The Mysteriousness of Irrigation: A performance assessment on farm level in Tiquipaya, Bolivia

M.Sc. Thesis by Matthijs H.G.I. Danes

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ABSTRACT:
For decades, agriculture is the largest fresh water consumer in Tiquipaya, Bolivia. The 'remainder' has been allocated to the city for domestic purposes. This allocation limits in the current situation the city's development and is gradually resulting in high pressure on the available water sources. This research explores whether it is possible to increase the water productivity in agriculture, without affecting the yields. The objective is to save water that potentially could serve other purposes. Between October and December in 2006, three farmers have been intensively monitored. Each farmer represents the upper-, middle- or lower section of the irrigation system. Unfortunately it was not possible to obtain all the data required for a WP assessment for the farmer in the upper-section. Nevertheless from the analysis it became clear that none of the farmer experienced sever water stress situations, which did not result in a production limitation. However, still a lot of water can be saved by improving the water user efficiency (WUE). Farmers do not seem to distinguish any importance among cultivations and just divided water equally among parcel surfaces. With a different strategy a lot if water could be saved. For example, a water division based on soil depletion and ground coverage.

1 INTRODUCTION

Irrigation is often seen as a 'pole' for development, which can be used as a tool to fight poverty (Bustamente *et al*, 2005). However, if the majority of the available water quantity is consumed by irrigation it can also, especially in arid areas, limit certain developments. Especially since the expected population growth is estimated to concentrate in the urban areas, it is expected that the demand for domestic water in urban areas will rise (Carr, 2005). Parallel to the increase in demand for domestic water, agricultural activities should increase their production to ensure the food security for the increased population. Since the development in both the urban area and agrarian sector demand more water, water becomes scarce and pressure can build up on the available water sources. Water scarcity can result in confrontations among water users, as Duran *et al*. (2004) states; *"The competition for scarce water has been exacerbated and there is increasing potential for conflicts between different stakeholders including, irrigators, municipalities, locally-managed domestic water systems, and urban domestic water utilities."*

The objective of this article is to evaluate water productivity in irrigated agriculture on farm level. Since irrigation is commonly the largest water consumer it is important to see if there is any potential to increase the water productivity in the agrarian sector.

1.1 Concepts

"Increasing productivity of water is particularly important where water is a scarce resource" (Molden *et al*., 2003). The scarcity of water can be related to physical scarcity, when more water is demanded than available. However, water scarcity can also be caused by economic scarcity or management-induced scarcity. With economical scarcity, water is available for beneficial purposes, but financial means are lacking to access it. Management-induced scarcity occurs in a situation where sufficient water is available, but it is inadequate distributed among the water users. A phenomenon commonly described as head-tail problem is a clear example of this.
In water productivity (WP) the production is evaluated per transpirated amount of water. The goal is to achieve maximum yields with the water availability. In practice, the term is frequently confused with water use efficiency (WUE). WUE is also expressed in amount of water in relation to the crop yield, but additionally includes the total applied water volume. Since WP only considers the net evapotranspiration, it can be applied on different scales. WUE on the other hand is scale depended. Although WUE's of different scales are interrelated, it can lead to contradicting conclusions when WUE is evaluated on a specific level only (Barker *et al*, 2003). This becomes clear in the following example; if a lot of water is lost on field level, due to runoff, it is clear that the WUE on field level is low. However, if the uncommitted outflow is reused downstream it is considered to be beneficial again, which result in a higher WUE on delivery system.

To explore whether it is possible to improve the WP, this research focuses mainly on the WP and WUE on farm level. Such improvements of the WP lead in water scarce areas to optimized yields. Additionally it will be interesting to see if the WP is related to spatial circumstances.
Next to WP and WUE it is very interesting to include the economical productivity (EP), which is expressed in Bs[1]/m^3. The economical return can be an explanation for the water productivity and visa versa. These results can be of use for a better understanding on the relationship between water productivity and economical wealth (Gerbrandy *et al*, 2006).

1.2 Area of interest

The sub-basins of the municipality Tiquipaya form the area of interest during this project. Tiquipaya is located approximately

[1] Bolivian monetary unit, 1 Bs is equal to 0.1309 U.S. Dollar.

11 km northwest from Cochabamba[2] (see figure 1) and is enclosed by a high mountain range in the north. Due to its location, large fluctuations in altitude are experienced within relatively small distances. From north to south, Tiquipaya changes gradually from a mountainous area into a fertile valley. In 2001, the municipality had a population of 37,800 inhabitants with, according to census, a population growth of 4.5% per year (INE, 2001). Other sources report that the growth exceeds 11% per year (Duran *et al.*, August 2004). Despite the urbanisation, the area keeps its rural character based upon traditional irrigation systems.

In Tiquipaya, two major water supply systems exist. The first system collects and distributes water from the river *"río Khora"* and is called *"Machu Mit'a"*. The second system supplies water from a large reservoir situated in the surrounding mountains, which is called *Lagum Mayu*. *Lagum Mayu* delivers water in different *largadas* with more or less the same quantity. A *largada* is a period of several days in which the dam releases water. When all the users received their turn the dam is closed until the next *largada*. The frequency of the *largadas* dependent on the amount of precipitation. In a wet year, more water is stored, which allows more *largadas*. To distribute the water, *Lagum Mayu* uses the same conveyance structure as *Muchu Mit'a* (Carlos Maita *et al.*, 1993).

Figure 1 Bolivia (Source: Wikipedia, 02-06-2006)

Next to surface water, groundwater is extracted as an additional water source for irrigation. However, groundwater extraction is relatively expensive and farmers prefer other alternatives. In some landholding, like *Tolavi*, groundwater tables used to rise closely under the soil surface during the rainy season. However, since the introduction of groundwater exploitation in 1970, groundwater tables dropped and people started to experience droughts (Durán *et al.*, August 2004).

[2] Cochabamba is a regional capital, which carries the same name. The city lies on the fringes of the Andes and is located approximately 380 km southeast from the nation's capital La Paz. Cochabamba has over 800,000 inhabitants, which makes it the third city of Bolivia (Source: Bolivia Web, 02-06-2006).

2 METHODLOGY

Water productivity (WP) is profoundly interrelated with the availability of nutrients, water and the crop specie. This research focuses only on the influence of water on the productivity. Since it neglects the presence of nutrients, it will be assumed that any yield reduction is the result of water stress. When water stress is taken responsible for underdevelopment, it is possible to validate the yield estimation according to the water availability.

In order to determine the water fraction that is used effectively for evaporation, it is necessary to elaborate the water balance. One advantage of a water balance is that the water use efficiency (WUE) can also be easily derived.

A water balance normally includes; precipitation, irrigation, runoff, percolation, capillary rise and evapotranspiration (see figure 2). However, the effect of capillary rise on the water balance are considered to be negligible, since farmers complain about sever droughts and since it is difficult to monitor.

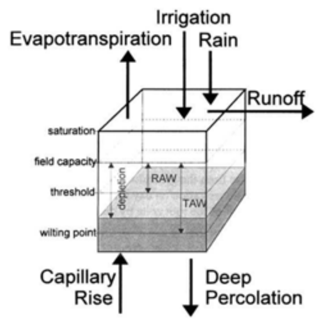


Figure 2 Water balance (Source: FAO Irrigation and Drainage paper 56, chapter 8)

This research investigates the WP on three different farms in the municipality of *Tiquipaya*. Each farmer represents the upper-, middle- or the lower-section of the irrigation system and is carefully selected in cooperation with *Centro AGUA*[3]. The data collection in this research took place in the period October until December 2006. October and the beginning of November are experienced as most critical, concerning the water shortage. In November, the rainy season starts and farmers get less dependable on irrigation supplies.

The subsequent paragraphs introduce the selected farmers and explain the different elements of the water balance that are monitored.

2.1 Farmers selection

During this research, irrigation practices of three farmers are investigated. To see whether the achieved productivity is related to external factors, farmers are selected according the following selection criteria:

- Different types of farms with different combinations of production processes;
- Different farm sizes, because it is interesting to investigate if there is a relation between the farm size and the WUE;
- The distance between the intake of an irrigation system and a farm, should differ between the selected farmers in order to see if there is a relation between the location and water productivity;

[3] Centro AGUA, Andean centre for Water Management.

Table 1 Selected farmers

Name	Type of farm	Farm size (ha)	Cultivated fraction (%)	Community	Section in irrigation system
Gregorio Alaka	Flower- and Horticulture	1,1	42	Montecillo	Upper
José Haas	Meat production and Diary farming	45,2	62	Tolavi	Middle
Rosendo Rocha & Mario Vera	Horticulture and Dairy farming	2,7	87	Coña Coña	Lower

- Many farmers speak *"Quechua"*, however, to prevent complexities during field work; farmers should be able to communicate in Spanish;
- Centred parcels, to prevent complex situations during measuring.

With the help of the board of *Machu Mit'a* tree different families where contacted. Table 1 summarizes the general information of the selected families. Al the families are located within *Tiquipaya* except the farm of *R. Rocha & M. Vera*. Although this farm lies in the municipality of *Colcapirhua*[4], it represents a type of farm, which is common in the southern parts of *Tiquipaya*.

2.2 Precipitation

"Violeta", a weather station situated in the centre of *Tiquipaya*, keeps daily records from the general climatic circumstances. The weather station is modified in July 2006 and from that moment all information is automatically recorded and directly sent to the main office in La Paz. Unfortunately, this also means that the climatic data after the modification is not accessible anymore and therefore not available for this research. However, the information during the first six months can be used to validate precipitation measurements taken by one of the farmers, located in the middle-section of the irrigation system.
The farmer's records have an average deviation of -3.8 mm, which can be explained by the used equipment or by natural deviation in precipitation. Nevertheless, since it shows the same trend as the records kept by *"Violeta"*, the values are assumed to be valid and representative for the whole area of interest.

2.3 Irrigation

There are two different sources that supply irrigation water. The first source is groundwater. Groundwater is relatively expensive because of pumping costs and provides only small quantities. In addition to groundwater, surface water is used. Surface water is generally cheaper, but can only be obtained in intervals.
In order to estimate the derived quantities from both sources, discharge measurements have been carried out. Groundwater extractions are considered to be constant and easily to measure. However, it is difficult to estimate the operation frequency, since farmers are not always open to tell about their groundwater use.
From surface water daily records are kept by the irrigation boards about water distribution. It means that the obtained data from the irrigation dates and duration are considered to be more reliable compared to groundwater. However, the received quantities are still difficult to estimate, since the discharge of the distributed flow is not being monitored. To overcome this issue, the received discharge by surface supply systems is intensively monitored during the fieldwork of this research, with a propeller measurement device. Unfortunately, it was not possible to take measurement on pre-established intervals, since in some cases different plots were irrigated simultaneously.
Especially *Lagum Mayu* operates in largadas with more or less a constant discharge. Therefore it is assumed that discharges of this surface water supply system are similar to the averaged measured discharges during the field study. This will in practise not be the case for the discharges received by *Machu Mit'a*. Like stated before, *Machu Mit'a* is a water supply system based on a river and has to deal with natural discharge fluctuations. The measurements were taken at the end of the dry period, which makes it assumable that the annual river discharge is higher than experienced during the dry period. It is likely that this also has it influences the operation discharge of *Machu Mit'a*, and that farmers receive annually higher discharges than measured. However, since no information could be obtained about the river natural discharge variation the discharges in this research are considered to be constant.

Ones the inflow on farm level is determined, it is the task to downscale the inflow to field level. This process can expose any strategies during water division among the parcels. For example, a farmer can prefer to use certain quality water for specific cultivations, or can discriminate between the importances of different cultivations. Information on water division on farm level is received by questionnaires and partly by observations. The pattern observed during the fieldwork will be hold as representative for the remaining part of the year. If no clear pattern arises, the received quantities will be equal divided -according to parcel size- among the cultivations.

2.4 Runoff

Runoff occurs when water crosses the borders of the parcel. It can occur simultaneously on different locations with a fluctuating discharge. To be able to estimate these runoff quantities, with a propeller device, regular flow measurements have been carried out on each outflow point. Such a propeller device actually measures the velocity in m/s. Together with the wet-surface, the discharge can be calculated. Like the irrigation inflow the runoff discharge fluctuates and should therefore be closely monitored with fixed intervals. However, in practice several parcels were irrigated simultaneously, which made it impossible to work with pre-established intervals. To be able to estimate the quantity lost by runoff, the measured discharges are weighted according to the measurements interval.

On farm level, more water can be lost during the distribution of water among the property. However, since most properties are relatively small, they are neglected during this research.

2.5 Percolation

A fraction of the applied water volume infiltrates and is stored in the root-zone. If more water is applied than the storage capacity of the root-zone, the soil becomes saturated and water

[4] *Colcapirhua* is the neighbouring municipality south from *Tiquipaya*.

is lost by percolation. The storage capacity extent is determined by the depleted fraction in reference to field capacity. In order to estimate the quantity lost due to percolation, the depleted fraction should be subtracted from the applied quantity.
However, since no soil moisture measurements have been carried out, the depleted fraction is estimated. When detailed information about irrigation turns is available, a computer programme called *"Cropwat"* can be used. Even though the dates on which the farmers received their irrigation turns are known, it is not always clear which plots are being irrigated with the available water. That is why this research calculated manually, for each plot, the annual depleted fraction in time steps of ten day. This soil moister balance starts in January, which is in the middle of the rainy season when the soil is considered to be on field capacity. During the remaining part of the year, the soil gets depleted according to the difference between evaporated fraction and the applied water volume.

2.6 Evapotranspiration

The evaporated fraction differs along the growth cycle of every crop. Each growth cycle can be subdivided into four different stages. During the first stage the seed sprouts and starts to develop small roots and leaves. Most energy that is used during this stage is stored in the seed. In the subsequent stage, the small plant evolutes to its full extend. Along with the increase in biomass, the evapotranspiration capacity increases as well and results in a higher water demand. In the mid-season, the crop flowers and its evapotranspiration capacity consolidates. After flowering, the late season starts which means that the yields are formed and the evapotranspiration decreases until the crop is harvested.

The evapotranspiration capacity in the different growing stages of a crop is dependent on climatic circumstances. In this research the reference evapotranspiration (ET_o) (in mm/day) is obtained from a master thesis (Rocha, 2003), which is based on climatic data from the year 2001. The climatic data from this research is obtained from a weather station in *Vinto*, called *"Pairumani"*, approximately 11 km away from *Tiquipaya* and is considered to be representative for the research area since the altitude, temperature and precipitation are comparable.

The reference evapotranspiration (ET_o) is commonly derived from a vegetation type like grass. To calculate the actual evapotranspiration of a crop (ET_c), the reference evapotranspiration needs to be multiplied by a crop factor (K_c). Each different growing stage has its own crop factor, see figure 3. These crop factors define a fixed relation between the reference evapotranspiration and the actual evapotranspiration that is valid in several climatic regions (Doorenbos & Kassem, 1979).

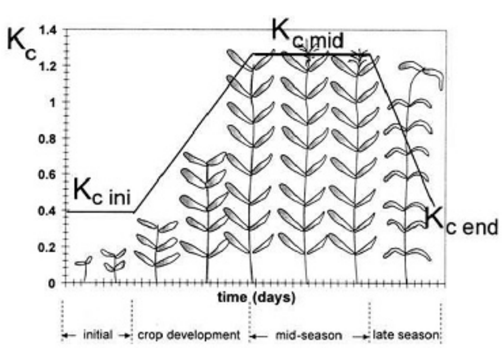


Figure 3 Crop factors related to the crop development stage

By multiplying the K_c with the ET_o, the maximum evapotranspiration (ET_m) is obtained. In practise the evapotranspiration often deviate from the ET_m, which is called the actual evapotranspiration (ET_a). The reason why the ET_a often deviates can be due to shade effects, water stress, insufficient nutrition in the soil, etc. Like explained before, any deviation of the ET_a from the ET_m in this research is considered to be the result of water stress. In other words, the ET_a is dependable on the soil depletion.

As long as there is sufficient "readily available water" (RAW, see figure 2) present, the ET_a is comparable with the ET_m. When all the RAW is depleted, the plant needs to put more energy to subtract moister. The extra effort the plant needs to put in water subtraction will negatively influence the plants performance and is called water stress. The effects of water stress on the plant are related to the level of water shortage. In this research it is assumed that any percentage of soil depletion, lower that the RAW, reduces the plant's evaporation capacity by 5 %. If no water is applied during this stress period, the plant will continue extracting water until the "wilting point" (see figure 2). Even though there is still some moister present at this wilting point, the soil suction tension becomes too strong and the crop dies.

2.7 Yield

In the evaluation of water productivity, the evaporated quantities are compared with the yields. Water shortage will result in water stress, which often leads to yield reduction. In most cases water stress is the result of low application efficiencies, but it can also be caused by large irrigation intervals. The sensibility of a crop for water stress differs among crop species. However, not only does the plant specie affects the sensibility for water shortage, it is also affected by the crops development stage. The yield response factor (K_y) describes the relation between the decrease in evapotranspiration (%) and the decrease in yield (%), see figure 4. In every growth cycle, four different stages can be distinguished, namely: initial, crop development, mid-season and late season. To prevent severe yield reduction a farmer should try to prevent water stress in the crop development or during the yield formation (see figure 4). If no sufficient water is available in one of these two stages, the crop can not develop to its full extent nor has the energy to create a high yields (Doorenbos & Kassem, 1979).

Since water availability is the most important factor that is taken responsible for water stress occurrences, it is necessary to evaluate the frequency and the length of these occurrences. During this evaluation, the soil depletion balance, developed to determine the percolation losses, is used. This balance clearly visualises the moister in the root zone in a temporal relation.
Even though the frequency of stress occurrences can be recovered, the impact on yield reduction is much harder to estimate. If detailed information is available, it is possible to calculate the yield reduction with computer software *"Cropwat"*. Once detailed information is lacking there are complex measures to calculate the yield reduction. Nevertheless in this research the yields are estimated according the annual consumed quantities, since most crops were not harvested during the field study of this research. On a dairy farm for example, the produced forage is consumed by the stock of cattle. Since the daily diet of dairy cattle is relatively fixed, it is considered to be most suitable for estimating the annual production.

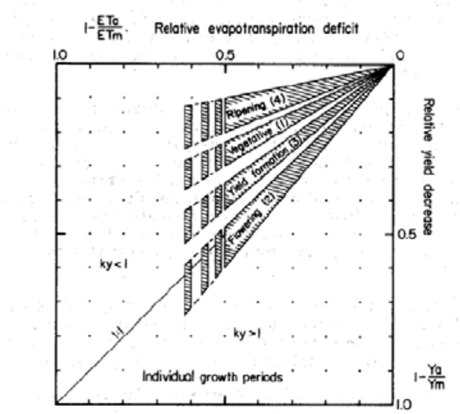


Figure 4 The yield response in different crop development stages

2.8 Productivity

Finally, this research will end with a productivity evaluation among the investigated families. During this evaluation the WP and EP will be calculated and compared. The EP is very dependent on the local value of the products. To obtain these values, research is done on the local market.

3 RESULTS

3.1 Precipitation

Based on the precipitation measurements of the farmer in the middle-section of the irrigation system, the monthly available precipitation quantity is estimated. Like discussed before, the received precipitation quantity is considered to be equal in the entire municipality. From the derived data, see figure 5, it is clearly to see that there is little precipitation available between May and October.

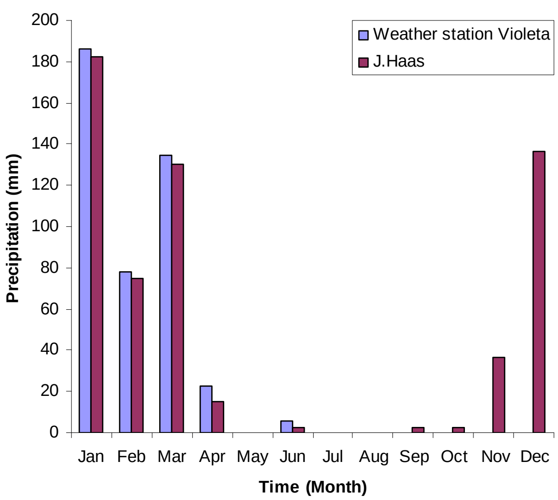


Figure 5 Monthly precipitations in mm of the year 2006

If this is not sufficient compensated by irrigation supplies it is assumable that water stress occurs. This drought period is confirmed by the drought period described by Boelens & Hoogendam (2002) and Pardo Claure & Rocha López (2003).

3.2 Irrigation

Additional water is derived from irrigation systems or by groundwater extractions. The quantities received from irrigation systems are estimated based on discharge measurements, together with information about the frequency and duration of the operation on farm level. It is assumed that the discharges of groundwater extractions are relative constant. The operation frequency on the other hand cannot be verified, which makes it impossible to estimate the accuracy of the estimated values.
To estimate monthly-received quantities from irrigation systems, regular discharge measurements have been taken at the inflow point of farms during irrigation turns. Unfortunately, it was not possible to measure with pre-established intervals and the measuring intervals fluctuate between ten minutes and one hour.
As representative discharge a weighed average from the measurements is taken, see table 2. Like the table shows, on different locations in the irrigation system the discharge can vary. One would expect that the discharge in the upper-section is higher and reduces further down the sections, like the average discharge measurements received from *Lagum Mayu* indicates. However, this trend does not return in the average discharge measurements derived from *Machu Mit'a*. Remarkable is difference between the received discharge in the middle-section and the upper-section. One explanation could be an increasing discharge during the measurements in the middle-section. Since a decent sewage system in the area is lacking, sewage is discharged in the conveyance structure of the irrigation systems, which temporally influence the water discharge. However, if the differences of received discharge in the middle- and lower-section are compared for both systems, one can state that it is similar. It is therefore more likely that the received measured discharge of *Machu Mit'a* in the upper-section is some how under estimated. For example, a lot of water can be lost due to tremendous conveyance losses between the farm intake and the parcel. However, since this does not seem to happen with received water from *Lagum Mayu* this is unlike. A second and more realistic option could be that water was stolen during the time of the measurements. Since there is no evidence for this explanation, the received discharge from *Machu Mit'a* in the upper-section will not be corrected.

Table 2 Average received discharge per farmer

System	Upper-section	Middle-section	Lower-section
Machu Mit'a (l/s)	45	54	46
Lagum Mayu (l/s)	136	104	99
Groundwater (l/s)	-	1	1

In contrast to the estimated discharges, the operation frequency is much more reliable. Farmers receive a receipt every time they settle the fee for their water right. The farmer in the upper-section did not preserve these receipts, which made it impossible to obtain detailed information on his water availability. However, since both irrigation systems operate in rotation of a pre-established interval, a good estimation could be made about the irrigation interval in the upper-section.
Finally, the annual water availability could be calculated (see figure 6), based on the irrigation interval, irrigation duration and average discharge. After analyzing figure 6, it is clear that the water availability decreases from the upper-section downwards. Nevertheless, it is the farmer in the middle-section who receives the least amount of water. With this amount of water, it is not possible to cultivate the entire property. Because of the reduced water availability in the middle- and lower-sections, farmers are forced to search for alternative sources, like groundwater.

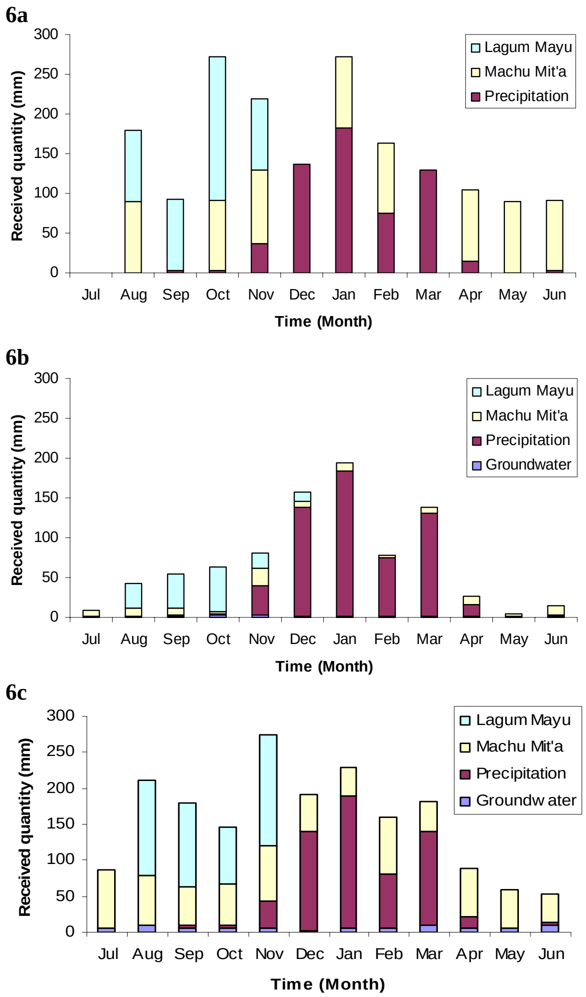


Figure 6 Annual water availability from the upper- (a), middle- (b) and lower-section (c).

3.3 Runoff

Runoff only occurs when the too much water is applied, or with a too high discharge, and is in some cases more difficult to measure. For example in furrow irrigation; runoff can easily be monitored by using a small flume device.
Basin irrigation on the other hand applies for a different measuring method. In theory the parcel should be levelled properly, so water will inundate the parcel evenly.

If there is no clear boarder, runoff can occur along the whole parcel boarder in even proportions. Even though the losses can be substantial, they are difficult to determine. However, in practice, most parcels have something like a boarder or parcels are badly levelled, which ensures a concentrated outflow. Nevertheless, outflows commonly occur simultaneously on several locations.
If the runoff is some how concentrated, the discharge can be measured with a propeller device. Together with the wet perimeter, it is possible to estimate the runoff discharge. In order to estimate the complete quantity lost by runoff, the discharge should be regular monitored. Especially, since the irrigator laboured influences the runoff discharges by adapting the water flow upstream. Nevertheless, it was not always possible to monitor the runoff discharge with a pre-established interval, since frequently several runoff outflows occurred simultaneously on different locations. Table 3 summarizes the average measured fraction lost by runoff.

Of course, more water is lost in the upper-sections, compared to the other sections, due to the steep slopes. In the lower-section on the other hand, runoff does not occur at all. All the water is kept on the field by small dikes and infiltrates.

Table 3 Average fraction lost by runoff, referred to the inflow, per cultivation

Upper-section		Middle-section		Lower-section	
Description	Runoff (%)	Description	Runoff (%)	Description	Runoff (%)
Oxy Daisy	80	Maize	35	Alfalfa	0
Barley	60	Oats	34	Artichoke	0
Potato	48	Alfalfa	27	Barley	0
Raspberry	36			Maize	0

Not only does the fraction loss differ among the different sections, there is also a difference on farm level among different cultivations. Generally speaking, in cultivations with high ground coverage less water is lost compared to cultivations type with low ground coverage. The only exception is potato in the upper-section. Since the farmer constructed diagonal furrows, the slope was less steep compared to the flow direction in other plots, which reduces partly the runoff.

3.4 Percolation

Like already stated before, the fraction lost by percolation is based on a manually calculated soil balance. If the soil allows less storage than the applied water quantity, percolation occurs. The average lost quantity per cultivation can be found in table 4.

Opposite to runoff, the most sever percolation losses occur in the lower section, than the middle-section and upper-section. This results could also been expected after seeing the runoff fractions. Especially in the lower-section, where all applied water infiltrates.
Additionally, there is a difference between different cultivations on farm level. For example, cash crops receive more water than they evaporate, probably because they have a high economical return. More generally, different cultivations seem to receive similar amounts of water. It results in more percolations losses for crops with a lower evapotranspiration capacity. Less loses occur when a large part of the root zone is depleted.

Table 4 Average fraction lost by percolation, referred to the inflow, per cultivation

Upper-section		Middle-section		Lower-section	
Description	Percolation (%)	Description	Percolation (%)	Description	Percolation (%)
Raspberry	39	Oats	48	Barley	52
Oxy Daisy	8	Maize	17	Artichoke	47
Potato	6	Alfalfa	6	Maize	34
Barley	0			Alfalfa	33

3.5 Evaporation

By subtracting the runoff and the percolation from the total available water quantity, the effective used fraction that is stored in the root zone is obtained. It is interesting to see that generally water is used more efficient in the lower-section compared to the other sections. This is partially due to the difference in slopes and soil but also because a different vegetation. Especially maize and alfalfa have a large root zone to store water. Another argument is that in the lower-section small dikes surrounding the parcels prevent any loss by runoff.

From the effective fraction, the evaporation of different crops can be derived.

Table 5 Average effectively used fraction, referred to the inflow, per cultivation

Upper-section		Middle-section		Lower-section	
Description	Effective (%)	Description	Effective (%)	Description	Effective (%)
Potato	46	Alfalfa	67	Alfalfa	67
Barley	40	Maize	48	Maize	66
Raspberry	25	Oats	18	Barley	48
Oxy Daisy	12			Artichoke	53

However, from raspberry, oxy daisy and artichoke no information could be obtained about root depth, crop factors or yield response factor. Therefore, they are left out the remaining analysis of this chapter. For the other crops, sufficient information was available to compare the average actual evapotranspiration with the maximum evapotranspiration. Figure 7 summarizes both the maximum evapotranspiration as the actual evapotranspiration for the upper-, middle- and lower-section.

In the upper-section of the research area, permanent crops are cultivated, like oxy daisy and raspberry. Additionally, potato and barley are produced between August and December. The cultivation period of potato and barley can be explained by two reasons. First, around August the first *Lagum Mayu* supplies are distributed, so sufficient water is available. Second, the period is still dry and warm enough in order to deplete the soil around the harvesting stage. Except for the first days after transplanting sufficient water seems to be available to realize the maximum evapotranspiration.

In the middle-section only forage corps are produced. From September until February, most of the water is used for the production of maize. The received irrigation supplies during the remaining part of the year are used for the production of Alfalfa and Barley/Oats. These crops are relatively water stress resistant and still provide a reasonable yield in the dry period. Nevertheless, more water shortage is experienced compared to the upper-section. This also influences the actual evapotranspiration negatively, which reduces the yields. The most critical situation is experienced between October and December when water shortage is most critical.

Finally in the lower-section, most cultivated crops are for forage purposes, like alfalfa, barley and maize. Besides forage crops, artichoke is cultivated as a cash crop. It is a permanent crop and has the largest priority during irrigation. To prevent water stress situations, artichokes are additionally irrigated with groundwater. The second permanent crop is alfalfa, which is relatively resistant to water shortage.

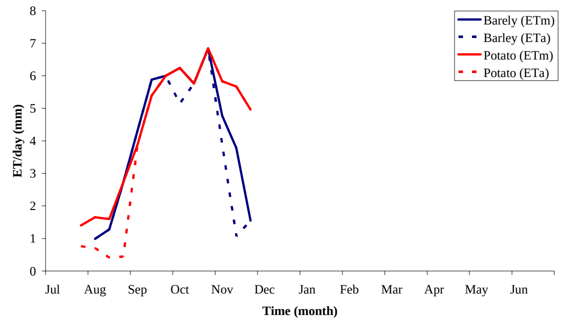
Between August and November barley is cultivated, with the same reasons as in the upper-section. During this period sufficient irrigation water is available and it is still dry enough to deplete the soil around the harvesting time. The production of maize on the other hand is concentrated around the raining period where there is an abundance of precipitation.

However, sufficient water is available during the entire year to prevent severe stress situation, even though the lower-section has the least opportunity to obtain water.

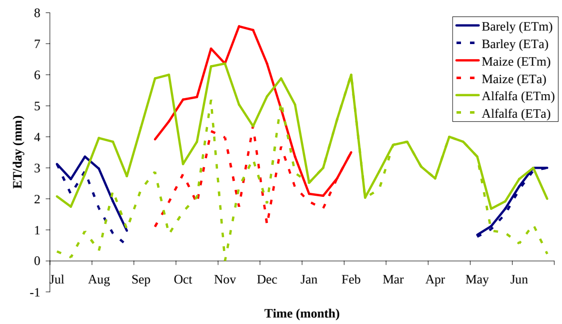
3.6 Yield

Determining the yields was difficult, since most crops were not harvested during the time of the field study. To overcome this issue, it is decided to evaluate the consumed quantities. The consumed quantities together with the bought or sold quantities explain the size of the production.

7a



7b



7c

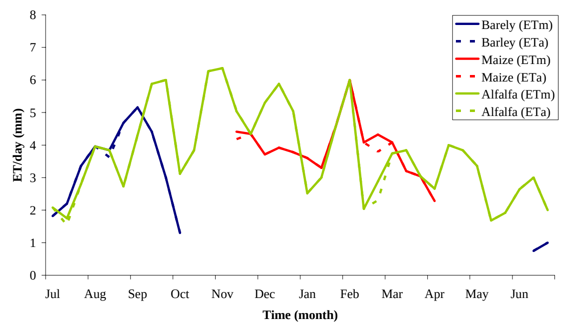


Figure 7 Maximum and actual evapotranspiration; upper- (a), middle- (b) and lower-section (c).

Table 6 summarizes the different productions per cultivation in the different sections of the irrigation system. Unfortunately, it was not possible to obtain any results from the farmer in the upper-section, which made a detailed comparison not possible. Additionally, the production of alfalfa in the lower-section is questionable. It is not likely that such high production rates are achievable in any part of *Tiquipaya*. More assumable is that the farmer from this region brought extra forage crops, without revealing this. Furthermore, it is remarkable that the production rates of maize are similar in both the middle- as the lower-section; especially because more water stress is expected to occur in the middle-section. It is therefore assumable that the water availability in the middle-section is underestimated. Since there is no more surface water available, additional water has to be provided by groundwater. Even though the farmer complains about drought, groundwater tables are probably high enough to reach the root zone. However, groundwater measurements are not included in this research and any influence is therefore neglected.

Table 6 Average production per cultivation

Upper-section		Middle-section		Lower-section	
Description	Production ($kg*10^3/ha$)	Description	Production ($kg*10^3/ha$)	Description	Production ($kg*10^3/ha$)
Potato	-	Maize	22.3	Alfalfa	197.2
Raspberry	-	Oats	20.9	Barley	32.9
Barley	-	Alfalfa	18.1	Artichoke	26.5
Oxy Daisy	-			Maize	24.7

3.7 Productivity

The WP and the EP are strongly depended on the produced yield. Since part of the yield information is missing and remaining estimations are questionable, the total dry matter of the yield per hectare is obtained from literature. According literature alfalfa has a production of 6.6 ton/ha (Berdahl et al., 2001), Maize: 18 ton/ha (MAF, 2007), Potato: 5.0 ton/ha (Prince Edward Island, 2008), Raspberry: 2.2 ton/ha (Mohadjer et al., 2001) and Wheat: 4.5 ton/ha (Oweis et al., 2000). These production rates from literature can only be applied for situations that do not experience water shortage. Like already indicated in paragraph 3.6 about yield, there seems sufficient water available to prevent water stress situations, except for the middle-section. Looking to the historical situation, it is assumable that this water shortage in the middle section is partly or entirely nullified by groundwater influences. Especially since the other investigated sections experience hardly any water stress, it can be argument that the situation in the middle-section is similar. This assumption will positively influence the ET in the middle-section, however, since the exact actual ET remains unclear the maximal ET will in the following WP calculation.

Based on all the obtained information and assumption it is now possible to calculate the WP and the EP. Table 8 shows the WP and EP in the different sections. In the upper-section, generally vegetables and fruits are produced, compared to the forage crops in the remaining sections. The vegetables and fruits have a low WP, but instead give a high economical return.
The cultivations in the remaining section are more comparable and similar WP's are achieved. Remarkable is the difference between the WP of maize and oats/barley in the middle- and lower-sections. Even though both productivities do not experience any water shortage, adapting the cropping pattern slightly can save water. Like shown in figure 7, both farmers produce maize, whereas the maize in the lower-section demands less water.

Table 8 Water- and Economical-productivity, per cultivation

Decription	Annual production ($kg*10^3/ha$)	Unit price (Bs)	Annual ET (mm)	WP (kg/m^3)	EP (Bs/m^3)
Upper-section					
Barley	4,5	0,60	260	1,73	1,04
Potato	5,0	2,00	380	1,32	2,63
Raspberry	2,2	30,00	550	0,40	11,99
Middle-section					
Maize	18,0	0,25	734	2,45	0,61
Oats	4,5	0,60	276	1,63	0,98
Alfalfa	6,6	0,31	1373	0,48	0,15
Lower-section					
Maize	18,0	0,25	582	3,09	0,77
Artichoke	26,5	1,21	1441	1,84	2,23
Barley	4,5	0,60	362	1,24	0,74
Alfalfa	6,6	0,31	1366	0,48	0,15

When the calculated WP is compared to literature (Molden, 2007); maize 0.2-2 kg/m3, potato 3-7 kg/m3 and wheat 0.2-1.2 kg/m3, the achieved WP is relatively high. It means that it probably is possible to increase the WP, but only with a lot of effort.

The WP approach is pointed to optimize the yield when the water availability is limited. However, this is not the case in Tiquipaya. This research proved that there are hardly any stress occurrences in the investigated section. Nevertheless there are still a lot of opportunities, by increasing the WUE, to save water without affecting the yields.
During this research there has not really been a difference in irrigation strategy among the different cultivations. Water has been equally divided among parcels, concerning the parcel sizes. However, a farmer should more concern about the soil depletion than the parcel size. Only if the soil is sufficient depleted, a high application efficiency can be achieved. In the case of the lower-section, artichoke was irrigated too frequent, which resulted in a lot of percolation losses.
If more water wants to be saved on farm level, one should divide the water according to soil depletion, rather than parcel size. Additionally field dimensions and supplied discharges should be evaluated to see whether runoff can be prevented. If the WUE efficiencies can be optimized, al lot of water can be saved without affecting the WP. The EP on the other hand is more dynamic, since it is exposed to price fluctuations on the market.

4 DISCUSSION

The precisions of some of the results are doubtful, like for example the water availability in the middle-section. In this particular case it would have been helpful to have more information available about groundwater fluctuations. Especially since it seem to have a very important role.
Other results that are doubtful are the obtained yields. Apparently not all farmers are open to tell about their production rates. One should use an alternative method to validate the estimated produced yields. In practice it can be confusing if only the annual consumption is used as annual production because part of the consumption can be cultivated somewhere else. The only way to validate the production rates is by measuring them during harvesting.
Additionally one could argue about the number of investigated farmers. In order to exclude all uncertainties more farmers need to be investigated. However, since the temporal extent of this project it was not possible to select more farmers.
Finally one can judge the situation in 2006. Even though the results show that there was no water shortage and that farmers can save a lot of water by increasing the WUE, it is not clear whether this is also applicable for a dry year. To find answers on all these uncertainties, further research should be carried out, in order to investigate more farmers, different years and to find more information about groundwater influences.
Like this research has proven, it is frequently difficult to measure all elements in a water balance, and in particular runoff. Runoff often occurs on different locations simultaneously, without one clear concentrated outflow, which is difficult to measure. In practice farmers also irrigate at night, which makes it even more difficult to spot all the different outflow locations. Additionally, night irrigation in Bolivia can be quite dangerous and it is not always safe to measure an irrigation turn. An alternative method could be monitoring the soil moister in and below the root zone. If one knows the applied quantity, the runoff can be calculated by simply subtracting the percolated and stored fraction in the root zone. Another advantage is that these measurements can still be done

after the irrigation took place. On the other hand, this technique demands expensive equipment and quite some preparation time.

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