Improved Irrigation Efficiency as a Tool for Climate Change Adaptation in Arid Environments

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Abstract. *Potential changes in irrigation efficiency were investigated to assess their impact on agricultural and urban water demand in the Rio Grande basin in Jujuy province, Argentina, over the 50-year period from 2010 to 2060 within the context of three climate change scenarios derived from the Fourth Assessment of the Intergovernmental Panel on Climate Change and applied to two Global Circulation Models. The basin is an arid region that suffers from water scarcity, seasonal shortages and competition among water users, including urban, agriculture, food processing, and hydropower. The case-study evaluated feasible improvements in the efficiency of irrigation water systems to determine whether water savings from such improvements would be sufficient to off-set anticipated growth in water demand. This study is an attempt to contribute to the broader assessment of applying the principles of 'climate-smart agriculture' to arid, water scarce environments, and correlates the improvement in water efficiency to two other objectives: achieving equal or greater agricultural yields of current crops; and mitigating the ecological damage caused by traditional, extensive agricultural regimes . This paper focuses on two potential irrigation interventions providing irrigation efficiency greater or equal to 60% and the baseline ('no-intervention') option using reference transpiration derived from CROPWAT calculations based on five decadal climate projections for sugar cane and tobacco and suggests that improved irrigation efficiency is a critical intervention for climate change adaptation. Irrigation efficiency is one of the major component tools of 'climate-smart agriculture'*

Keywords. Climate-smart Agriculture, Food Security, Global Circulation Models, Irrigation Efficiency, Water Scarcity

Introduction

Water scarcity

Those most in need of poverty and undernourishment reductions live in the most water-scarce environments. Currently, about 700 million people in 43 countries suffer from water scarcity. A region is experiencing water stress when annual water supplies drop below 1,700m^3/capita. When annual supplies drop below 1,000m^3/capita the population faces water scarcity, and when annual water supplies drop below 500m^3/capita the population faces absolute scarcity (UN, 2005). "By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water-stressed conditions" (FAO, 2007). Food insecurity increases as populations transition from water-stressed conditions to water-scarce conditions (Bellarby, Foereid, Hastings, & Smith, 2008; DuBois, Chen, Kanamaru, & Seeberg-Elverfeldt, 2012; Murphy & Boyle, 2012). Almost half the world's population will be living in areas of high water stress by 2030. In addition, water scarcity in some arid and semi-arid places will displace between 24 million and 700 million people (FAO, 2007).

Greenhouse gas emissions

Agriculture accounts for more than one-third of all greenhouse gas emissions and consumes 36% of all arable land (Rockstrom, Gordon, Folke, Falkenmark, & Engwall, 1999), and agricultural irrigation consumes 70% of the world's available water (Agricultural Water Conservation Clearinghouse, 2009). Climate scientists posit that the planetary threshold for the percentage of global land cover converted to cropland is 11.7% (Rockstrom, et al., 2009) and, that if traditional extensive farming techniques continue to expand, the percentage of global arable land under agriculture will grow to an unsustainable 60% by 2050 (Rockstrom, et al., 2009). Reducing the need for additional land conversion to agriculture represents nearly as much GHG emissions as those directly generated from agricultural activities (Branca, McCarthy, Lipper, & Jolejole, 2011). The problem addressed in this research is how agricultural production can be improved intensively in arid regions (on currently cultivated land) within the context of projected climate change impacts over the next five decades while also providing available water for urban consumption.

Arid warm-dry regions have average (mean) carbon sequestration values of approximately 1.14 tons of CO_2 equivalent/hectare/year (European Commission, 2011). Carbon sequestration for "set-side" land,i.e., land that is not transformed to agricultural production from a natural state, in warm-dry areas has an average (mean) of 3.93 tons of CO_2 equivalent/hectare/year (European Commission, 2011). They key metric for reducing greenhouse gas emissions is the extent to which agricultural yields are increased on extant agricultural land. According to the United Nations Framework Convention on Climate Change (UNFCCC) "emissions from the conversion of grassland to cropland were 29.3 Mt CO_2 and removals from the conversion of cropland to grassland were -31 MT CO_2. Thus, a net contribution from total land conversion between cropland and grassland was a slight sink of -2.5 Mt CO_2" (European Commission, 2011).

Climate-smart agriculture

The methodology to: mitigate the environmental damage that is caused by traditional agricultural regimes; adapt to changing environmental conditions; and improve agricultural production and profitability for the grower, is referred to as "climate-smart agriculture" (CSA). Improved irrigation efficiency and intensive agricultural production are key tools of CSA and make up the scope of this research. Other tools that complement improvements in irrigation efficiency and intensive agriculture include: conservation tillage; integrated pest and nutrient management; utilization of green (rain) water; water harvesting; runoff capture; improved drainage; terracing; and the utility of hybrid cultivars.

Research questions

The research questions for this study are:

- What will be the urban and agricultural water demand by 2060 in an arid region in response to a range of downscaled climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC)?
- What will be the theoretical implications of different degrees of irrigation efficiency on urban and agricultural water availability over the same period?
- What are the potential reductions in greenhouse gas emissions as a result of improved irrigation efficiency?

Materials and methods

This study does not empirically measure outcomes of interventions on agricultural farmland. Rather, this research models a baseline agricultural regime and then calculates the potential change in yields, environmental indicators and overall water availability as a function of changes in irrigation efficiency.

Climate modeling methodology

The framework for this research design is scenario planning. Climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) describe future developments. Scenario planning for this research is based on IPCC Climate scenarios, which emanate from the Fourth Assessment of the IPCC, for three storylines or socio-economic scenarios—A2, A1B, B1 (IPCC, 2008). These three storylines represent worst, moderate, and best case projections, respectively. The A2 scenario projects an increase of 3.4^0C best estimate for the period 2090-2099; A1B—2.8^0C; and the B1 scenario—1.8^0C. (IPCC, 2008). These scenarios were downscaled by use of the online climate projection tool known as Climate Wizard to project changes in temperature and rainfall for the period under investigation. Downscaling climate data is a method for generating locally relevant data by utilizing Global Circulation Models (GCMs) that provide estimates for climate change in a given spatial and temporal setting. Two GCMs are integrated in the research: the Commonwealth Scientific and Industrial Research Organization (CSIRO) MK3 model and the UK Met Office (UKMO) Hadley CM3.1 model. The CSIRO model is utilized by the World Bank for 'dry' scenarios. The CSIRO Mk3 GCM has a spatial resolution of 1.25o latitude by 1.875o longitude with 38 layers in the vertical extending to over 39 kilometers making it reliably representative over the study area (Science and Technology Facilities Council: Natural Environment Research Council, 2011. The UKMO model has been frequently used for climate projections in Argentina.

Computations for this research were carried out in twelve successive steps in the following manner:

1. Identification of the "combined basin of the Rio Grande and the upper Rio San Francisco" (Wyatt, et al., 2012) of Jujuy Province and estimation of the stream flow of the basin using data provided by the Hydro-BID watershed modeling tool in the IDB and RTI study (Wyatt, et al., 2012).

2. Selection of the agricultural sample for the study. This research does not use a randomly selection sample but, instead includes 100% of all the sugarcane and tobacco fields in Jujuy Province, Argentina: 14,238 Hectare (ha) tobacco, and 19,122 ha sugarcane (equivalent to 35,597 and 48,030 acres, respectively).

3. Integration of reliable data for baseline precipitation and temperature for the period 1974-2010 from the local Jujuy Province El Perico airport station as reported by the Argentine National Weather Data service.

4. Identification of the current and estimated growth in population of San Salvador de Jujuy and per capita water supply. San Salvador is the capital city of Jujuy Province and has a current population of 265,249, the water supply is 74,400 m^3/day corresponding to a daily per capita supply of 273 liters. Population growth is about 1.5 percent/year and increases in rural water consumption is estimated at 2.5 percent/year (FAO, 2008; Wyatt, et al., 2012)

5. Downscaling of the three socio-economic scenarios based on two GCMs: the Commonwealth Scientific and Industrial Research Organization (CSIRO) MK3 model; and the UK Met Office (UKMO) Hadley CM3.1 model. for the Jujuy Province utilizing climate wizard.com. The climate scenarios are based on IPCC's Fourth Assessment: A2, A1B, B1 (IPCC, 2008).

6. Projection of temperature and precipitation changes for the decades 2010-2060 based on the three climate scenarios for each GCM.

7. Conversion of precipitation (P) to "effective precipitation" (Pe) using the calculations provided by the Food and Agriculture Organization of the United Nations (FAO). Pe= (0.8P)-25 if P>75 mm/month; Pe-(0.6P)-10 if P<75 mm/month. (FAO, 2008)

8. Calculation of Etr for each decade from CROPWATER 8.0, a software program, and verfied as locally reasonable. Kc factors were derived from multiple professional agricultural sources including the FAO (FAO, 2010).

9. Calculation of "Irrigation Need" $IN=(ETr-P_e)*(K_c)*(A_i/E_o)$ where, IN=Irrigation need; ETr=Reference ET (mm/month); Pe=Effective precipitation (mm/month); Kc=Crop coefficient (percent/month); Ai=Area irrigated; and Eo=Overall efficiency of the irrigation system, which is calculated by multiplying the efficiencies of water

conveyance (Ec) and water application (Ea). The water conveyance system is a control variable

10. Recalculate IN by inputting three variations of Eo (37%, 60%, 90%). 37% represents no-intervention which is characterized by unscheduled, furrow irrigation; 60% represents solid-set sprinklers; and, 90% represents a drip irrigation system.

11. Summarize and analyze water availability for irrigation and urban use for socio-economic scenarios.

12. Provide estimate for 'set-aside' land. Set aside land is the aggregate change in greenhouse gas emissions for every unit reduction in land not required for agricultural production. This method follows the formula that says that for every unit reduction in agricultural land (due to increased yield, or, 'intensive agriculture') for each season, the aggregate mean change in greenhouse gas emissions will be 3.93 tons of CO_2 equivalent/ha (t CO_2-eq/ha).

Study area: Jujuy Province Rio Grande river basin

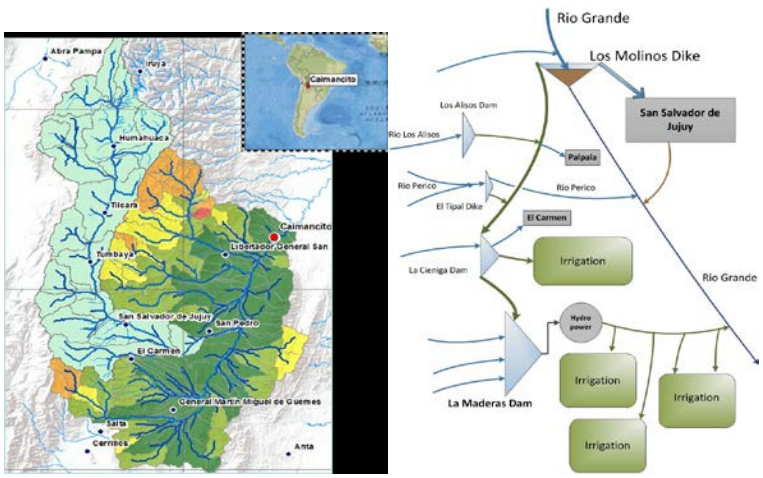

Figure 1 Jujuy watershed and Schematic Rio San Francisco river basin

This research study area is the Jujuy Province in northwest Argentina which is one of the most remote and least developed provinces in the country. The water basin under study is an arid region that suffers from water scarcity, seasonal shortages and competition among water users, including urban, agriculture, food processing, and hydropower. The two predominant crops in the province are tobacco and sugar cane. This is a predominantly agricultural region that was first selected as a test site to assess the negative consequences of climate change on water resources for the five decadal periods, 2010-2060 by the Inter-American Development Bank (IDB) and RTI International in (Wyatt, et al., 2012) .
Water diverted for irrigation is stored in four downstream dams with total capacity of 341 million cubic meters (Mm^3). Local data reports that sugar cane consumes about 77 Mm^3/year; tobacco consumes about 48Mm^3/year. Observations from the field indicate that sugarcane consumes about 103 Mm3/year and tobacco about 77 Mm^3 (Wyatt, et al., 2012).
Water demand for irrigation varies monthly. Baseline data indicate that there is surplus of water from January-April and a deficit from May-December. Industrial, urban and hydropower consumption is constant throughout the year.

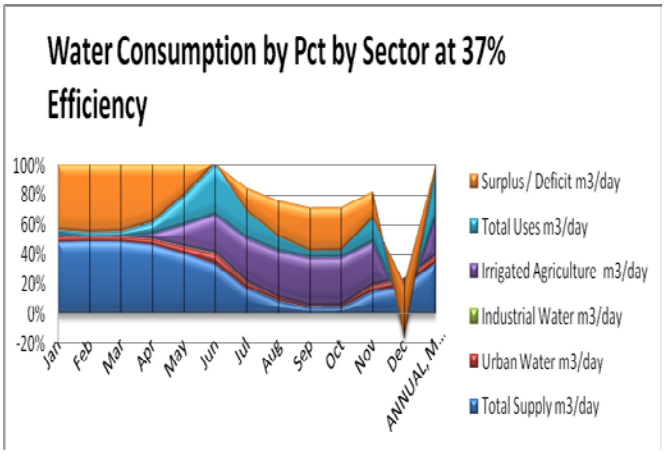

Figure 2 Water consumption by sector

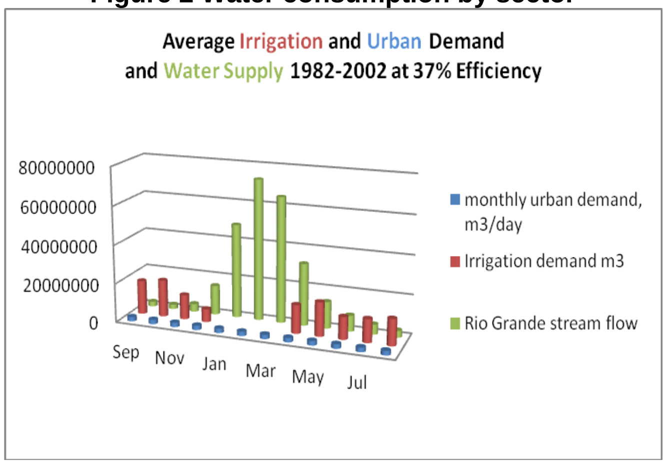

Figure 3 Average irrigation and urban demand 1982-2002

Agricultural production

Tobacco and sugarcane are the dominant crops in the Jujuy Province. Together they make up about 99% of all agricultural production.

Table 1 Irrigated agriculture in Jujuy province (Wyatt A. , 2013)

Irrigation Area (Ha)				
PLACE	Tobacco	Sugar Cane	Other	Total
	Ha	Ha	Ha	Ha
Carmen (10)	12392.80	1646.30	150.00	14189.10
Palpalá (9)	1058.50	183.00	200.00	1441.50
San Antonio (11)	539.10	0.00	65.00	604.10
Dr. M. Belgrano (8)	182.00	0.00	45.00	227.00
San Pedro (12)	66.00	17382.50	25.00	17473.50
Total	**14238.40**	**19211.80**	**485.00**	**33935.20**
%	**0.42**	**0.57**	**0.01**	**1.00**

Records of production of tobacco and sugar cane have been kept since the 1980's in Jujuy province but production over that period has been relatively stagnant (Province of Jujuy, 2010) as the figures below illustrate.

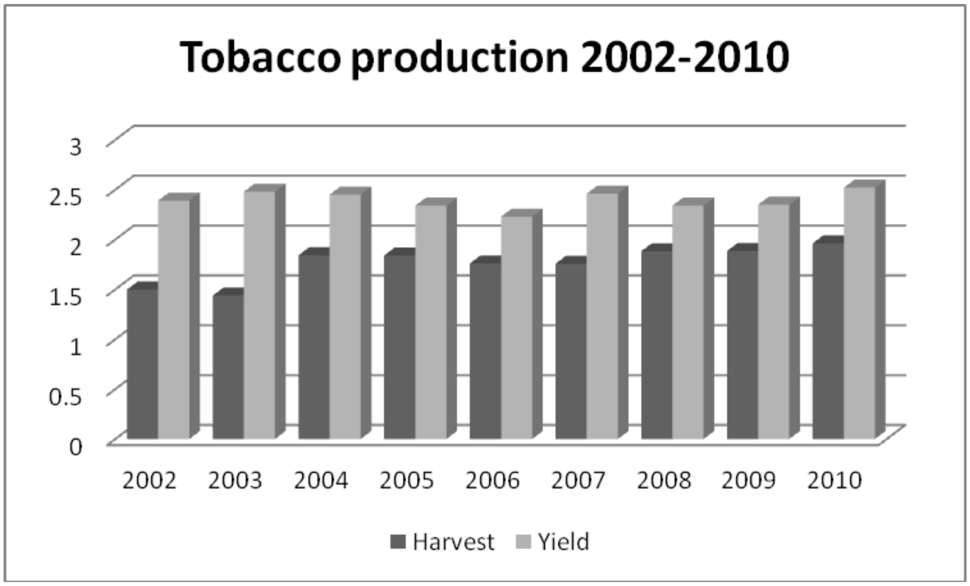

Figure 4 Tobacco production in Jujuy 2002-2010 (Province of Jujuy, 2010)

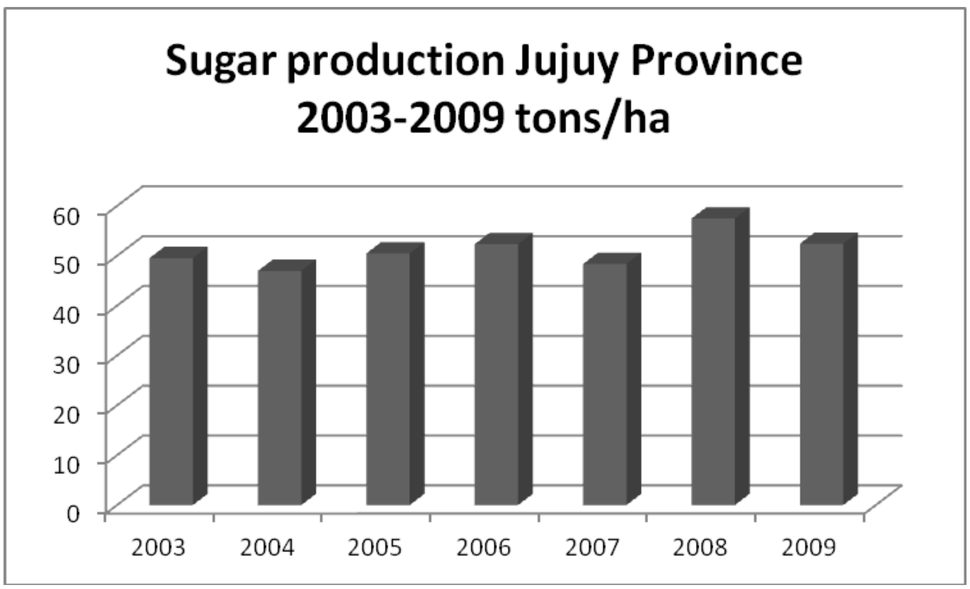

Figure 5 Sugarcane production in Jujuy 2003-2009 (Province of Jujuy, 2010)

Potential yields

By utilizing crop coefficient data over the growing season, regardless of irrigation regime, it is possible to achieve improved production. The basic proposition is that delivering irrigation applications at varying degrees over the growing season will improve production. The general schematic illustrating this procedure follows.

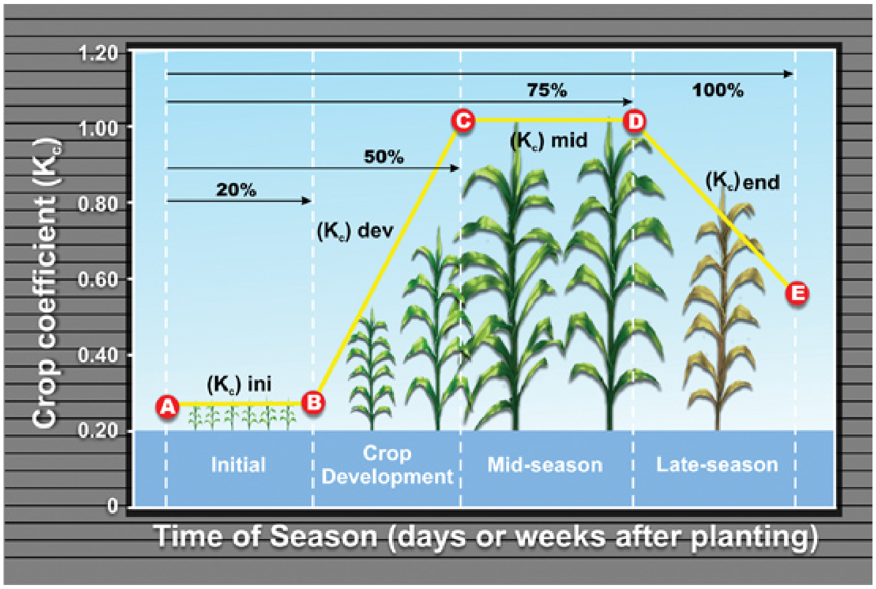

Figure 6 Crop coefficient schematic (Irmak, 2009)

Conducting an empirical evaluation of all the salient variables necessary to achieve optimal agricultural production is beyond the scope of this research but it is necessary to briefly explain that scheduled irrigation regimes provide yield benefits.

For sugarcane the critical inputs for optimal production include: land preparation; planting patterns; spacing; proper seeding rates; weed control; applications of pre-emergence and post-emergence herbicides; proper selection, installation and maintenance of the irrigation system; crop irrigation scheduling; seasonal fertigation; 'hilling-up' soil; detrashing; propping; and harvesting properly (Barak, 2012). Under these conditions yields can reach between 140-160 tons/ha or about 2.5 times the current yield in Jujuy (Barak, 2012).

For tobacco, yields for the past decade have consistently been between 2-2.5 tons/ha. Irrigation in tobacco is complex because tobacco is susceptible to over watering and its water content requires attention throughout the growing season. Nonetheless, drip irrigated tobacco regularly achieves yields between 3 and 3.5 tons/ha (Duncan & Warner, 2003)

Baseline Data

Baseline data for the research area were derived by consultants on the ground who discovered disparities between reported water usage and actual consumption. (Wyatt A. , 2013).

- Baseline data for irrigated agriculture is 37% efficient.
- Baseline ETr was reported to be 433.67 mm/year.
- Crop coefficients (Kc) for sugar cane were reported to be calculated at 1.15 for every month; Kc for tobacco at 0.95 for every month. Further investigation in the field revealed that no consideration of Kc values have been implemented.
- Sugar cane: ETr 433.57 mm; No data for precipitation; Total irrigation volume is 77,179,469 m^3/year. Further investigation in the field revealed that sugar cane water consumption was approximately 103 Mm^3/year.

- Tobacco: ETr 433.67 mm; Total irrigation volume is 47,252,053 m^3/year. Further investigation in the field revealed that sugar cane water consumption was approximately 77 Mm^3/year.
- Urban demand in San Salvador de Jujuy is provided by water treatment plants and is 26,438,410 m^3/year (72,434 m^3/day); population is 265,249. Average is 273 liters/capita/day but water only provided approximately10 hours per day.

	Sugar Cane	Tobacco
Area (ha)	19,212	14,238
Crop Coefficient (Kc/month)	1.15	0.95
Precipitation	NA	NA
Total irrigation volume (Mm^3/year)	77	47
Observed irrigation volume (Mm^3/year)	103	77
Application efficiency (E_a)	0.37	0.37
Irrigation modality	Furrow	Furrow
Average yield (ton/ha) (USDA estimate Sugar: (Rojas, 2004) USDA estimate Tobacco (Hager, 2000)	55	2

Figure 7 crop data

Hydrologic model

The Hydrologic Model for this research is illustrated below. The model utilizes the three scenarios of the IPCC Fourth Climate Assessment This research downscales the model using the UKMO-Had CM3 and CSIRO Mk3.0 GCMs. This model derives Temperature and Precipitation data to determine ETc, modifies the delivery systems based on irrigation efficiency and then assesses the availability of adequate water for irrigation and for urban use.

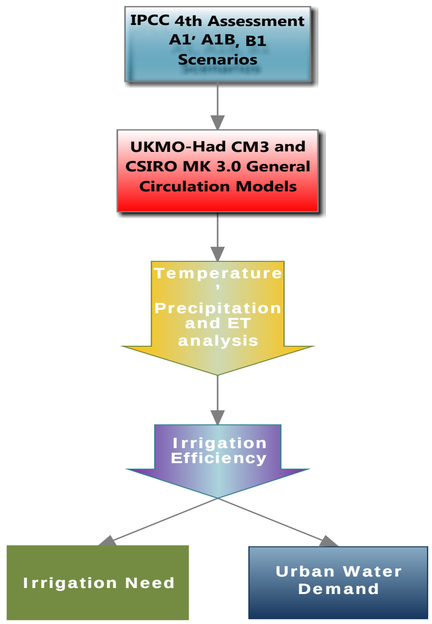

Figure 8 Hydrologic model

Scenario model

The graphic summary of the trend lines for the three scenarios for precipitation and temperature changes for each GCM in the study period, 2010-2060, is illustrated below. Significant to note is that the trend lines for changes in temperature are significant and positive, the trend lines for precipitation changes are positive and insignificant.

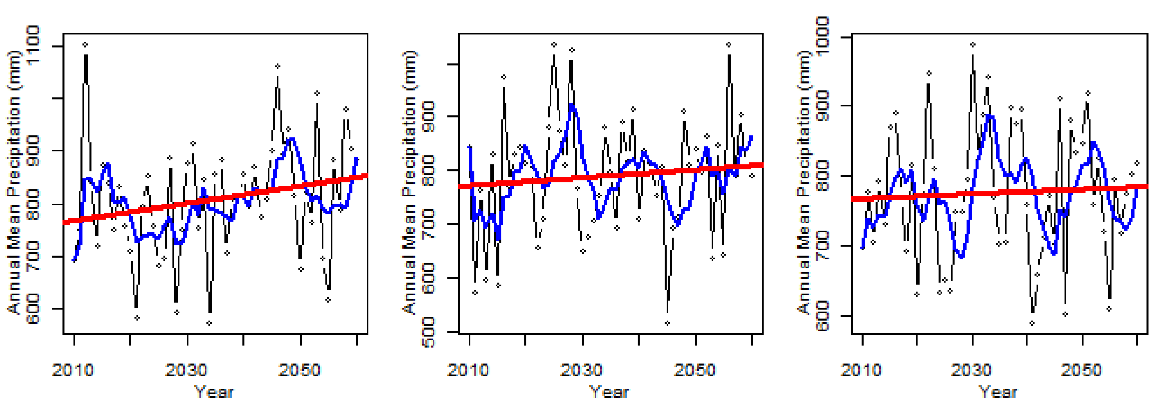

Figure 9 High (A2), Medium (A1B) and Low (B2) Precipitation changes, 2010-2060 CSIRO GCM

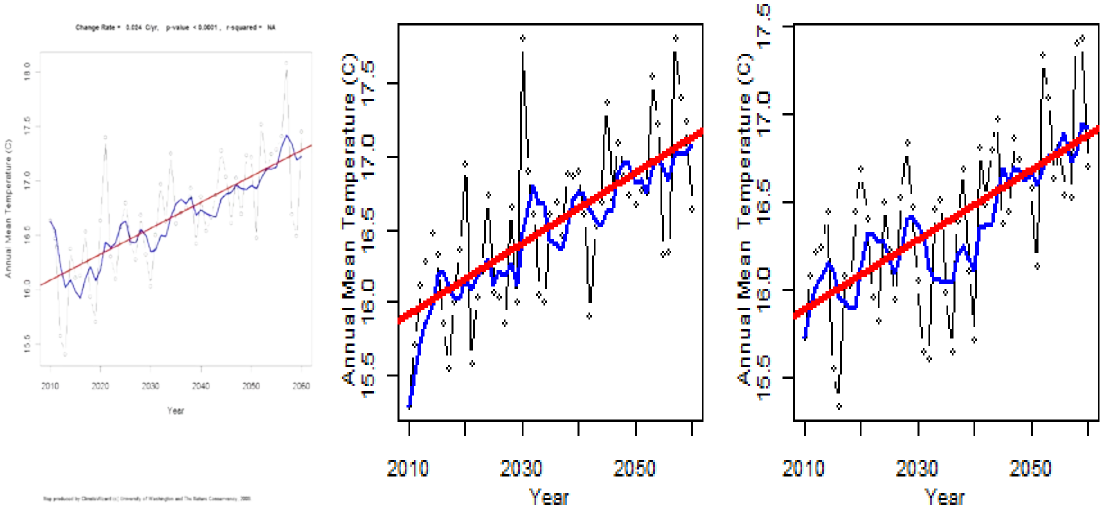

Figure 10 High (A2), Medium (A1B) and Low (B2) Temperature changes, 2010-2060 CSIRO GCM

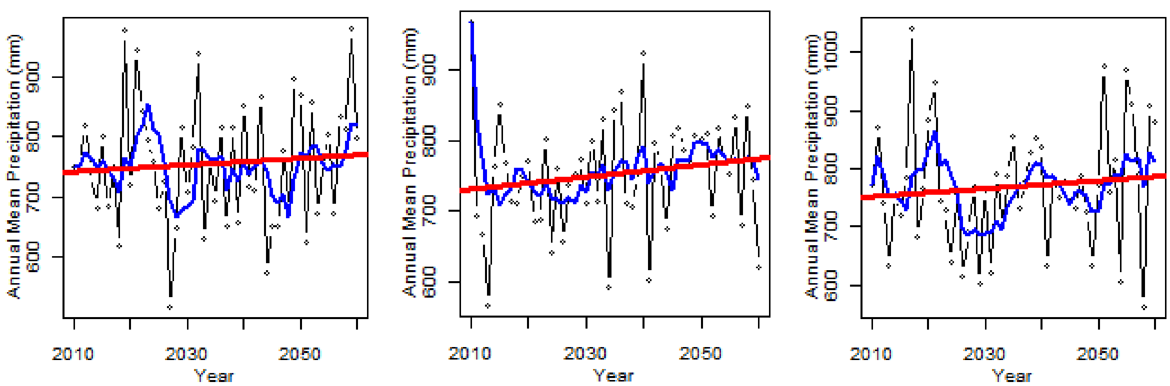

Figure 11 High (A2), Medium (A1B) and Low (B2) Precipitation changes, 2010-2060 UKMO GCM

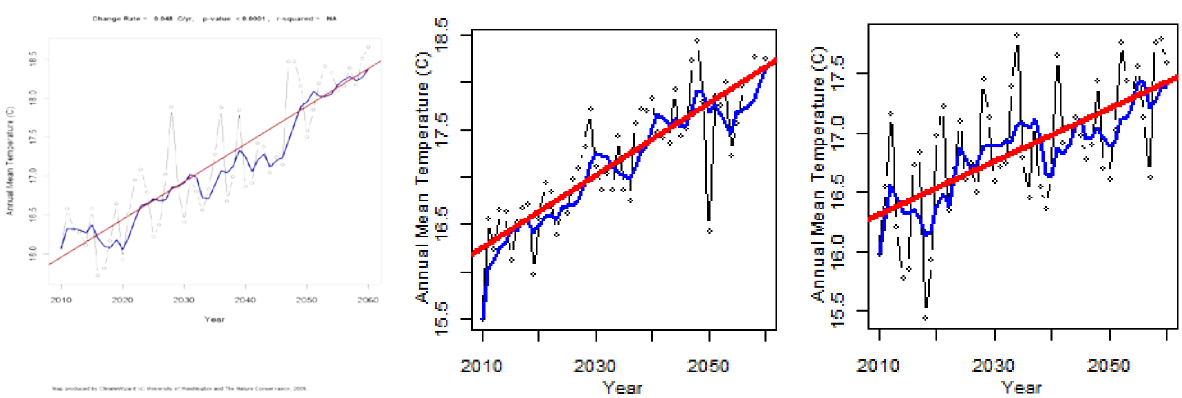

Figure 12 High (A2), Medium (A1B) and Low (B2) Temperature changes, 2010-2060 UKMO GCM

Table 2 Irrigation data

	Approximate Attainable Efficiencies	Value in study
Surface Irrigation		
Furrow	60-75%	37%
Sprinkler Irrigation		
Center Pivot or Linear Move	75-90%	
Solid Set	70-80%	60%
Trickle Irrigation		
Point Source Emitters	75-90%	90%
*Sub-surface Drip	90-95%	

Adapted from Solomon (Solomon, 1998).

Results: 2060 Ensemble

The results of the data analysis are illustrated below. Ensemble data refers to a "group of parallel model simulations used for climate projections. Variations of the results across the ensemble member provide an estimate of uncertainty" (IPCC, 2007). This research uses the 50th percentile which represents the median uncertainty values. The three scenarios produce different temperature and precipitation predictive values which are used as variables to produce different reference transpiration rates and effective precipitation rates, respectively.

The Irrigation Need is calculated according to the three degrees of irrigation efficiency: 37%, 60%, and 90%. The Irrigation Need formula determine the amount of irrigation water demanded by the crop.

All projections are based on 2060 scenarios.

GCM	CSIRO Mk3.0 2060 projection						UKMO-Had CM3 2060 projection					
Scenario	A2		A1B		B1		A2		A1B		B1	
Ensemble T (C) P (mm/year)	T	P	T	P	T	P	T	P	T	P	T	P
	16.7	809	16.5	791	16.4	777	16.9	756	17.2	753	17.1	769
Mean T; Pe	16.7	420	16.5	408	16.4	397	16.9	383	17.2	380	17.1	392

(mm/year)												

ETo (mm/year)-(Pe)	867	877	894	902	916	910

37; 60; 90 E_0 Sugar (m^3/ha)	5390	2100	1406	5452	2134	1422	5557	2176	1450	5608	2194	1486	5694	2228	1486	5656	2214	1476
Mm^3 19212 ha sugar	103	40	27	105	41	27	107	42	28	108	42	29	113	43	29	109	41	28

37; 60; 90 E_0 Tobacco (m^3/ha)	5398	2080	1404	5462	2104	1386	5557	2146	1430	5608	2164	1444	5694	2198	1466	5656	2184	1456
Mm^3 14238 tobacco	77	30	20	78	30	20	79	31	20	80	31	21	81	31	21	81	31	21

Figure 13 Ensemble data for 2060

Total available water (Mm^3/year) 2060	341
Total Urban demand (Mm^3/year) 2060	124

There are 341 Mm^3 water available in the basin. Anticipated population growth for the Jujuy province in 1.5% and increased water consumption is estimated at 2.5%. The projection for urban water use by the year 2060 is approximately 124 Mm^3/year, or about a 100% increase over current demands (Wyatt A. , 2013). The urban water supply efficiency is estimated at 70%, primarily because of leaking water mains (Wyatt A. , 2013).

Discussion

The three scenarios in each of the two GCMs projected mild changes in T and more significant changes in Pe.

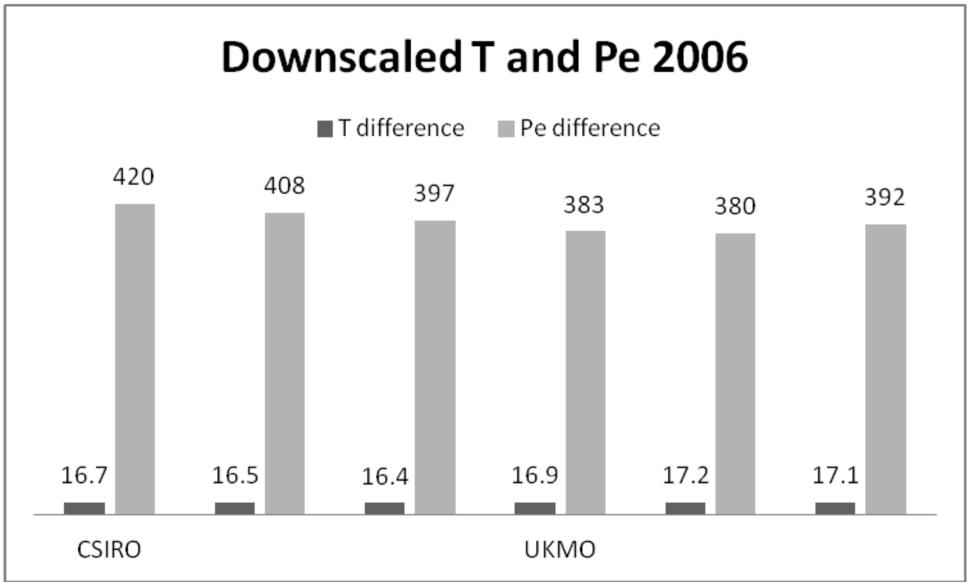

Figure 14 Downscaled T and Pe projections 2060

The range of Pe is 383-420 which correlates to a total water demand range of 171 Mm^3-318 Mm^3. The following figure illustrates that, regardless of GMC and regardless of scenario, the most significant change in availability of water is the efficiency of the irrigation system.

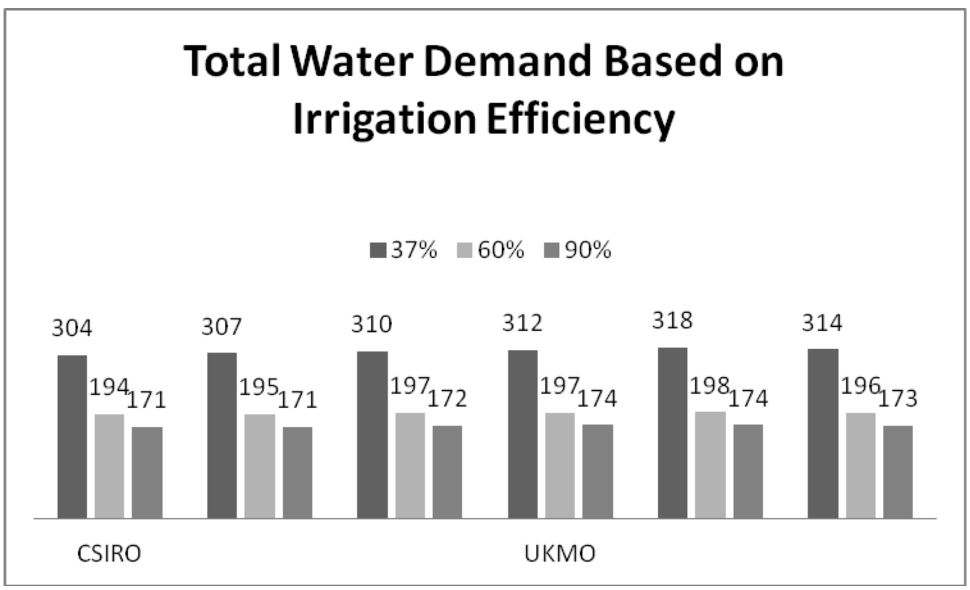

Figure 15 Total water demand based on irrigation efficiency

The research questions under consideration for this paper were:

- What will be the urban and agricultural water demand by 2060 in an arid region in response to a range of downscaled climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC)?

The changes to water demand based on the three scenarios of the two GCMs are negative and insignificant. .

- What will be the theoretical implications of different degrees of irrigation efficiency on urban and agricultural water availability over the same period?

The changes to available water in all scenario based on changes to the efficiency of the irrigation systems are positive and significant.

- What are the potential reductions in greenhouse gas emissions as a result of improved irrigation efficiency?

The potential savings in greenhouse gas emissions are significant and positive. With the adoption of any scheduled irrigation system, particularly at the 60% or 90% levels of efficiency, it is likely that for each year a savings of 3.93 t CO_2-eq/ha.

Conclusion

The total available water for Jujuy is 341 Mm^3/year. At current rates of consumption at 37% efficiency of the irrigation system, and 70% efficiency of the urban system, the total consumption is approximately 304 Mm^3/year. This represents consumption of 88% of available water. The infrastructure of the Jujuy water system is in disrepair and it is reasonable to expect that leaks, which currently amount to 30% loss in the system, will increase in number and severity. The current level of inefficiency is not sustainable.

Critical for solving improved agricultural production, mitigation of environmental damage that traditional agriculture causes, and for mitigating the encroaching problem of water scarcity, is the consideration of implementing regimes of improved irrigation efficiency.

Acknowledgements

The author respectfully acknowledges the outstanding research study on the Jujuy basin (Wyatt, et al., 2012) seminally carried out by the pre-eminent climate change and water resource scholars at RTI International: Alan S. Wyatt, Fekadu Moreda, and Eugene P. Brantly. The author is grateful for their scholarship and assumes sole responsibility for any errata in this paper.

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