mathrm{ms}} = k_{\mathrm{index}} \cdot T_{\mathrm{ave}} \ (\text{if } T_{\mathrm{ave}} > 0\,^{\circ}\mathrm{C}) + \Delta R / \\ [\lambda_{\mathrm{s}} \ (\text{if } T_{\mathrm{ave}} < 0\,^{\circ}\mathrm{C}) \text{ or } \lambda_{\mathrm{f}} \ (\text{if } T_{\mathrm{ave}} \geq 0\,^{\circ}\mathrm{C})]$$

In this equation K_{index} is a temperature driven snowmelt coefficient (kg m^{-2} °C^{-1}), T_{avg} is daily average air temperature, ΔR is net shortwave radiation on snow surface, λ_f is the latent heat of fusion (335 kJ kg^{-1}), and λ_s is the latent heat of sublimation (2835 kJ kg^{-1}). The first term is an empirical temperature index approach; the second term is a physical radiation-driven process.

Reference Evapotranspiration

The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. The reference evapotranspiration (ET_o), which expresses the evaporative demand of the atmosphere, is the evapotranspiration from a standardized vegetated surface (a hypothetical grass reference crop with specific characteristics). The Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith procedure is a common method to assess ET_0 from meteorological variables. This method has been selected because it closely approximates grass ET_0 at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters.

$$\mathrm{ET_o} = \frac{0.408\,\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T}+273} \mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\,\mathrm{u_2})}$$

where	ET_o	reference evapotranspiration [mm day^{-1}],
	R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
	G	soil heat flux density [MJ m^{-2} day^{-1}],
	T	mean daily air temperature at 2 m height [°C],
	u_2	wind speed at 2 m height [m s^{-1}],
	e_s	saturation vapour pressure [kPa],
	e_a	actual vapour pressure [kPa],
	e_s-e_a	saturation vapour pressure deficit [kPa],
	Δ	slope vapour pressure curve [kPa °C^{-1}],
	γ	psychrometric constant [kPa °C^{-1}].

Crop Evapotranspiration and Crop Coefficients

The crop evapotranspiration under standard conditions (ET_c) refers to the evaporative demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions. Differences in light absorption by the canopy, crop height, crop roughness, crop physiology, leaf age and crop rooting characteristics result in different ET_c in different types of crops under identical environmental conditions. Crop coefficients (K_c) account for the difference between the ET_c and ET_o). The crop coefficients depend on crop growth phases, and some research shows that K_c is related to the percentage of crop ground cover.

$$ET_c = ET_o * K_c$$

In our research, we estimate the K_c from LAI data, which reflects the crop ground cover. The leaf area index (LAI) product from the Moderate Resolution Imaging Spectroradiometer (MODIS) is important for monitoring and modeling global change and terrestrial dynamics at many scales. Products of vegetation green LAI from Terra MODIS at 1-km resolution and eight-day frequency (MOD 15) over a six year period (2001-2006) were used for our study. The different phases are measured from LAI time series during one growth season. The LAI values are standardized by comparing the maximum and minimum LAI values over one growth season. The crop coefficients for each day are calculated from the corresponding LAI in same period.

Climate Scenario

In the future, temperature, precipitation and other climate variables are expected to change due to increasing carbon dioxide in the atmosphere. This climate change will likely affect the already sensitive water cycle in Utah. Therefore, the final portion of our study attempted to predict the consequences of global climate change on crop evapotranspiration and snowpack. Potential impacts of climate change are estimated for climate change scenarios developed from the NASA Goddard Institute of Space Studies (GISS) General Circulation Model (GCM) under the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) B2 with increased levels of atmospheric CO_2. Figure 1 displays the figure that we used for our predictions. Climate variable changes are based on the comparison between the observed climate data and future climate change scenarios in Cache County.

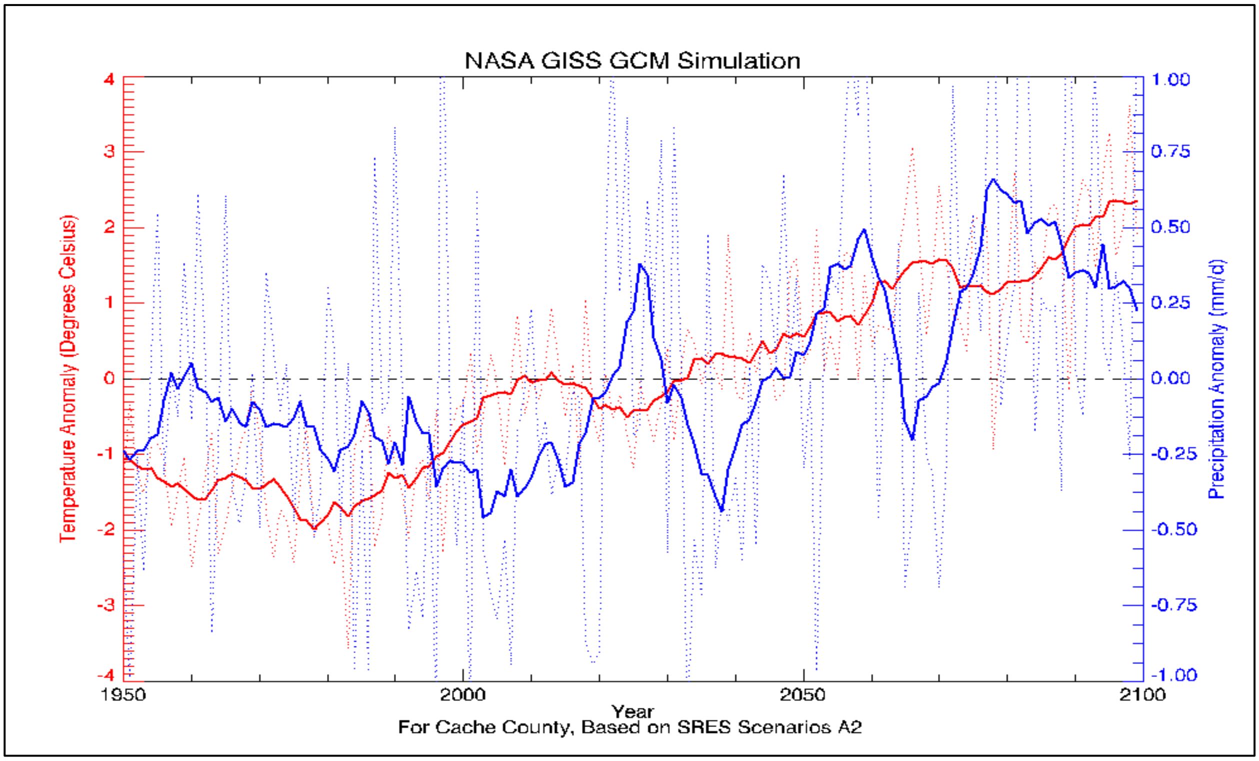

Figure 1. NASA GISS GCM Climate Change Scenario Used for Predictions. Annual Simulation (ghost line), and 10 Year Smooth Value of Simulation (solid line).

RESULTS

Water and Land Use

From water use data in the USGS 2000 Census, over 79% of the water supply in Cache County is used for irrigation. This corresponds to over 100 billion gallons of water used for irrigation per year, which is approximately one million gallons of water per acre per year for irrigation. Figure 2 is a map of Cache Valley land cover displaying areas devoted to both dry and irrigated crops and pasture, as well as commercial and residential land. Over 55% of land in Cache Valley is irrigated for either farm or pasture land and an additional 23% is used for non-irrigated farm and pasture land. Twelve percent of land in the county is residential and the remaining 10% is divided between streams, industrial, and riparian.

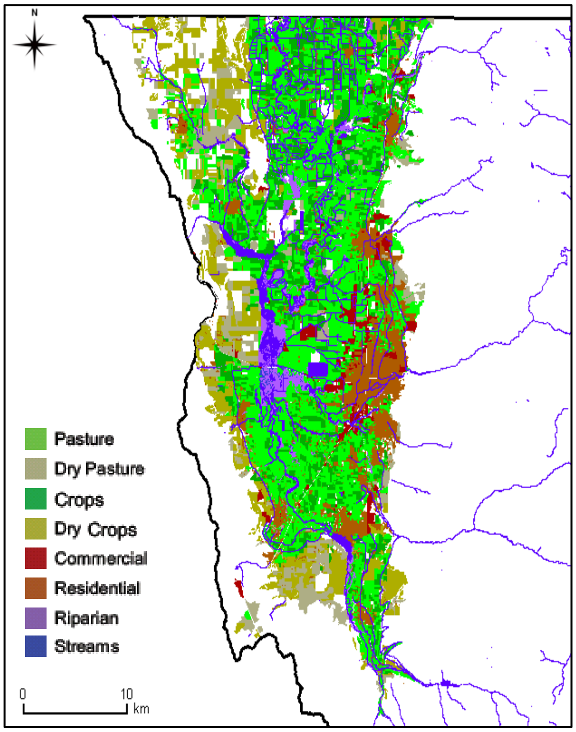

Figure 2. Cache Valley Land Cover.

Snowmelt Correlations

Spring-peak runoff is the primary source of water for cropland irrigation. There is a strong correlation between winter snowpack in the mountains and runoff amounts in rivers in Cache Valley. Figure 3a displays the annual snowpack at one SNOTEL site, created from monthly averages from 1993 to 1996. Figure 3b displays the annual discharge at one runoff site. The locations of these sites can be seen in Figure 4, which displays all of the SNOTEL and runoff sites used. In this figure, the gray circles represent SNOTEL sites and the yellow markers represent runoff sites. Snow water equivalent data points from each SNOTEL site

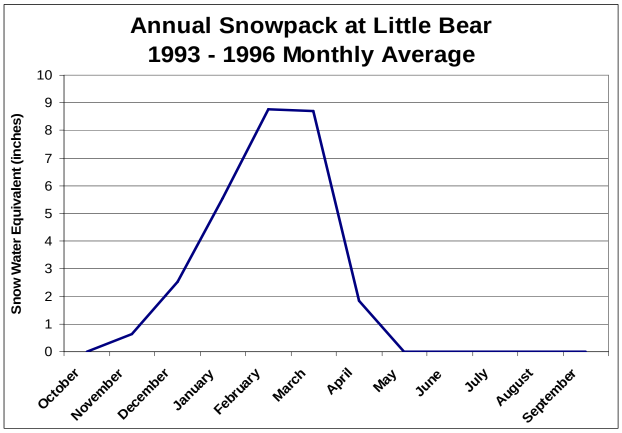

Figure 3a. Annual Snowpack.

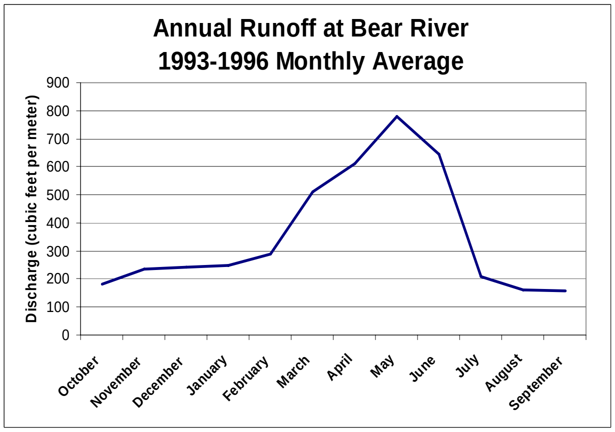

Figure 3b. Annual Runoff.

were plotted against discharge values from each runoff site. Table 1 displays the R^2 values of these correlations.

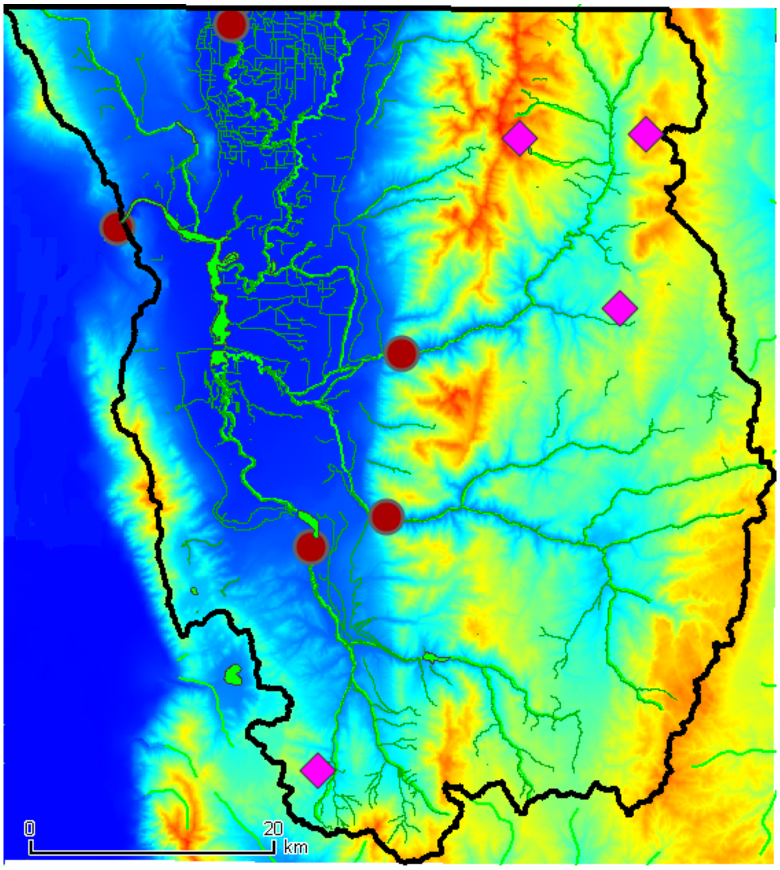

Figure 4. SNOTEL (pink diamond) and Runoff (red circle) Stations from USGS and NRCS.

Table 1. Snow Water Equivalent and Runoff Correlations

	Franklin Basin	**Tony Grove Lake**	**Temple Fork**	**Little Bear**
Bear River (ID)	0.5076	0.43	0.8144	0.7131
Bear River (BE)	0.608	0.5926	----	0.0118
Logan River	0.4838	0.3703	0.8857	0.0007
Little Bear	0.6244	0.6681	0.7773	0.6534

Reference Evapotranspiration and Crop Coefficient

The reference evapotranspiration map (Figure 5) was calculated using the FAO Penman Monteith equation and several gridded climate variables, including radiation, humidity, temperature, and wind speed. The crop coefficient map (Figure 6) was calculated using Leaf Area Index (LAI) data from MODIS.

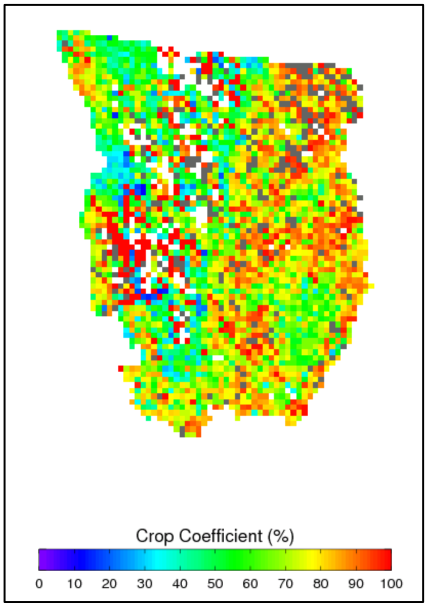

Figure 5. Crop Coefficient.

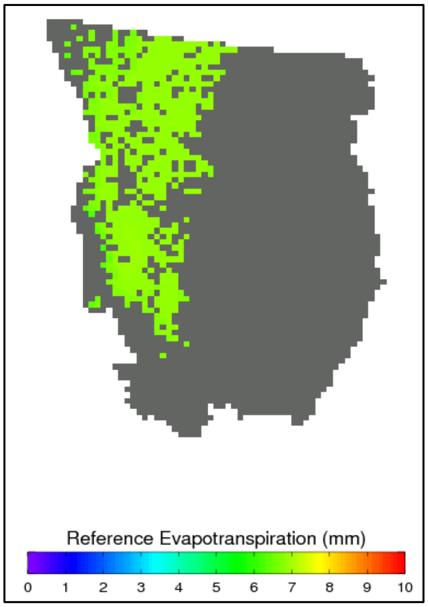

Figure 6. Reference Evapotranspiration.

Current Snow Cover and Crop Evapotranspiration

Figures 7 and 8 respectively display the current snow cover and crop evapotranspiration in Cache County. The snow cover map was produced using average climate data from 2001 to 2006. This map displays average snow cover in March, when winter snowpack is the highest. Figure 8 displays crop evapotranspiration (ET_c) in Cache County and was produced using data from 2001 to 2006 in July, when ET_c is the highest.

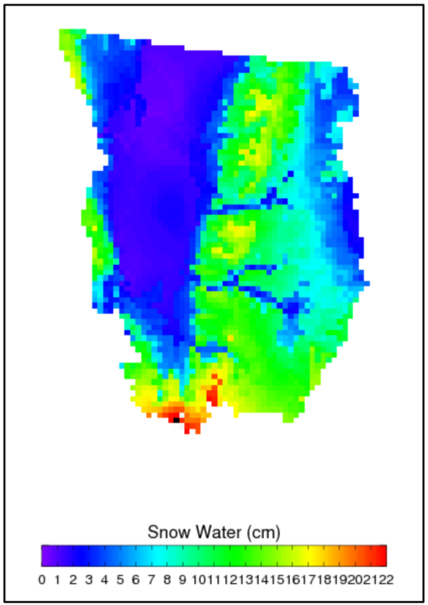

Figure 7. March Snow Cover Map.

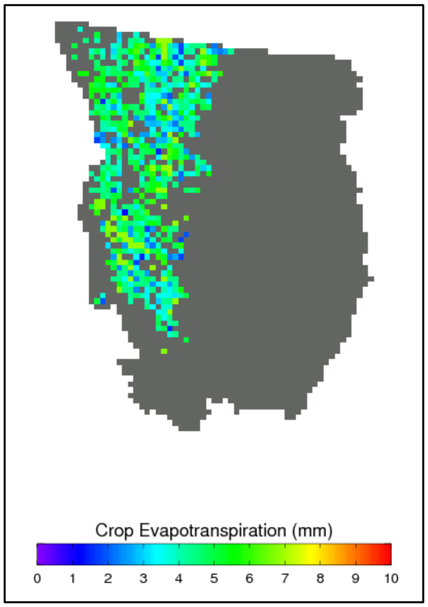

Figure 8. July Crop Evapotranspiration.

Irrigation Efficiency

The average irrigation efficiency was obtained by subtracting the amount of water needed for crop evapotranspiration from the amount of water used for irrigation plus the amount of water delivered from precipitation in Cache Valley, yielding an efficiency value of less than 30%.

Future Snow Cover and Crop Evapotranspiration

Based on the current snow cover and crop evapotranspiration data and the GISS GCM climate change scenario, we were able to predict the change in snowpack and crop evapotranspiration in year 2100. Figure 9 displays current annual snowpack in snow water equivalent and the prediction for the future based on the climate change scenario. The forecast for 2100 corresponds with a 24% decrease in snow cover and earlier snowmelt by about one week. Figure 10 displays current annual crop evapotranspiration and the future prediction, also based on the climate change scenario. This figure corresponds with a 2% increase in crop evapotranspiration by year 2100.

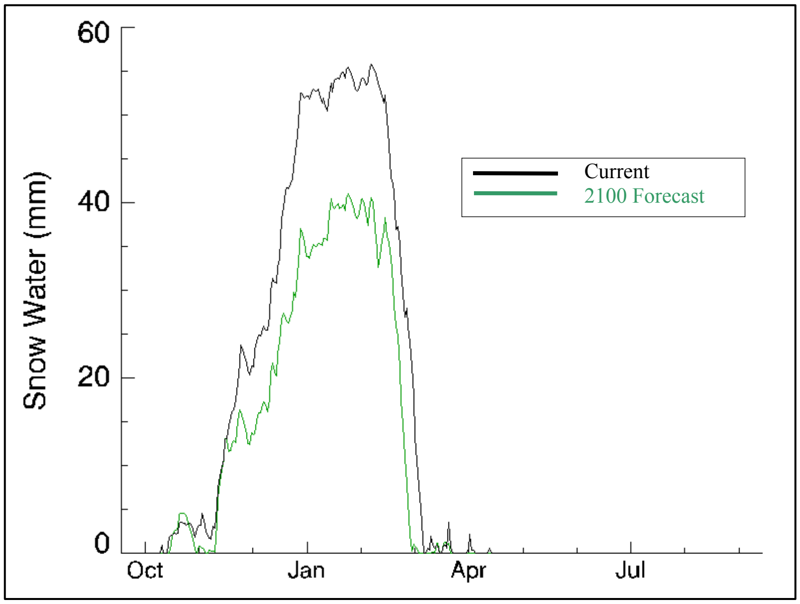

Figure 9. Current and Future Snowpack.

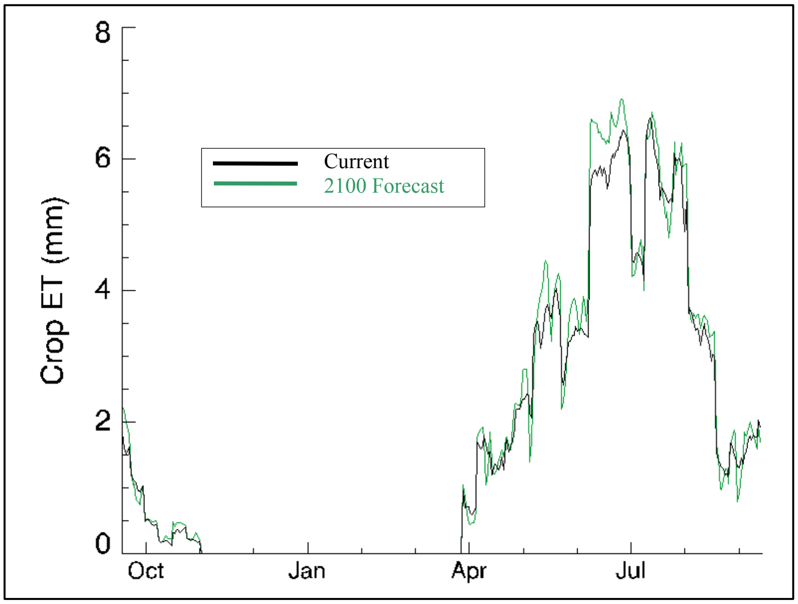

Figure 10. Current and Future Crop Evapotranspiration.

DISCUSSION AND CONCLUSIONS

The high correlation between winter snow depth in the mountains around Cache County and spring-peak runoff of rivers in Cache Valley indicates that with the current infrastructure in Cache Valley, cropland irrigation is extremely dependant on a large supply of snow in the mountains. Figure 3b shows the average annual runoff pattern of one typical river that runs through Cache County. Approximately 60 percent of the annual flow occurs during the three month spring snowmelt season of April, May, and June.

During the warmer period of July, August and September, the river level reaches its lowest point due to increased snowmelt and decreased precipitation. It is during this period that peak municipal demands occur, especially for cropland irrigation. Figure 10 shows the average annual evapotranspiration pattern in Cache County, displaying that the crop evapotranspiration is the highest during July and August. The temporal difference of water supply and demand creates the need to store water from spring snowmelt to prepare for the huge water demand in the summer. In the future it may be necessary to create more water storage reservoirs to assure consistent and dependable irrigation in Cache Valley. It is important to consider, however, the impacts of additional reservoirs on the aquatic ecosystem.

Table 2. Current and Future Municipal Water Needs in Cache County

Year	**2000**	**2010**	**2020**	**2050**
Water Demand	27,800	32,200	35,600	46,400
Reference Supply	43,200	43,200	43,200	43,200
Surplus (+)/ Deficit (-)	15,400	11,000	7,600	-3,200

Data from the Utah Governor's Office of Planning & Budget Population Projections is shown in Table 2. The Utah Division of Water Resources (2000) has predicted that the water demand in Cache County will rise in the future due to increased municipal need. Even without a decrease in water supply, a deficit is expected in Cache County by 2050. Our study, however, predicts increased evapotranspiration and a decreased amount of snowmelt as temperatures rise, placing a further strain on water resources in the future. Additionally, higher temperatures will cause the snowmelt period to both begin and end earlier, prolonging an already difficult summer drought season.

Urbanization is expected to occur in Cache Valley, resulting in the conversion of some farm land to residential areas. The residential water use will increase with as population grows in the future. However, Cache Valley will remain a primary agricultural producer and there will continue to be a huge potential for water conservation through increased irrigation efficiency.

The TOPS forecast can help scientists and members of the Cache County agricultural community to estimate the appropriate amount of water that will be available for irrigation in the upcoming future. Additionally, the information can be used to help improve current irrigation efficiency since these values are currently as low as only 30%. By comparing water supply to water demand, TOPS can estimate the water supply during growth season and determine when and how much irrigation is effective. Following a precise irrigation schedule that considers crop type, time of year, and actual evapotranspiration can help to improve water efficiency. Finally, based on this study's prediction of the future water cycle, policymakers could adjust current management to better conserve the limited water resources in places like Cache Valley.

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REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. Crop evapotranspiration: Guidelines for computing crop water requirements, *FAO Irrigation and Drainage Paper No. 56*, Rome.

Clapp, R.B., G.M. Hornberger, 1978. Empirical equations for some soil hydraulic properties, *Water Resources Research*, 14, 601-604.

Justice, C.O., J.R.G. Townshend, E.F. Vermote, E. Masuoka, R.E. Wolfe, N. Saleous, D.P. Roy, and J.T. Morisette, 2002. An overview of MODIS Land data processing and product status, *Remote Sensing of Environment*, 83:3-15.

Nemani, R.R., M. White, L. Pierce, P. Votava, J. Coughlan, and S. Running, 2003. Biospheric monitoring and ecological forecasting, *Earth Observing Magazine*, 12:6-8.

Rango, A., J. Marinec, 1995. Temperature index melt modelling in mountain areas, *J. Hydrology*, 282(1-4):104-115.

Thornton, P.E., 1998. Description of a numerical simulation model for predicting the dynamics of energy, water, carbon, and nitrogen in a terrestrial ecosystem, Ph.D. dissertation, University of Montana, Missoula, MT.

Utah Division of Water Resources, 2000. Bear River Development, URL: http://www.water.utah.gov/Brochures/BRDev.PDF (Date last accessed: 22 August 2008).

Utah Division of Water Resources, 2001. Utah's Water Resources, Planning for the Future, URL: http://www.water.utah.gov/waterplan/ (Date last accessed: 22 August 2008).

White, M.A., and R.R. Nemani, 2004. Soil water forecasting in the continental United States: Relative forcing by meteorology versus leaf area index and the effects of meteorological forecast errors, *Canadian Journal of Remote Sensing*, 30:717-730.

White, M.A., P.E. Thornton, S.W. Running, and R.R. Nemani, 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: net primary production controls, *Earth Interactions*, 4:1-85.