Water management improvements for agriculture by applying efficient crop schedules in the highland forest of Vilcabamba, Peru

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Abstract: The current work is aimed to improve the water management for agriculture, by applying efficient crop schedules in Vilcabamba -and similar areas of the Andean highland forest-, which can satisfy most of the water requirements with rainfed irrigation and maximise the crops yield. For this purpose, two field practices were carried out during the dry (September 2012) and wet season (February 2013) to measure rivers and canals flows with the velocity/area method. Nineteen soil samples were collected on-site and analysed, presenting prevalent sandy loam and loam textures. Cropwat programme and data on climate, crops and soil were used to estimate crop water requirements and scheme irrigation requirements, indicating that crop evapotranspiration is low due to humidity and cool temperature. Crops did not need any water during the rainy season (December to April), although irrigation requirements occur in the dry season, with a maximum flow capacity of 1.72 L/s in May. The flow capacity can be satisfied, since small ditches convey approximately 2 L/s to 6 L/s on the same season. Rainfed farming can be practised, but an initial pre-irrigation that needs to be applied for crops should not be water stressed. However, if soil is not pre-irrigated the production can be affected, with vegetables and potato crop yields reduced by 4.7% and 1.4%, respectively. To minimise these effects, both crops are suggested to be planted one month later, adapting their growth period to the rainy season.

Keywords: Crop scheduling, crop water requirements, rainfed irrigation, water management for agriculture, Cropwat

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1 Introduction

Agriculture in Vilcabamba faces many challenges at present. In recent years, local governments have been benefited with regional mining and gas revenues, channelising these funds to employ a large part of the community workforce for construction and administrative tasks. As a result, the agricultural sector has been neglected, dramatically decreasing its productivity and competitiveness with neighbour regions, leaving few local farmers to cultivate small parcels, with an average cultivated area in the range of 0.25 and 1 ha per farmer (Cobos, 2013; Santa Cruz, 2013). In addition, limited research on Vilcabamba agriculture has been done, for this valley is isolated in the highlands forest and transport is not regular from nearby cities and towns, especially during the wet season.

Therefore, in order to foment agriculture in Vilcabamba and in similar areas, irrigation water requirements have been addressed with simulation techniques. For this task, local climate records (Sehamhi, 2013; FAO, 2006; IMA, 2010), cropping patterns (Santa Cruz, 2013; Cobos, 2013), and soil properties (IMA, 2005; Checya, 2011) were modelled in Cropwat programme (FAO, 2009) resulting in crop water requirement and irrigation water requirement estimates. Crop water requirement is the amount of water needed to

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compensate the evapotranspiration loss from the cropped field, while irrigation water requirement represents the difference between the crop water requirement and the effective precipitation (Allen et al., 1998).

Rivers and streams flow during dry and wet seasons were measured on-site to resolve whether water deficit can be satisfied. Moreover, this research aims to determine if the water management in Vilcabamba is adequate and suggests cropping schedules improvements to increase agricultural productivity.

Physical setting and irrigation practices

Vilcabamba Region (13º04′-13º08′S, 72º55′-72º57′W) is located on the east flank of the Andes of South Peru, with an average elevation of 2900 m laying between the Andean valleys (up to 4000 m in the high mountains) and the rainforest (1,500 m). The climate is semi-cold, rainy and with dry winter. The dry season in Vilcabamba is from May to November, with scarce rain, cold nights and warm days, while the wet season is humid, with precipitation running from December to April, when nights are cold and rainy. The average minimum temperature is 6.5°C in July, rising to an average maximum of 19.9°C in August; while the monthly mean temperature is almost constant throughout the year (13-14°C). The average annual precipitation in Vilcabamba is 1,820 mm.

The landscape is made of moderate and steep hills, with slopes from 15% to over 50%, along the alluvial valleys of River Vilcabamba flowing northbound. The main localities are underlined on Figure 1 (left), including Vitcos Inca site. On the same figure (right) the scarped topography of this region is illustrated on 3D, obtained from IGN (2010) maps on ESRI©ArcGis™ version 10 (ESRI, 2010).

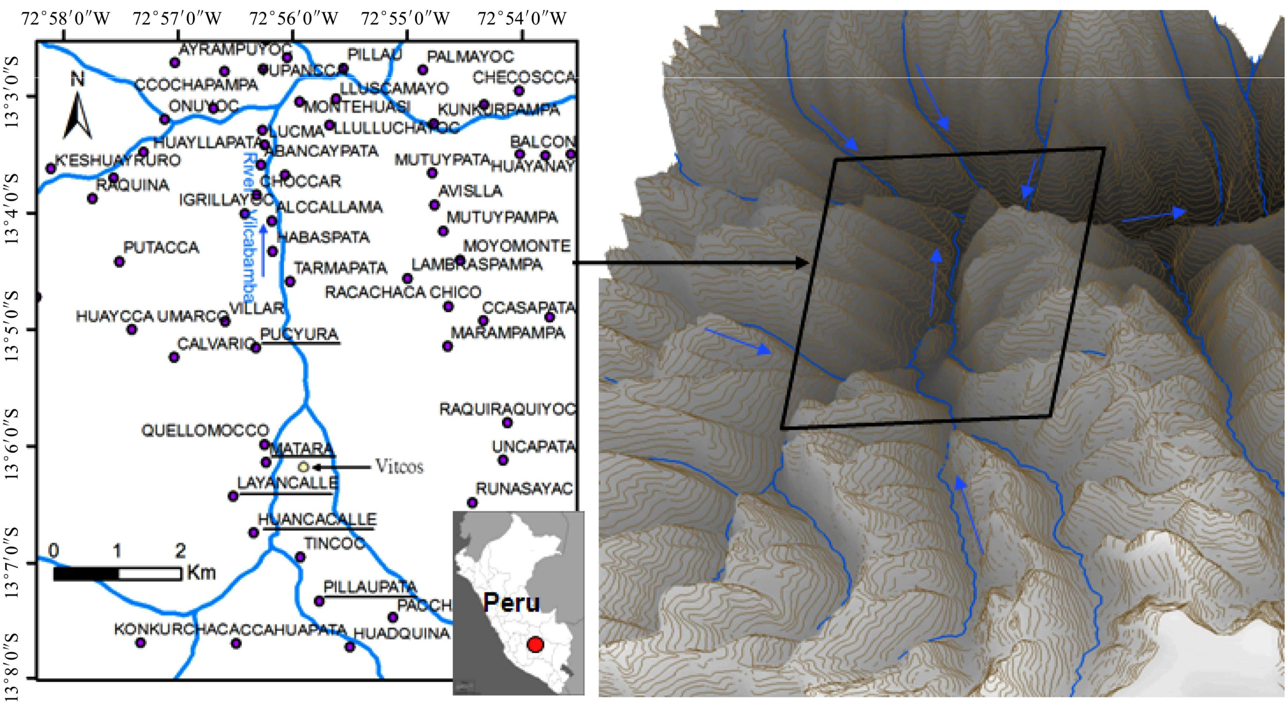


Figure 1 Vilcabamba area and main sites (left) and 3D topography map (right)

Streams flow from the top of the mountains to the rivers, while most of the farming is practiced on upper lands (Figure 2), with limited water use from rivers for irrigation due to the lack of arable land at that level. Thus, most farmers practise rainfed irrigation, although some small scale farmers combine it with furrow irrigation. This method is not efficient since water is being consumed at higher places during the dry season, reducing the flow as it descends the hill (Cobos, 2013). Sprinkler irrigation is also practised at a small scale (Santa Cruz, 2013) and rudimentary techniques are still in use, such as soil ploughing

Therefore, the irrigation water requirements were studied by addressing climate, cropping pattern and soil properties, in order to determine whether the water management is adequate in this area and to suggest crop schedules improvements to increase the agricultural production.

Figure 2 Vilcabamba valley, with River Cayco at the bottom (dotted lines)

2 Materials and methods

2.1 Crop water requirements

Cropwat programme version 8.0 (FAO, 2009) was used to estimate crop water requirements and irrigation scheme based on climate, soil, and crop data. The modified Penman-Montieth method (FAO, 1998) was employed to calculate the reference evapotranspiration and crop evapotranspiration through Equation (1) and Equation (2) respectively.

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad (1)$$

$$ETc = ETo \times Kc \quad (2)$$

where, ETo reference evapotranspiration (mm/d); Rn net radiation at the crop surface (MJ m/d); G soil heat flux density (MJ m^2/d); T mean daily air temperature at 2 m height (°C); u_2 wind speed at 2 m height (m/s); 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); g psychrometric constant (kPa/°C); ETc crop evapotranspiration (mm/d) and Kc crop coefficient (dimensionless value).

2.2 Climatic data

Vilcabamba area lacks of meteorological stations, thus SENAMHI (2013) closest stations of Vilcabamba (4,000 m) and Machu Picchu (2,459 m) available climate records were used, this stations are located 7 km west and 40 km east of Vilcabamba area, respectively. The sites are on the same latitude of 13°S and the place of study is within the stations altitude.

Vilcabamba station daily data were available only for years 1964-1970, while Machu Picchu station had a wider range of data: years 1964-1977 and 1998-2009. In this extent, a direct comparison was not suitable for calculation, and a two stage process was applied.

On the first stage, both stations monthly average climate from the 1960s and 1970s was related to the elevation of the three locations, estimating the climate of the study site for that period. This comparison is due to the lapse rate, where an atmospheric variable (e.g. temperature) decreases according to elevation (Glickman, 2000). Hence a linear interpolation (Equation (3)) was applied to the elevation-temperature relation on Table 1.

$$x2 = [(e2-e1)*(x3-x1)]/(e3-e1)+x1 \quad (3)$$

Table 1 Elevation-temperature relation by linear interpolation method

Location	Elevation	Temp for period 1964-1977
Machu Picchu station	$e1$ = 2459 m	$x1$
Vilcabamba area	$e2$ = 2900 m	$x2$
Vilcabamba station	$e3$ = 4000 m	$x3$

On the second stage, Vilcabamba area results were related to the same climate period of Machu Picchu station (1964-1977) and cross-multiplied by Machu Picchu overall climatic records of 26 years (1964-1977 and 1998-2009). This results in an overall, modern climate data for Vilcabamba area ($t2$) applying Equation (4) on Table 2. This method was applied according to temperature, humidity and wind speed.

$$t2 = (x2*t1)/x1 \quad (4)$$

Table 2 Modern temperature by cross-multiplication method

Location	Temp periods	
	1964-1977	1964-1977, 1998-2009
Machu Picchu station	$x1$	$t1$
Vilcabamba area	$x2$	$t2$

Sunshine duration is related to solar radiation, which also plays an important role on crop evapotranspiration (FAO, 1998). The sunshine duration records were used from the nearest available FAO meteorological stations: Ayacucho and Abancay, about 140 km west and 60 km south of the study area respectively, covering a period from the 1970s to 1990s. Mean daily sun hours per month from both stations were averaged to obtain the sunshine duration in Vilcabamba area.

Precipitation is the main contributor in satisfying the crop water requirements in the study site. Due to the lack of precipitation records in Vilcabamba area, this was estimated from the mentioned SENAMHI stations by using the two stages method as for temperature, humidity and wind speed. However, crops use a fraction of the total rainfall, known as the effective rainfall, due to rain losses from surface runoff or deep percolation below the root zone. Thus, an effective rainfall of 75% was suggested by the Institute of Water Management and the Environment of Peru, based on precipitation studies in all the provinces of Cusco Region (IMA, 2010) including the study site.

Soil properties

IMA (2005) describes the soil taxonomy of Vilcabamba as orthents (USDA, 1999), equivalent to the regosol type of FAO (1974). Checya (2011) analysed two samples on a vicinity area showing a neutral pH ranging from 6.8 to 7.2, low in nitrogen with 0.26 ppm on average, very high phosphorous on the first sample (102.5 ppm) and medium concentration on the second (28.3 ppm). Both samples presented very high potassium concentration (812.5 ppm on average), medium range of organic matter (5.22% on average), a very low electrical conductivity (EC) of 0.67 ms/m on average, with loam and sandy clay loam textures. Whereas 19 soil samples were analysed by the author at Huancacalle Town in Vilcabamba, presenting sandy loam, sandy clay loam, loam and silt loam textures, but predominantly sandy loam and loam. Soil colour ranges from brown to reddish brown. Thus Vilcabamba land is comparable to red loamy in Cropwat (2009) soil types, with total available moisture of 180 mm/m depth and a maximum infiltration rate of 40 mm/day for irrigation water requirements calculations.

2.3 Cropping pattern and scheme irrigation requirements

Interviews to local farmers such as Grimaldo Santa Cruz (2013), Former Deputy Major of Vilcabamba Municipalty, were conducted with regard to crops, yields and crop schedules in Vilcabamba, consequently, a cropping pattern of the main crops was estimated. Albeit Vilcabamba is isolated and little research has been done, books and theses about this region, such as IMA (2005, 2010), Checya (2011) and Guzman (2008), were also consulted.

The scheme irrigation requirements were the water supply for the entire irrigated area. This was obtained by sequential equations (FAO, 2009), beginning with the irrigation water requirements (IWR) in (mm/dec) for a given crop (Equation (5)):

$$IWR = ETc - \text{Effective rainfall} \tag{5}$$

The net scheme irrigation requirements were calculated, when each crop irrigation water requirements is multiplied by its percentage of area planted (Equation (6)):

$$\text{Net scheme irrigation} = \text{IWR} * \text{Percentage of area planted} \tag{6}$$

The net scheme irrigation requirements were multiplied by the scheme irrigation efficiency, expressed in mm/day or L/s/ha, resulting in the gross scheme irrigation requirements, which is the overall water needed for irrigation, as described on the Equation (7) below:

$$\text{Gross scheme irrigation} = \text{Net scheme irrigation} \times 100/e \tag{7}$$

The scheme irrigation efficiency (e) is calculated as follows (Equation (8)):

$$e = (ec \times ea)/100 \tag{8}$$

where, ec conveyance efficiency, representing the efficiency of water transport, e.g. canals; ea field application efficiency, representing the efficiency of water application in the field.

The flow capacity (Q), expressed in L/s or m³/s, is the amount of water required by the overall planted area, it results from the gross scheme irrigation requirements multiplied by the total area planted (Equation (9)):

$$Q\ (\text{L/s}) = \text{Gross scheme irrigation (L/s/ha)} * \text{Total area (ha)} \tag{9}$$

2.4 Water bodies

Two field practices were carried out during the dry (September 2012) and wet season (February 2013) to estimate the flow discharge from water bodies and to determine whether they satisfied the gross scheme irrigation requirements. Thus rivers, streams, canals and springs discharge (Q) was calculated with the velocity/area method, by measuring the average velocity of flow (V) and the cross-sectional area (A) of the water body, using the following Equation (10):

$$Q\ (m^3/s) = A\ (m^2) \times V\ (m/s) \tag{10}$$

The velocity was calculated by measuring the time taken for a floating object to travel a measured distance downstream (FAO, 1993).

River Vilcanota discharge was compared to precipitation records of a nearby meteorological station in Machu Picchu. The Vilcanota is one of the main rivers in the South Peruvian Andes and “Km 105” hydrometric station measures its river discharge, which is located 35 km east of the study site and 10 km northwest of Machu Picchu.

2.5 Results

Temperature

Temperature in the study areas was estimated on two stages. First, Vilcabamba and Machu Picchu meteorological stations data from 1964 to 1977 were interpolated by their elevations to obtain the temperature of Vilcabamba area for the same period (Table 3).

Second, Vilcabamba area results were related to the same period of Machu Picchu climate (1964-1977) and cross-multiplied by Machu Picchu overall climate (1964-1977 and 1998-2009), resulting in the modern climate data for the area of study. Minimum temperatures in Vilcabamba area occur on the evenings, while maximum temperatures are during daylight. The estimated average minimum temperature is 6.5°C in July, rising to an average maximum of 19.9°C in August (Table 4); while the monthly mean temperature is almost constant throughout the year (13-14°C).

Humidity and wind speed

Humidity and wind speed parameters were estimated with the same method as for temperature. Humidity monthly results ranged from 85% to 93%, with a yearly average of 89%. Monthly wind speed estimates varied from 2.9 to 3.6 m/s, with an annual average of 3.2 m/s.

Actual sunshine duration

Average monthly values of sun hours per day from Abancay and Huamanaga meteorological stations were calculated, obtaining sunshine duration data for Vilcabamba area (Table 5).

Table 3 Minimum and Maximum Temperatures (°C) monthly averages (years 1964-1977) for Vilcabamba area (middle row), obtained from Machu Picchu and Vilcabamba meteorological stations data, interpolated by elevation

Site	Elevation (m.a.s.1.)	Years	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		De		Average	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Machu Picchu station	2459	1964-1977	11.1	19.5	11.2	19.4	10.8	20.3	10.5	20.3	9.2	21.6	8.5	21.8	7.9	21.5	8.7	22.0	10.1	21.7	10.9	21.7	11.2	21.3	11.1	20.4	**10.1**	**21.0**
Vilcabamba area	2990	Interpolation	**9.3**	**17.4**	**9.5**	**17.5**	**9.2**	**18.1**	**8.8**	**18.6**	**7.6**	**19.2**	**6.8**	**19.4**	**6.1**	**19.3**	**6.9**	**19.7**	**8.3**	**19.3**	**9.1**	**19.2**	**9.5**	**18.9**	**9.4**	**18.0**	**8.4**	**18.7**
Vilcabamba station	4000	1964-1970	5.0	12.1	5.2	12.8	5.3	12.5	4.7	12.6	3.7	13.2	2.4	13.4	1.8	13.6	2.5	14.0	3.9	13.1	4.6	13.1	5.2	12.9	5.1	12.1	**4.1**	**12.9**

Note: Elaborated by the author based on Senamhi (2013).

Table 4 Monthly Minimum and Maximum Temperatures, °C in Vilcabamba area (results on last row). Period 1964-1977 data from Machu Picchu and Vilcabamba area cross-multiplied by overall climatic data from Machu Picchu (periods 1964-1977, 1998-2009)

Site	Years	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		De		Average	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Machu Picchu station	1964-1977	11.1	19.5	11.2	19.4	10.8	20.3	10.5	20.9	9.2	21.6	8.5	21.8	7.9	21.5	8.7	22.0	10.1	21.7	10.9	21.7	11.2	21.3	11.1	20.4	**10.1**	**21.0**
	1964-1977, 1998-2009	11.3	19.8	11.4	19.8	11.1	20.2	11.0	21.1	9.9	21.6	9.0	21.7	8.3	21.5	9.1	22.2	10.4	22.2	11.1	21.9	11.4	21.7	11.4	20.5	**10.5**	**21.2**
Vilcabamba station	1964-1977	9.3	17.4	9.5	17.5	9.2	18.1	8.8	18.6	7.6	19.2	6.8	19.4	6.1	19.3	6.9	19.7	8.3	19.3	9.1	19.2	9.5	18.9	9.4	18.0	**8.4**	**18.7**
	Cross-multiplication	**9.6**	**17.7**	**9.7**	**17.9**	**9.5**	**18.0**	**9.3**	**18.7**	**8.2**	**19.2**	**7.2**	**19.2**	**6.5**	**19.2**	**7.3**	**19.9**	**8.5**	**19.7**	**9.3**	**19.4**	**9.7**	**19.2**	**9.7**	**18.2**	**8.7**	**18.9**

Note: source: Elaborated by the author based on SENAMHI (2013).

Table 5 Mean daily sun hours per month in Vilcabamba area, based on Abancay and Huamanga stations averages (1970s to 1990s records)

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Average**
Abancay station	5.7	5.6	5.7	6.9	7.6	7.7	7.8	8.0	6.9	7.2	7.0	5.7	**6.8**
Huamanga station	6.4	6.3	5.7	6.9	7.6	7.8	7.3	7.0	7.2	7.2	7.7	6.7	**7.0**
Vilcabamba area	**6.1**	**6.0**	**5.7**	**6.9**	**7.6**	**7.8**	**7.6**	**7.5**	**7.1**	**7.2**	**7.4**	**6.2**	**6.9**

Note: FAO (2006).

Reference crop evapotranspiration

The reference evapotranspiration (ETo) was estimated with the Penman Monteith method (FAO, 1998), ranging from 2.71 mm/d in May to 3.40 in November (Figure 3), with an average of 2.97 mm/d, see details on Table 6 for monthly climate, radiation and ETo values. ETo values in Vilcabamba correlate well to humid, tropical regions with cool-temperate climates, as described in the parameters of Table 7, where cool temperatures of 10°C relate to 2-3 mm/d and moderate temperatures of 20°C correspond to 3-5 mm/d (FAO, 1998).

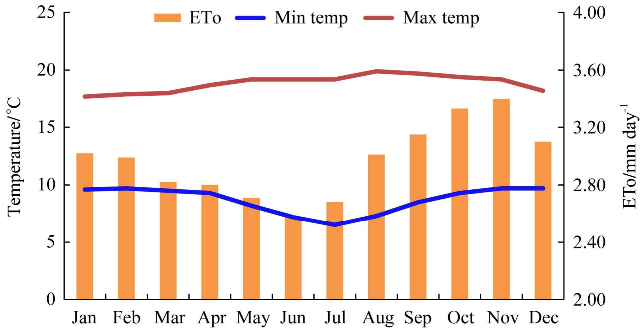


Figure 3 Monthly temperature (maximum and minimum) and reference evapotranspiration (ETo), (SENAMHI (2013), FAO (2009))

Table 6 Reference evapotranspiration (ETo) in Vilcabamba area

Country: Peru Station: Vilcabama area

Altitude: 2900 m. Latitude: 13.05 °S Longitude: 72.56 °W

Month	Min temp /°C	Max temp /°C	Humidity /%	Wind /m s^{-1}	Sun /hours	Rad /MJ (m^2 d)$^{-1}$	ETo /mm d^{-1}
January	9.6	17.7	93	3.0	6.1	19.8	3.02
February	9.7	17.9	93	2.9	6.0	19.5	2.99
March	9.5	18.0	92	2.9	5.7	18.2	2.82
April	9.3	18.7	91	3.0	6.9	18.3	2.80
May	8.2	19.2	88	2.9	7.6	17.3	2.71
June	7.2	19.2	87	3.1	7.8	16.5	2.58
July	6.5	19.2	85	3.3	7.6	16.7	2.68
August	7.3	19.9	85	3.6	7.5	18.3	3.01
September	8.5	19.7	88	3.6	7.1	19.6	3.15
October	9.3	19.4	89	3.5	7.2	21.0	3.33
November	9.7	19.2	90	3.6	7.4	21.7	3.40
December	9.7	18.2	92	3.1	6.2	19.9	3.10
Average	8.7	18.9	89	3.2	6.9	18.9	2.97

Note: SENAMHI (2013), FAO (2006), FAO (2009).

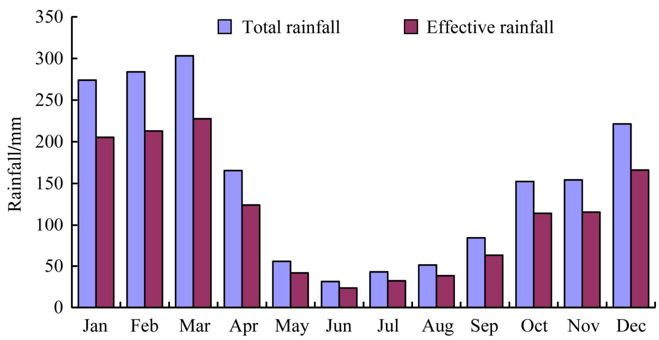
Table 7 Average ETo for different agro-climatic regions in mm/day. Vilcabamba area corresponds to subtropic, humid regions (dotted lines)

Regions	Mean daily temperature/℃		
	Cool ~10℃	Moderate 20℃	Warm >30℃
Tropics and subtropics			
-humid and sub-humid	2-3	3-5	5-7
-arid and semi-arid	2-4	4-6	6-8
Temperate region			
-humid and sub-humid	1-2	2-4	4-7
-arid and semi-arid	1-3	4-7	6-9

Note: Allen et al. (1998).

Rainfall

Rainfall data from SENAMHI (2013) stations were estimated with the same method as for temperature, with an annual precipitation of 1,820 mm. The effective annual rainfall is 1,365 mm/year, estimated from a fixed 75% crops use (IMA, 2010). Monthly total and efficient rainfall is illustrated on Figure 4.



Source: SENAMHI (2013), IMA (2010).

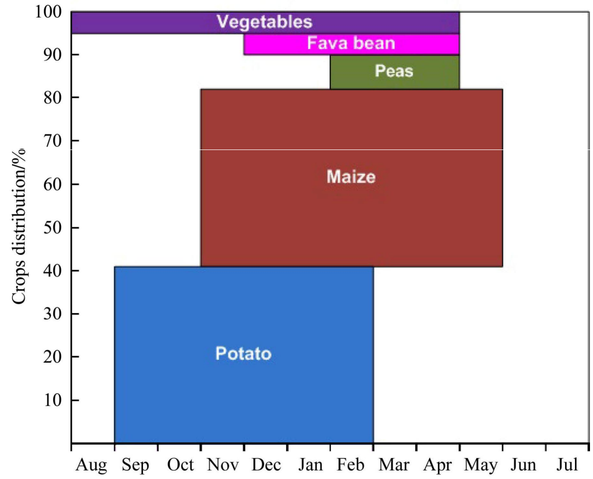
Figure 4 Total rainfall and effective rainfall (mm) in Vilcabamba area

Cropping pattern

Native Andean potato (*solanum tuberosum*) and the white maize (*zea mays*) suitable for highlands are the main crops in the study site, with a cultivated area of 15 ha each, covering 82% of the total area, and a yield of 8 and 3 ton/ha, respectively. Other crops include peas (*pisum sativum*), occupying 8% of the planted area with 3 ha and a yield of 1.3 ton/ha; fava beans (*vicia faba*) and mixed vegetables occupy 2 ha and 5% of the planted area each, with a yield of 1 and 4 ton/ha, respectively. Vegetable varieties include cabbage (*brassica oleracea*), lettuce (*lactuca sativa*), carrot (*daucus carota*) and tomato (*solanum lycopersicum*), which are mainly used for personal consumption. Planting average days were set for calculation purposes for potato, maize, peas, fava beans and vegetables, on the first day of September, November, February, December and August respectively. See Figure 5 for cropping pattern with planting schedules and crops distribution.

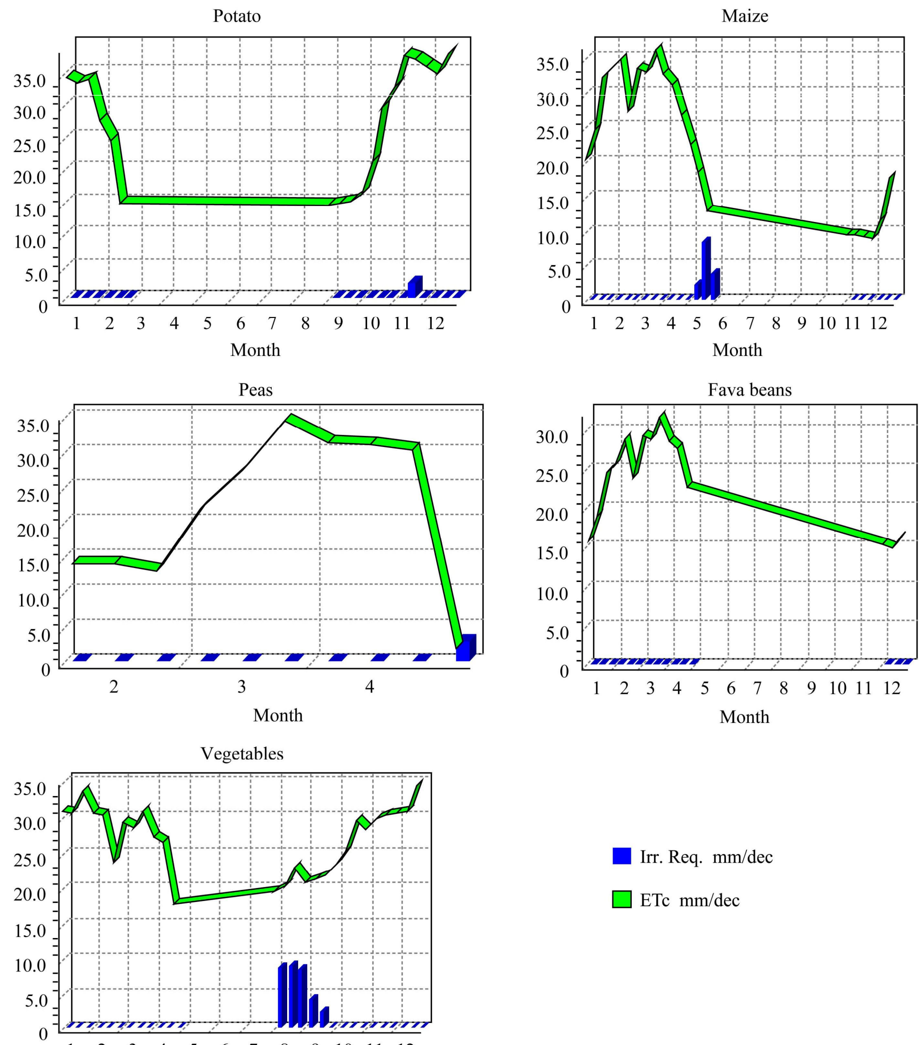
Irrigation and crop water requirements

Water balance results (Figure 6) established that potato irrigation water requirements (IWR) were 2.3 mm in November (mid season) with crop water requirements (CWR) of 38.5 mm. Maize IWR were 14.1 mm in May (late season) with CWR of 56.1 mm. Peas IWR were 3 mm in May (late season) with CWR of 3 mm. Fava beans had no IWR through its growing season. Vegetables IWR were 26.4 mm in August and 6.5 mm in September (initial season), with CWR of 64.9 mm and 43.7 mm, respectively. During the intense rainy season (December to April) crop water requirements are fully satisfied by precipitation and no irrigation is required.



Source: Santa Cruz (2013), Guzman (2008).

Figure 5 Cropping pattern.



Source: Cropwat 8.0 (2009).

Figure 6 Irrigation requirements and crop water requirements (ETc) for each crop

Scheme irrigation requirements

The irrigation scheme presented water deficits in May, August, September and November, requiring a flow capacity of 1.72, 0.38, 0.09 and 0.27 L/s, respectively (Table 8). For instance, in May, the irrigation requirements for maize and peas were 14.1 mm/mon and 3 mm/mon respectively. Each crop multiplied by its planted area resulted on net scheme irrigation requirements of 0.2 mm/d for that month:

Net scheme irrigation = 14.1×41% + 3×8% = 6.02 mm/mon = 0.2 mm/d

Table 8 Scheme irrigation requirement for Vilcabamba area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. POTATO	0	0	0	0	0	0	0	0	0	0	2.3	0
2. MAIZE (Grain)	0	0	0	0	14.1	0	0	0	0	0	0	0
3. PEAS	0	0	0	0	3	0	0	0	0	0	0	0
4. FAVA BEANS	0	0	0	0	0	0	0	0	0	0	0	0
5. VEGETABLES	0	0	0	0	0	0	0	26.4	6.5	0	0	0
Irrigated area												
(% of total area)	0	0	0	0	49	0	0	5	5	0	41	0
Net scheme irr.req.												
in mm/month	0	0	0	0	6.021	0	0	1.320	0.325	0	0.943	0
in mm/day	0	0	0	0	0.201	0	0	0.044	0.011	0	0.031	0
Gross scheme irr.req.												
in mm/day	0	0	0	0	0.401	0	0	0.088	0.022	0	0.063	0
in l/s/ha	0	0	0	0	0.046	0	0	0.010	0.003	0	0.007	0
Flow Capacity Q (l/s)	0	0	0	0	1.72	0	0	0.38	0.09	0	0.27	0

The scheme irrigation efficiency was estimated from two factors: a conveyance efficiency of 75% for a loamy, earthen canal of medium length (200-2000 m); and a field application efficiency for furrows and sprinklers corresponding to 60% and 75% respectively -related to local practices-, resulting in 67.5% on average. Hence the scheme irrigation efficiency (e) is approximately 50%, with gross scheme irrigation requirements of:

Gross scheme irrigation = 0.2 mm/day × 100/50 = 0.4 mm/day = 0.046 L/s/ha

Finally, the gross scheme irrigation requirements were multiplied by the total planted area of 37 ha, obtaining a flow capacity (Q) of 1.72 L/s in May, as shown below. A similar methodology was used for the other months with water deficits.

$$Q = 0.046 \text{ L/s/ha} \times 37 \text{ ha} = 1.72 \text{ L/s}$$

Water discharge related to rainfall

Monthly minimum, average and maximum flow data of River Vilcanota was available for a period of 47 years, from 1958 to 2007, not including years 1962, 1963 and 2000 (EGEMSA, 2008). This data were related to the monthly precipitation of Machu Picchu meteorological station (SENAMHI, 2013). Figure 7 illustrates that rainfall begins to increase intensively from August and September; however River Vilcanota flow is not affected during these months, suggesting that the dry soil absorbs most of the rainwater.

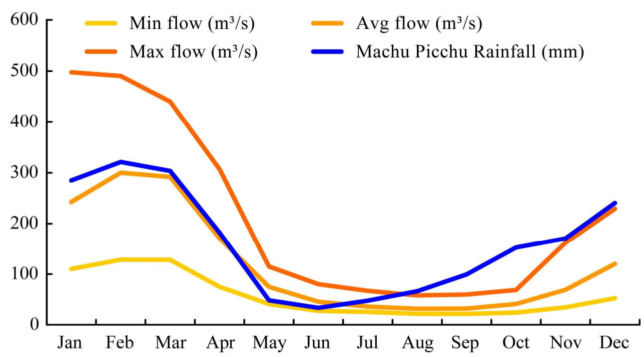


Figure 7 River Vilcanota flow related to rainfall (EGEMSA (2008))

Rainfall continues in October and the river discharge begins to increase, following a similar pattern of the precipitation, this indicates that the land has become saturated and rain runs off into the river. Through the rainy season (November to March) rainfall impacts on the river flow, to then sharply decrease from April to June. This indicates a close correlation between these two parameters. The average flow of River Vilcanota during the dry season (May to November) is 47.15 m^3/s, increasing to 225.16 m^3/s in the wet season (December to April), resulting in a variation of 478%, almost five times higher.

Field measurements were carried out on water bodies during the dry and wet seasons, resulting in considerable variation from one season to another. Table 9 illustrates main rivers and springs flows in the study area, where discharge can decrease to less than 13 times from wet to dry season. Relating these results to the scheme flow capacity, irrigation requirements can still be satisfied during the dry season, as field measurements from September 2012 sustain that small ditches convey 0.006 and 0.002 m^3/s, covering the maximum flow capacity required in May (0.0017 m^3/s).

Table 9 Flow capacities of rivers and canals in Vilcabamba area during February 2013 (wet season) and September 2012 (dry season)

Watercourse	February 2013 (Wet season)				September 2012 (Dry season)			
	Depth, m	Width, m	Velocity, m/s	Q, m³/s	Depth, m	Width, m	Velocity, m/s	Q, m³/s
River Cayara	1.70	8.00	3.48	**47.33**	0.76	5.00	1.11	**4.22**
River Cayco (S of Vitcos)	2.00	8.70	2.38	**41.43**				
River Cayco (W of Vitcos) - estimated				**88.76**				
River Pachaco (Anden)	0.50	4.00	2.48	**4.95**	0.45	1.50	0.57	**0.38**
River Habaspata (Pucyura)	0.10	5.00	2.54	**1.27**				
Inca Canal (towards East terraces)	0.11	0.47	1.18	**0.06**				
Ditch on Anden No.1 - East Terraces	0.15	0.80	1.27	**0.15**				
Ditch on Anden No.3 - East Terraces	0.13	0.72	1.33	**0.12**	0.10	0.45	0.13	**0.006**
Spring - Northeast Terraces					0.05	0.48	0.10	**0.002**

2.6 Discussion

Vilcabamba area lacked of meteorological stations, thus climate records from SENAMHI nearby stations were interpolated according to altitude to estimate minimum and maximum temperature, humidity, wind speed and rainfall. The sun hours were averaged from two FAO stations. Results on annual mean temperatures in the study area oscillated between 8.7ºC and 18.9ºC, with an annual average radiation of 18.9 MJ/m²/d and a reference evapotranspiration of 2.97 mm/d. This indicates a cool climate with low water requirements and a precipitation of 1,820 mm/yr, being especially intense from December to March when the main rainy season occurs. Cool climate and the rainy season are similar through the Peruvian Andes, where cold intensifies as altitude increases, while rainfall is heavier as the landscape descends to the east flank of the Andes into the Amazon rainforest. Due to this pattern, cultures from the past such as the Incas and Wari knew well their environment, adapting the crop schedules to the rainy season and mastering agriculture techniques.

The research modelling results determined that crop water requirements are low in Vilcabamba area and most of the water needs can be satisfied by rainfall. If rainfed irrigation is practised applying only an initial pre-irrigation, the crop yields would not be reduced. This indicates that farmers from these highland regions have a good crop scheduling management, taking advantage of the wet season. Still, the gross scheme is affected by lack of water in May, August, September and November, with flow capacities of 1.72, 0.38, 0.09 and 0.27 L/s respectively. Flow measures on-site indicate that the flow capacity can be satisfied by small streams, even during the dry season when streams can reach 2 to 6 L/s.

On the other hand, if crops were only rainfed but no pre-irrigation is applied to moist the land, the crop yield would be affected. As a general practice on this area, potato is sown at the beginning of September (September 1 for calculation purposes), using this schedule the soil depletion would be 65% with an initial available moisture of 63 mm/m, and the crop yield would be reduced by 1.4%. For vegetables sown at the beginning of August (August 1), the soil depletion would be 80% due to the dry season, with an initial available moisture of 36 mm/m out of 180 mm/m for loamy soils, the crop yield would be reduced by 4.7%. Therefore, it is suggested to delay the sowing of these two crops by one month. For instance, if potato planting is rescheduled to October 1, the yield would not be reduced, saving a production loss of 1,700 kg. If vegetables' planting is modified to September 1, the yield reduction would be only 1.2%, avoiding a loss of 260 kg. Note that the vegetables planted area is small and it is cultivated in small parcels for personal consumption, where water is easier to manage than on larger irrigation fields.

3 Conclusions

The research determined that the water management for agriculture can be improved in Vilcabamba highlands and in the Andean highland forest with similar altitudes, by adapting the scheduling criteria of crops to obtain efficient rainfed irrigation practices. The research determines that the water requirements are low because of the cool, sub-humid climate of Vilcabamba area, where soil and crop evapotranspiration are not significant. Another factor for the low water requirement is because the crops growing season is scheduled during the rainy season, when heavy rainfall occurs from December to April and soil preserves its moisture, covering the water requirements from crops. This knowledge has been mastered in an empirically way through centuries in the Andes.

However, it is necessary an adequate crop scheduling when applying rainfed and no pre-irrigation practices. In this matter, simulation techniques based on climate, soil and crop data suggest if selected crop planting schedules were delayed by one month, the yield would be maximised and crops will be less water stressed. If affordable, sprinkler irrigation is recommended, as a more efficient alternative to furrows. This irrigation surplus can be used to moist the land before ploughing and sowing, as during the dry season such as May and August, to overcome the water deficit in crops.

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