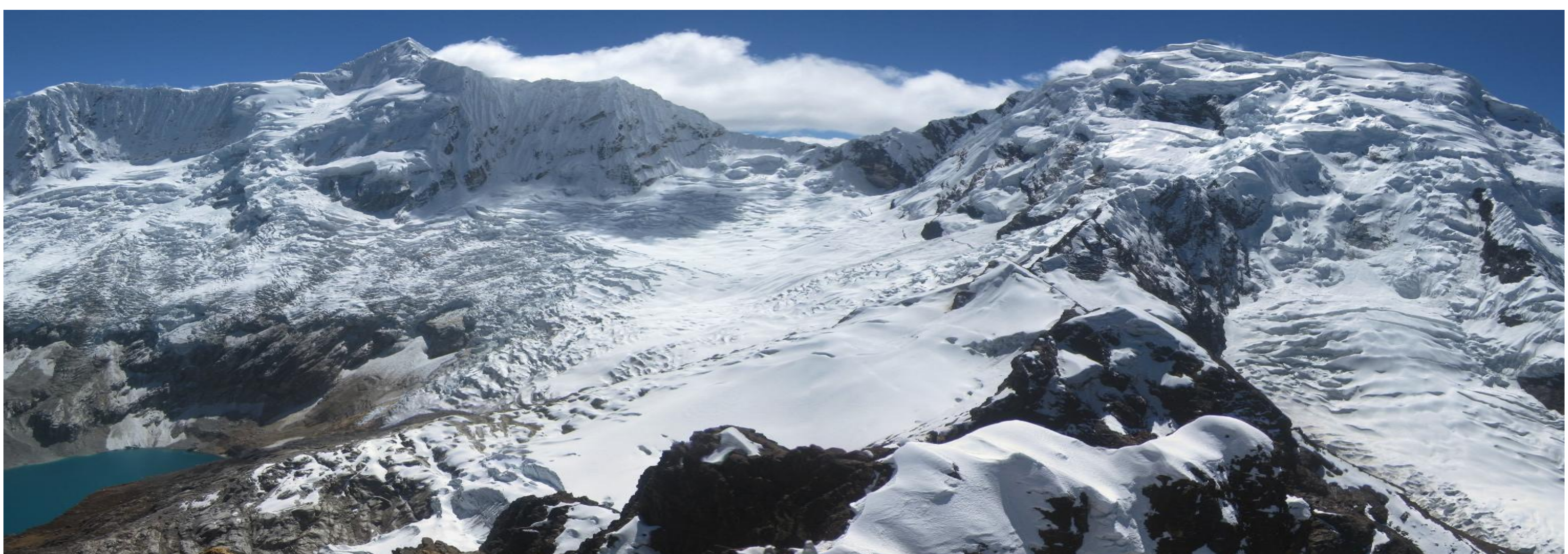
Quilcay Watershed Management Model

Water Resources Planning and Management



Final Term Project

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1.1. Background

In many areas of the world snow pack or glacier buildup during the winter season serves as a reservoir, providing a steady flow of water in the dry months to downstream communities. In the high altitude regions of the Andes glaciers store water as ice during the rainy season that then melts in the warmer, dry season. Since the end of the Little Ice Age, though, glaciers in the Andes have retreated steadily (with a few exceptions when some glaciers expanded for a year or two) (Rabatel et al., 2013). Although glacier retreat initially results in higher outflows to the downstream basin, water storage and flow in the dry season will eventually lessen or disappear altogether. In addition to the glacier's retreat, a trend that existed even before the onset of climate change, expected shifts in weather patterns due to global climate change further threaten water resources from glaciers.

Glacial retreat can also result in the creation of lakes at the base of glaciers that threaten downstream communities. Melt water often collects at the base of glaciers behind a natural dam (termed moraine) of rocks, soil and debris pushed forward by the previously expanding glacier. Terminal moraines tend to be unstable, in part because they often contain ice that is also melting. When a terminal moraine fails, because of the pressure from the growing lake or an avalanche triggered wave, the sudden outflow of water (termed a Glacial Lake Outburst Flood or GLOF) can cause devastation to downstream communities.

GLOF risk mitigation strategies usually consist of draining water from the glacial lakes and lowering the lake level. By lowering the lake level pressure on the moraine will be diminished and the surge of water flowing downstream will decrease in the event of a flood, inundating a smaller footprint. Although lowering the lake level reduces the risk and damage from a GLOF, it also decreases water storage in the lake and could cause supply shortfalls for users. This project focuses on a water resources conflict that has emerged in recent years around the world: how to ensure a consistent water supply to growing populations while also protecting them from the devastation of a GLOF.

1.2. Project Scope

For this project we focus on Lake Palcacocha, which has formed at the base of Palcarajú glacier in the Cordillera Blanca of Peru. Outflows from Lake Palcacocha combine with other tributaries to form the Rio Paria, which in turn provides water to inhabitants of the City of Huaraz and farmers living downstream of Lake Palcacocha. Lake Palcacocha has also produced at least two GLOFs in the past one of which devastated the city of Huaraz in 1941. Currently government officials and international scientists are collaborating to design and implement a risk mitigation project for the lake. The inhabitants of Huaraz and upstream communities are concerned, though, that risk mitigation projects will affect the availability of water in the future.

For this project we will construct a WEAP model to simulate the dynamics of the inflows, outflows and storage in Palcacocha Lake for 2003 to 2010. We will then use this model to simulate how lowering the lake level would have affected water supply during these years. We will rely on the literature and publicly available databases to estimate the model inputs consisting of glacial melt rate, municipal water demand, agricultural water demand, watershed terrain model, hydrological dynamics and precipitation.

2. Methodology

2.1 Model Structure

The Quilcay basin water system is as complex as the amount of hydrological interactions occurring within it, naturally or artificially generated: glacier accumulation and ablation at the head of the basin; precipitation runoff; evapotranspiration; glacier and lake storage; and agricultural and urban withdrawals. We simplified the water system in order to achieve a reasonable representation using available data. Figure 1 shows the simplified model. The system head inflows arise from the estimation of the Palcarajú Glacier and Palacacocha Lake interaction, which we modeled as a pair of connected reservoirs. The only net head inflow comes from precipitation data for 2003-2010 period.

Mass balance in the glacier is given by the difference between inflow (precipitation) and outflow (melting water). The glacier mass balance (satellite derived data) allowed us to estimate the glacier outflows (melting/ablation). The glacier outflow depends on the difference of precipitation and mass balance change. Both time series are treated as known data in the WEAP model: precipitation and outflow. Assuming that all precipitation feeds the glacier (that is that all precipitated water becomes ice) can overestimate the accumulation component of the mass balance and underestimate the outflow (melting/ablation) water. Therefore, the model results will be subjected to the accumulation overestimation error.

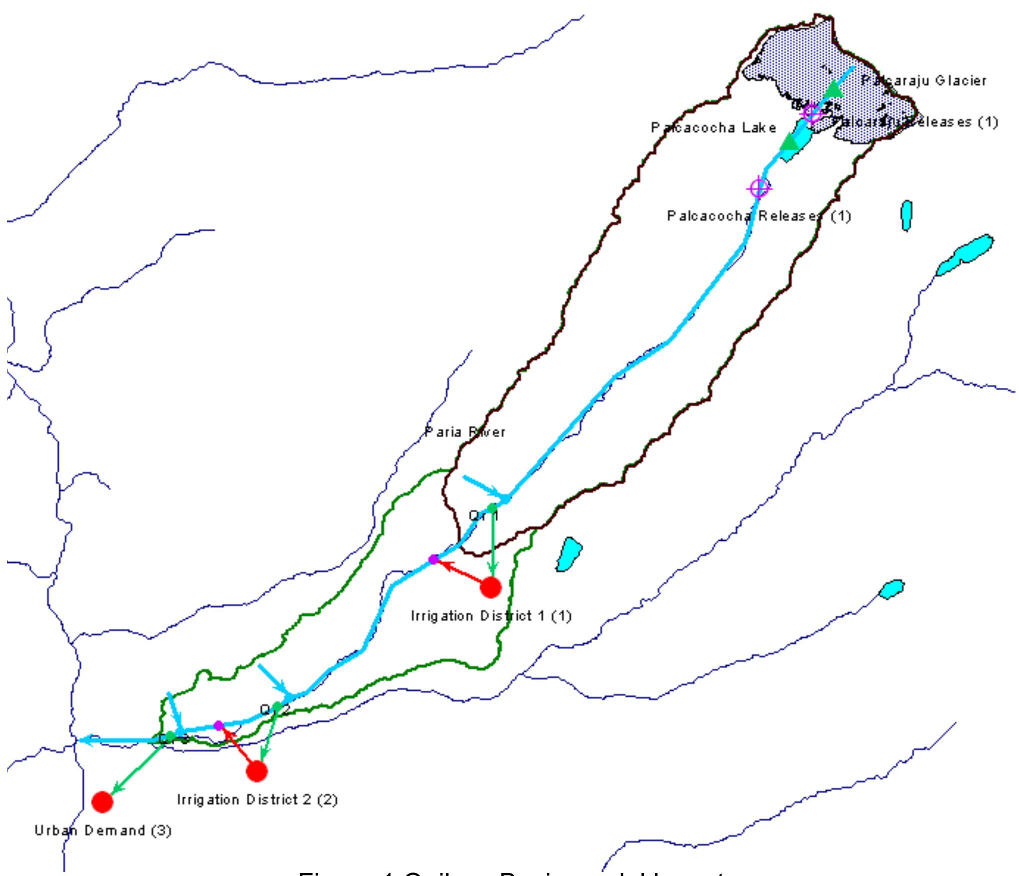

Figure 1 Quilcay Basin model layout

There are no full series of volume data or outflow from Palcacocha Lake. The only available records of volume oscillations for the lake come from satellite estimations that we present in greater detail in the inputs description section. In the WEAP model we set lake outflows to fit the known lake volumes. In order to do this we estimated an outflow function based on the lake available head (height) for each time period.

Additional inflows are added downstream from the lake to account for precipitation-runoff processes within three independent catchments, each one has its outlet just before every new demand node. We neglected evapotranspiration and groundwater processes, so all the precipitation becomes run-off (impervious catchments).

The first two nodes represent agricultural demands while the third one denotes the total urban demand in Huaraz city. Upstream demands have highest priority (irrigation districts 1 and 2) and the urban demand, being the last withdrawal, has the lowest priority. We assigned equal return flow percentages for each of the agricultural demands (25%). Otherwise, urban water return is set to zero given that such return flows out of the basin, discharging into Santa River.

To study the effects of changes in Palcacocha Lake storage capacity over the entire system, we defined two scenarios:

- Current situation: It reproduces 2003-2010 Quilcay basin under the conditions and assumptions described above.
- Water level reduction in Palcacocha Lake: It contemplates a 10m reduction in Palcacocha Lake's maximum level, so its storage capacity is reduced according to the lake level-volume curve. The rest of the parameters (inflows and demands) remain unaltered for this second scenario.

2.2 Water Inflows and Demand Inputs

Water Inflows

A simple precipitation-runoff model is assumed; all the rainfall in the watershed will reach the river (impervious surface) and evapotranspiration losses are neglected. The supply inputs to the WEAP model are the following: (1) Inflow to Palcacocha Lake due melting of the Palcaraju Glacier and (2) Inflow to Paria River due direct runoff; in which the Paria watershed was divided into four sub catchments.

1. Inflow to Palcacocha Lake from melting of the Palcaraju Glacier: The change in storage in the lake (ΔS) is equal to the precipitation in the lake's watershed plus/minus the gain/loss of water due the melting, estimated with the GRACE data ($\Delta S = \mathrm{P} \pm \mathrm{G}$).

2. Inflow to Palcacocha Lake from direct runoff: An impervious surface was assumed, the water flowing into the river in a given month is equal to the precipitation times the area of the sub catchment.

❖ Precipitation Data

The source of precipitation data is the Tropical and Rainfall Measuring Mission (TRMM) from NASA. The mean monthly precipitation was computed for the Paria watershed from March, 2003 to December, 2010. The mean annual precipitation computed using TRMM (456 mm/year) diffesr greatly from the one reported in Quesquén, 2008 (734 mm/year); in order to take the mean difference into account and match the means of the two sources, the TRMM precipitation values were scaled by a factor of 1.61.

Figure 2 shows the distribution of mean monthly precipitation during the period of time of the study (March, 2003 – December, 2010); the precipitation distribution is typical of tropical weathers with the main rain season in the summer.

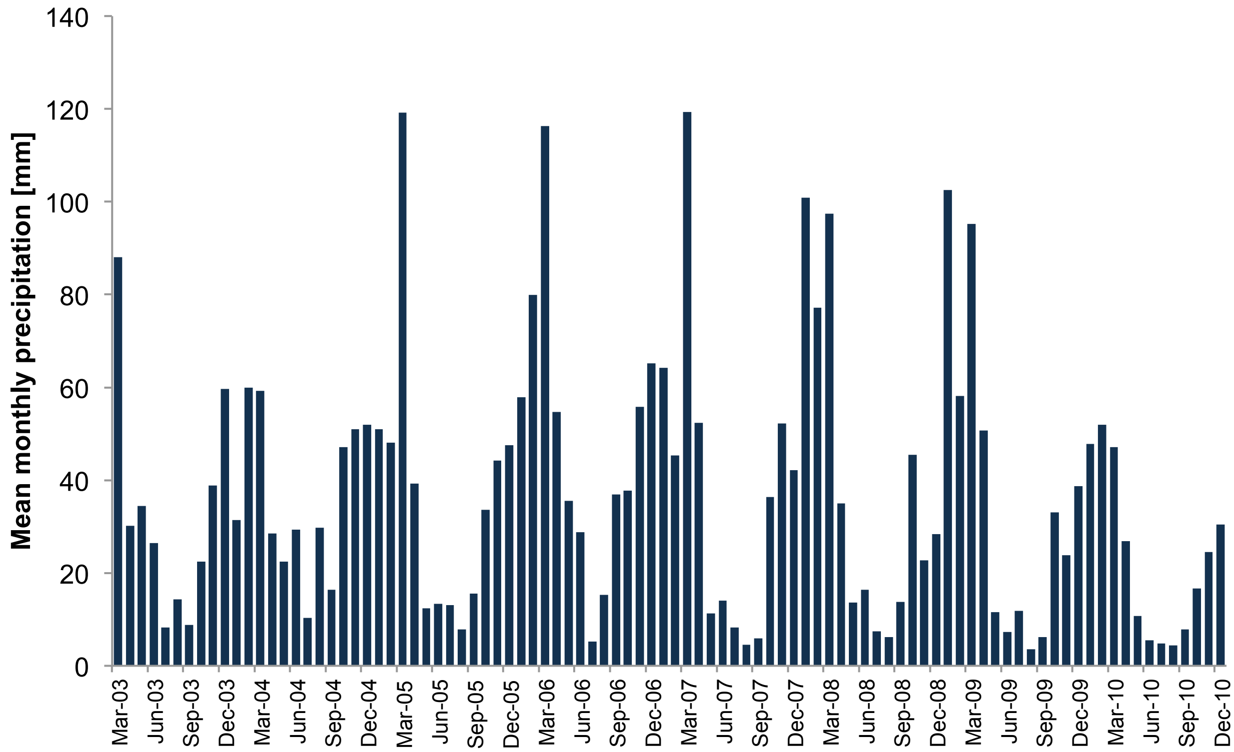

Figure 2: Monthly precipitation data for the Paria river watershed using TRMM data and a scaling factor.

❖ GRACE Data

The melting rate of the Palcaraju Glacier was estimated using the Gravity Recovery and Climate Experiment (GRACE) project from NASA. The mean water equivalent depth gain or loss in a month was computed for the Cordillera Blanca; the local melting rate in the Palcaraju Glacier was assumed to be the same as the gain or loss of water using the GRACE signal in the Cordillera Blanca. There is correlation (0.58) between the estimated volume of Palcacocha Lake and the cumulative gain/loss of water in the GRACE signal. Figure 3 show the GRACE records for the monthly change in water equivalent depth in the Cordillera Blanca.

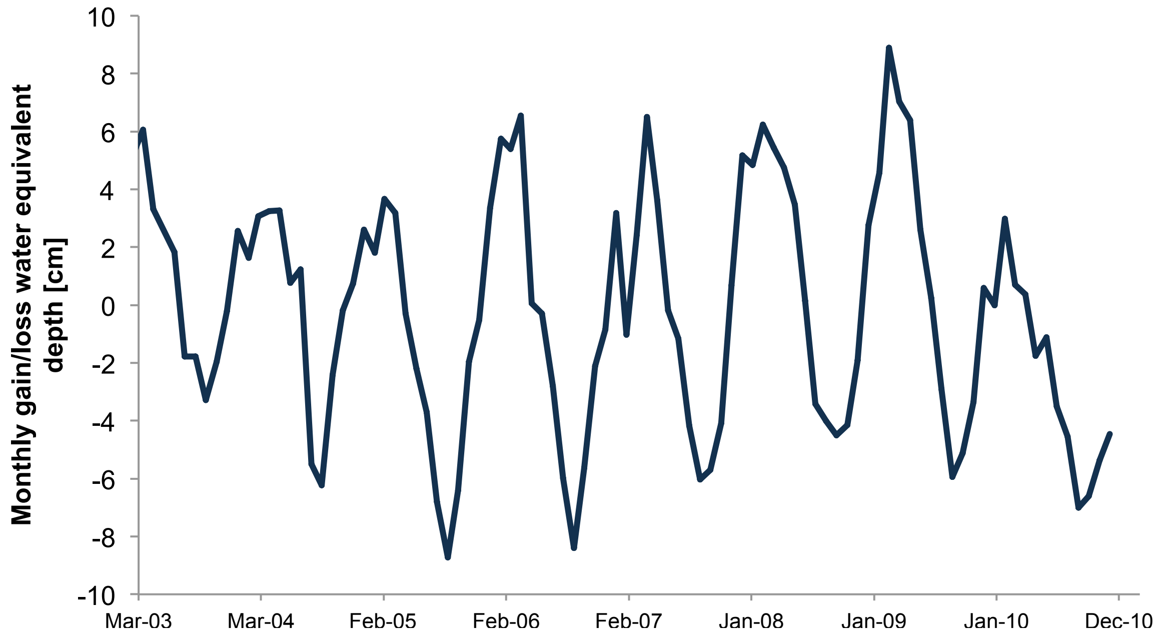

Figure 3: Water equivalent depth gain/loss for the Cordillera Blanca using GRACE records.

Water Demand

The water demand needed to fulfill the agricultural and municipal necessities of the region was obtained using the population of Huaraz and literature sources. The National Institute of Information and Statistics of Peru (INEI 2012) provided the population projections used in this project. Since the data available for the water inflows was available from March 2003 to December 2010, we estimated the agricultural and municipal water demand for the same years.

❖ Municipal Water Demand

The main sources of water supply for Huaraz are the Rio Paria and Rio Auqui. Based on an analysis of vulnerability of the city water system, we estimated that 68% of the city's demand is provided by Rio Paria and 32% by Rio Auqui. According to the stakeholder EPS Charvin SA (2006), the total water needed to satisfy the municipal demand in 2005 was 7,350,905 m^3/year. Considering INEI (2012) population projection, we calculated a water demand of 205 liters per capita per day in 2005. We used this water demand for the analyzed period, assuming that there has not been any water conservation program in the last decade.

❖ Agricultural Water Demand

Upstream of Huaraz there are two irrigation canals fed by the River Paria. These two canals serve the Cojup and Nueva Florida agricultural districts. A 2008 report on water demands in the Rio Santa Basin (which includes the River Paria) estimates irrigation demands for the Cojup and Nueva Florida districts. Given the lack of historical information for agricultural water demand, we assumed that the water demand calculated in 2008 was constant for the 2003 to 2010 period.

3. Results

The WEAP model helped us to obtain the deficit (D_t) of water supplied in the 2003 to 2010 period for the two irrigation districts and the City of Huaraz. To evaluate the performance of the system we estimated the reliability, resilience and vulnerability for each scenario.

- Reliability is the frequency with which the demand is satisfied.

$$\text{Reliability} = \frac{\#\text{ of times } D_t = 0}{\text{total number of simulation periods}}$$

- Resilience is the probability that once the system is in a period of deficit, the next period is not a deficit.

$$\text{Resilience} = \frac{\#\text{ of times } D_t = 0 \text{ follows } D_t > 0}{\#\text{ of times } D_t > 0 \text{ occured}}$$

- Vulnerability is the average magnitude of deficits

$$\text{Vulnerability} = \sum_{D_t>0} \frac{D_t}{\#\text{ of times } D_t > 0 \text{ occured}}$$

3.1 Scenarios Results

Table 1 shows the performance criteria based on the deficit given by the WEAP model for scenario 1.

Performance Criteria	Irrigation District 1	Irrigation District 2	Huaraz
Reliability	82.29%	100%	87.50%
Resilience	56%	-	58%
Vulnerability	301,101 m^3/month	0	124,447 m^3/month

Table 1. Scenario 1 Performance Evaluation

Table 2 shows the performance criteria based on the deficit given by the WEAP model for scenario 2.

Performance Criteria	Irrigation District 1	Irrigation District 2	Huaraz
Reliability	80.21%	100%	87.50%
Resilience	53%	-	64%
Vulnerability	242,323 m^3/month	0	130,220 m^3/month

Table 2. Scenario 2 Performance Evaluation

3.2 Analysis of Results

From the results obtained after modeling both scenarios, we can see that:

- The water available for the Irrigation District 1 has a high percentage of reliability in both scenarios, and the capacity of recovering after a failure is around the same order of magnitude. An important difference comes when analyzing the average magnitude of difference, which in scenario 1 is more significant.
- The water demand for the Irrigation District 2 was always satisfied for both scenarios.
- The water available for Huaraz City also has a high percentage of reliability in both cases. The capacity of recovering after a failure is better for scenario 2, and it is slightly more vulnerable than in scenario 1.

As we can see from the results, scenario 2 (reduced storage capacity) favors irrigation district supply reducing the vulnerability for these districts, while it increases urban supply vulnerability.

4. Conclusions

The above analysis shows that lowering the level of Palcacocha lake by 10 meters has a very small effect on the water supply indicators calculated (resiliency, vulnerability, etc.). We can conclude that with regular precipitation and constant water inflows from Palcaraju glacier residents downstream of the glacier and in Huaraz can expect only small changes in their water supply. In the short term, we expect our conclusions and assumptions to hold. We were unable to make projections for glacier outflows and precipitation in the future, so our work does not inform the long term effects of lowering the lake level. With better projections of water inflows and outflows to the Rio Paria watershed our model could inform the long term effects of lowering the level of Palcacocha lake for downstream consumers.

There are two main sources of error in the conceptual hydrological model: first, the overestimation of glacier accumulation due to precipitation and second, overestimation of runoff by assuming an impervious basin. As a consequence, upstream flow results (between Palcacocha Lake and the first demand node) are expected to be lower than the actual streamflows. On the other hand, runoff overestimation is affecting simulated downstream flows, making them higher than the actual values. There are no real measurements to give a sense of the magnitude of error introduced by these assumptions.

The estimation of the melting rate in the Palcaraju Glacier using GRACE data is an innovative approach and provides data that is not available from other sources. However, the assumption that that the GRACE signal in the Palcaraju Glacier is the same as the signal in the Cordillera Blanca has to be verified, in order to assure precision in the discharge rates from the glacier into the Paria River. Due to the coarse resolution of GRACE data, we were not able to isolate Palcaraju Glacier from the rest of the Cordillera Blanca in estimating the melt rates.

The simple precipitation-runoff model can also be improved. Additional factors such as infiltration, groundwater recharge, groundwater outcrop, and evapotranspiration losses can be included. The spatial scales between the precipitation grids from TRMM and the size of the watershed are not consistent (even with the scale factor). Another method or source for the precipitation data should be used to improve the results.

Therefore, while using GRACE data is an innovative approach, there remain some improvements to be made in order for this strategy to become a valid method for estimating melting rate in glaciers.

As analyzed and described previously in this report, it is estimated that the water needed to fulfill all uses of Huaraz urban activities is 205 l/capita/day. Although it is a reasonable amount of water, we estimated that the average magnitude of deficit, for both scenarios during the analyzed period, is approximately 130,000m^3/month. In order to be able to diminish this magnitude of deficit is important to take actions that involve the implementation of water conservation programs.

Agricultural water withdrawals from the River Paria are relatively small compared to all other demands. Nonetheless there are significant inefficiencies in irrigation in the area. The 2008 study used to estimate agricultural water demands approximated irrigation efficiency in the region to be 35% (Quesquen Rumiche, 2008); meaning that of the water withdrawn by farmers, 65% is wasted. The Food and Agricultural Organization (FAO) estimates that with changes in the irrigation method and channel design, irrigation efficiency can reach up to 85% (FAO, 1989).

Our WEAP model is structured to fulfill demands from the two irrigation districts on the river before supplying municipal demands. In our model the irrigation districts suffered few shortages during dry years, leaving municipal demands to bear the brunt of the shortage. There is significant room for improvement in irrigation practices and channel design that will decrease irrigation water demands and water deficiencies for downstream users. Policy makers should consider programs to encourage farmers to improve irrigation efficiencies as a means of increasing water availability downstream.

5. References

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