

## Assessing the capacity to meet irrigation water needs for viticulture under climate variability in the Chilean Andes

P. HUBLART<sup>1,4</sup>, D. RUELLAND<sup>2</sup>, A. DEZETTER<sup>3</sup> & H. JOURDE<sup>1</sup>

<sup>1</sup> UM2, <sup>2</sup> CNRS, <sup>3</sup> IRD – UMR HydroSciences Montpellier, Place E. Bataillon, 34395 Montpellier Cedex 5, France

<sup>4</sup> Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Raúl Bitrán s/n, La Serena, Chile

paul.hublart@um2.fr

**Abstract** Viticulture in semi-arid mountainous regions remains entirely dependent on surface water resources (SWR) to satisfy crop water needs through irrigation. Climate change is expected to increase the risk of water shortage by altering the timing and duration of both hydrological and phenological events while increasing crop evapotranspiration. This study focuses on the estimation of IWR in the Claro River Basin Chile (4196 km<sup>2</sup>) over the last decade (2002–2011). First, a process-oriented phenological model based on the accumulation of both chilling and forcing rates was built to predict the dates of budburst, full bloom and harvest events on the basin. Then a crop coefficient ( $K_c$ ) was adapted to each phenological stage and water requirements were computed following a water balance approach. Analysis of the ratio between simulated IWR and observed SWR at a 10-day time step show that water needs have frequently been unsatisfied over the period considered. This work is a first step towards an in-depth analysis of the impact of hydro-climatic variability on the capacity of the river system to satisfy IWR under various climate change and water use scenarios.

**Key words** irrigation requirements; climate variability impacts; water shortage; snowmelt regime; Elqui River, Chile

### INTRODUCTION

Climate change is expected to have substantial impacts on the capacity of freshwater systems to meet irrigation demands. In mountainous areas, warmer temperatures will reduce the fraction of precipitation falling as snow and tend to accelerate snowmelt, thereby leading to earlier peak flows in spring and decreased summer and fall flows (Barnett *et al.*, 2005). At the same time, higher temperatures in the cultivated valleys will affect the timing of phenological events (Cleland *et al.*, 2007), which drive the seasonal pattern of crop water needs. Although some beneficial effects of elevated CO<sub>2</sub> occur at the leaf level (Leakey *et al.*, 2007), crop evapotranspiration is also expected to increase at the regional scale (IPCC, 2008). In semi-arid catchments where irrigation water is derived from snowmelt-fed rivers, simultaneous shifts in streamflow seasonality and crop phenology could lead to a growing mismatch between irrigation requirements and surface-water resources. While both of these effects have been widely documented over the last decade, only a few studies have dwelt on their relationship. Phenological shifts have received little attention in agro-hydrological studies dealing with water availability for agriculture under present and future climate conditions.

A common method used to determine crop water needs is the so-called crop coefficient approach, which estimates crop evapotranspiration  $ET_c$  by multiplying a reference evapotranspiration  $ET_0$  by a crop-specific coefficient  $K_c$ . In the FAO–56 procedure (Allen *et al.*, 1998),  $ET_0$  provides an estimate of the atmospheric evaporative demand and is calculated using the physically-based Penman-Monteith equation for a hypothetical standardized reference grass. Crop coefficients account for crop characteristics and vary with the canopy height, cover and architecture. Recently, several studies have used this method to assess climate change impacts on water availability for irrigation at the regional (e.g. Milano *et al.*, 2013a) and basin (e.g. Rasmussen *et al.*, 2012; Collet *et al.*, 2013; Milano *et al.*, 2013b) scales. Many of these studies, however, relied on monthly estimates of  $K_c$  with the underlying assumption that these values estimated under current climate conditions will remain unchanged in the future. This is of course highly hypothetical. Even assuming that elevated CO<sub>2</sub> levels have no effect on crop water use at the basin scale, the effects of warmer temperatures on crop phenology still need to be accounted for. To overcome this limitation, crop growth models can be used in combination with the FAO crop coefficient model (Rosenzweig *et al.*, 2004). A major drawback in the use of these models is the large amount of data required for their calibration. As a result, growing degree-days (GDD) have been used in many studies to express the length of crop growth stages and eventually account for the effects of phenological shifts on irrigation water

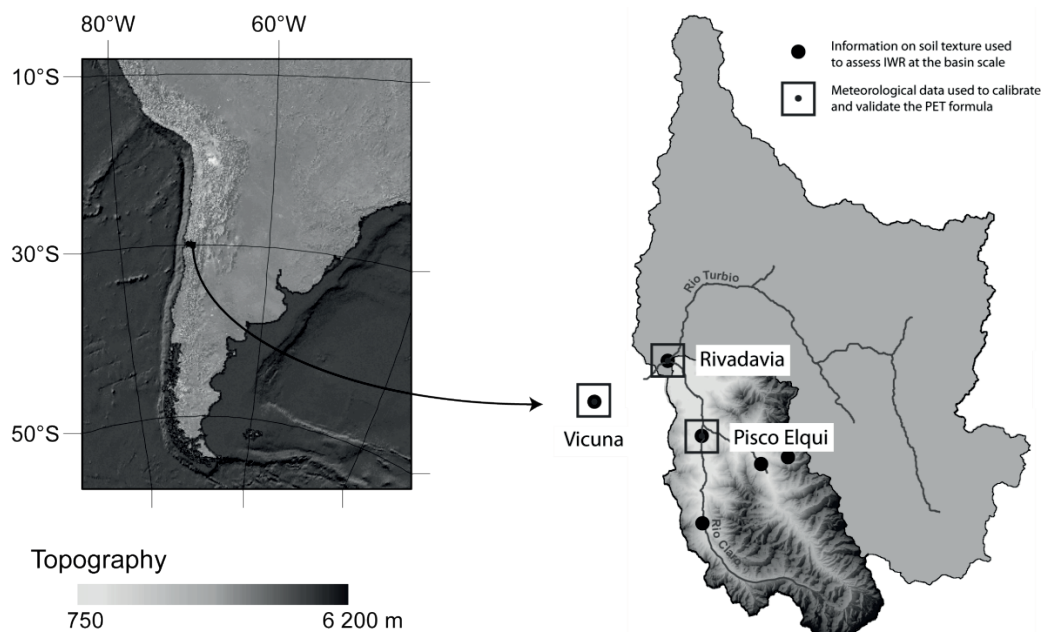
requirements (IWR) (e.g. Schoups *et al.*, 2005). In spite of its undeniable advantages in terms of data requirements, this method may prove to be ill-adapted to study future climate change impacts on IWR as it does not consider chilling requirements and fails to capture the effects of a temperature rise occurring below the temperature base of the GDD.

This paper thus investigates a more robust approach using a process-oriented phenological model with the same parsimony concern regarding data requirements. It presents the first results of an ongoing research project designed to assess current and future trends in water availability for irrigated agriculture in a semi-arid catchment of the Chilean Andes: the Upper Elqui Basin (UEB). The focus here is on the assessment of current IWR in the Claro River Basin, a sub-catchment of the UEB. A comparison with the observed discharge at the basin outlet provides a first estimate of the capacity to satisfy irrigation needs at the basin scale.

## STUDY AREA

The Claro River Basin (CRB) is the main sub-basin of the UEB located in the northeastern part of the Coquimbo region, Chile (Fig. 1). It drains an area of 4196 km<sup>2</sup> characterized by steep altitudinal gradients. Elevations range from 900 m a.s.l. at the basin outlet in Rivadavia to over 6000 m a.s.l. in the Andes Cordillera. Climate is semi-arid, with a mean annual precipitation of 104 mm at Rivadavia and mean annual temperatures above 16°C in the valleys. Precipitation occurs mostly during winter (June–August) through very occasional events (3 to 5 in a year) when the South Pacific High reaches its northernmost position. Most of the annual precipitation falls as snow at high elevations, where it accumulates in seasonal snow packs that are gradually released from October to April. The Claro River originates from a large number of small tributaries flowing either permanently or seasonally in the mountains.

Viticulture is by far the main agricultural activity in the catchment. Most grapes are grown to be sold as early-market table grapes (~850 ha), or processed into *pisco* (~670 ha), a brandy-like national drink (INE, 2009). The cultivated areas include most of the valley floors and part of the lower hill slopes. Yet, owing to the high seasonal and interannual variability in precipitation, grape growers remain entirely dependent on surface water resources to satisfy vine water needs. Water is diverted from the Claro River at 66 locations (*bocatomas*) and conveyed to the vineyards through a complex network of open, mostly unlined canals. All vineyards are drip-irrigated.



**Fig. 1** The Claro River Basin (4196 km<sup>2</sup>) within the upper Elqui catchment in Chile.

## MATERIALS AND METHODS

### A basin-scale integrated method

Irrigation water requirements over the last decade (2001–2010) and for the whole CRB were assessed in several steps. First, a process-oriented phenological model was used to predict the dates of budburst, full bloom and harvest at six locations selected in different parts of the basin where information on soil textures was available (Fig. 1). These locations were assumed to represent the full range of variation in soil properties and climate inputs across the basin. The predicted dates of budburst, full bloom and harvest were then used to construct  $K_C$  curves according to the FAO-56 methodology. These curves were used in an irrigation management model to assess IWR at a daily time step at each one of the six locations selected. Finally, mean IWRs among the locations were multiplied by the estimated planted area in the basin.

### Climatic data

Precipitation and temperature data from respectively 15 and 4 weather stations were interpolated on a  $5 \times 5$  km grid with the inverse distance weighting method. Elevation effects on temperature were considered using a digital elevation model and a constant lapse rate of  $0.65^\circ\text{C}/100$  m (Ruelland *et al.*, 2014, this volume). Potential evapotranspiration ( $PET$ ) was computed using the following formula proposed by Oudin *et al.* (2005):

$$PET = \frac{R_e}{\lambda \rho} \times \frac{T + K_2}{K_1} \quad \text{if } T + K_2 > 0 \text{ else } PET = 0 \quad (1)$$

where  $PET$  is the rate of potential evapotranspiration ( $\text{mm day}^{-1}$ ),  $R_e$  is the extraterrestrial radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ),  $\lambda$  is the latent heat flux ( $2.45 \text{ MJ kg}^{-1}$ ),  $\rho$  is the density of water ( $\text{kg m}^{-3}$ ) and  $T$  is the mean daily air temperature ( $^\circ\text{C}$ ). Oudin *et al.* (2005) determined the values of  $K_1$  and  $K_2$  by selecting those that gave the best streamflow simulations when the formula was used to feed hydrological models. In this study, a different approach was adopted since the objective was to estimate the evaporative demand in an irrigation management model. The FAO Penman-Monteith equation for a reference grass was used as a basis to evaluate and tune  $K_1$  and  $K_2$  at two different locations within the basin (Rivadavia, Pisco Elqui) and at one location outside the basin where the phenological observations were made (Vicuña). These locations were chosen to represent contrasted wind and relative humidity conditions. Calibration and validation of the formula were performed at a daily time step during years of data availability. Root mean square errors and coefficients of determination remained of the same order of magnitude during the calibration and validation periods, indicating an input error related to  $PET$  estimation of approximately 0.06 mm.

### Phenological data

Phenological records were obtained from the Experimental Center of the *Instituto de Investigaciones Agropecuarias* (INIA) located in Vicuña (Fig. 1). Observations were carried out over a 4-year period (June 2004–May 2008) on two main grapevine varieties that are cultivated to produce table grapes (Thompson Seedless) or *pisco* (Moscatel Rosada) within the basin. The experiment kept track of three major phenological events: budburst, full bloom and the beginning of harvest. Budburst was defined as the moment when the first leaf tips become visible and full bloom as the moment when 80% of the flower caps are off. The beginning of harvest depends on the intended use of the grapes. Table grapes generally require a lower sugar content ( $16^\circ$  Brix for Thompson Seedless) than the varieties used to produce *pisco* ( $22^\circ$  Brix) and are thus harvested a few months earlier.

### Phenological modelling

As part of the phenological modelling, the growing season was split into five phases (Fig. 2(a)). *Phase 1* starts at  $T = T_0$  (arbitrarily fixed to the 1 June) and covers a period of rest known as “true dormancy” during which the meristems are inactive because of endogenous physiological factors. To emerge from dormancy grapevines usually require an extended period of low temperatures that

can be described in terms of hours, days or rates of chilling. *Phase 2* starts at  $T = T_1$  and covers a period of “quiescence” during which buds remain dormant because of inadequate environmental conditions. This period ends with budburst at  $T = T_2$ . *Phase 3* spans from budburst to full bloom ( $T = T_3$ ). *Phase 4* extends from full bloom to ripeness, when grapes are ready for harvest ( $T = T_4$ ). *Phase 5* covers the post-harvest period that runs until the end of leaf fall, which was set at 80 days after the beginning of harvest.

Following this partition of the growing season, phenological modelling was based on three nested sub-models (Fig. 2(a) and (b)): a budburst (BB) model, a flowering (FW) model and a harvest (HV) model. The BB model relies on the accumulation of both chilling and forcing rates to simulate the timing of budburst. The FW model uses the date of budburst simulated by the BB model as a starting date for the prediction of full bloom. Lastly, the HV model uses the date of full bloom simulated by the FW model to predict the beginning of harvest. The BB model relies on a simplification of the general framework provided by Chuine (2000). The FW and HV models consider only heat accumulation.

Each sub-model was calibrated over the whole dataset (2003–2010) using a simulated annealing method to minimize the root-mean-square error (RMSE) in the parameter space, as recommended by Chuine *et al.* (1998). To increase the robustness of the model and ensure convergence towards a realistic solution during the optimization procedure, some parameter values were regarded as impossible from a biological viewpoint (Caffarra & Eccel, 2010). A Nash-Sutcliffe efficiency index (NSE) was thus used apart from the optimization to assess the performance of each sub-model when compared to the mean dates of budburst, full bloom or harvest over the period. Given the small number of observational data available (5 years) for calibration, a leave-one-out cross-validation approach was used to assess the robustness of the different sub-models.

### Irrigation scheduling

The irrigation management model uses a “tipping bucket” approach to compute the soil water balance of the root zone at a daily time step. A detailed description of the model can be found in Hublart *et al.* (2013). Irrigation efficiency was estimated by multiplying a water transport efficiency of 0.6 by a field application efficiency of 0.9, as is usually assumed by the FAO for earth canals and drip irrigation systems.

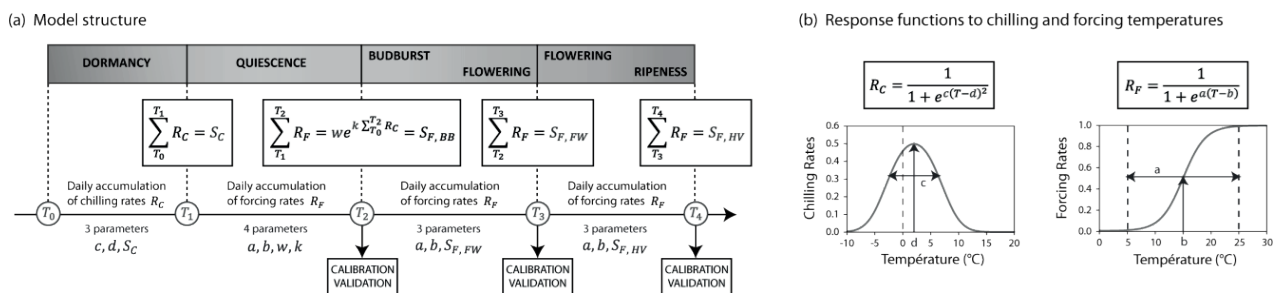


Fig. 2 Principles of the phenological modelling.

## RESULTS

### Efficiency of the phenological model

Calibration of the phenological model over the whole dataset resulted in low values of RMSE ranging from 0.00 (BB sub-model) to 1.94 (FW sub-model) with Thompson Seedless and from 0.00 (BB sub-model) to 4.10 (HV sub-model) with Moscatel Rosada (Table 1). The NSE criterion that was not considered during the optimization procedure is over 0.76 during calibration for both varieties, indicating that the model is a better predictor than the mean dates of budburst, full bloom and harvest over the period. Validation of the model was performed using the same criteria (RMSE and NSE) as for calibration. While the RMSE criterion presents very satisfactory values

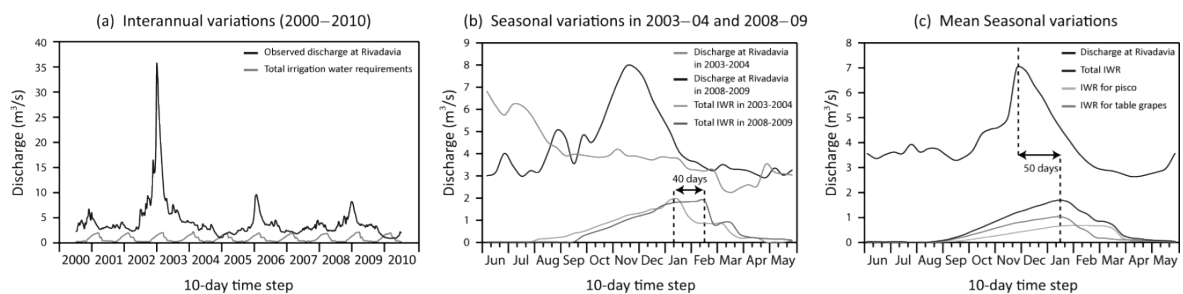
**Table 1** Efficiency of the phenological model.

Variety	Calibration						Validation					
	Budburst		Full bloom		Harvest		Budburst		Full bloom		Harvest	
	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE
Thomson Seedless	0.00	1.00	1.94	0.87	0.50	0.99	3.75	-5.67	2.25	0.75	2.50	0.78
Moscatel Rosada	0.00	1.00	1.80	0.82	4.10	0.76	2.77	-2.32	2.50	0.67	5.20	0.59

(errors not exceeding 5.2 days), negative values of NSE are obtained for the BB sub-model with both Thompson Seedless and Moscatel Rosada.

### Comparison of IWR at the basin scale with the discharge observed at Rivadavia

Irrigation water requirements for the whole basin were compared at a 10-day time step with the discharge measured at the basin outlet over the 2001–2010 period. At the interannual timescale, the observed streamflow largely exceeded irrigation requirements during at least four growing seasons (2002–03, 2003–04, 2005–06, 2008–09) but proved to be insufficient during two growing seasons (2004–05, 2009–10) (Fig 3(a)). Interannual variations in the timing of peak IWR can reach 40 days, as shown in Fig. 3(b) between the years 2003–04 and 2008–09. At the seasonal timescale, a time lag of 50 days can be observed between the mean peak irrigation requirement and the mean peak discharge (Fig. 3(c)). It must be noted, however, that the discharge observed at Rivadavia does not represent the natural flow regime of the basin, as upstream water withdrawals affect both the timing of peak flows and the volume of water received at the outlet. Consequently the comparison performed can only provide a first estimate of the actual balance between water availability and irrigation requirements at the basin scale.



**Fig. 3** Comparison of IWR with the observed discharge at Rivadavia: (a) Interannual variations; (b) Seasonal variations for the 2003–2004 and 2008–2009 growing seasons; and (c) Mean seasonal variations over the whole period (2001–2010).

### CONCLUSIONS AND PROSPECTS

In this study, an integrated modeling approach relying on low data requirements was developed to assess the impact of climate variability on irrigation water requirements (IWR) in a semi-arid Andean catchment, the Claro River Basin. A process-oriented phenological model was combined with an irrigation management model to compute irrigation needs at a daily time step.

Two major sources of uncertainty were identified in the phenological modelling. Firstly, it must be highlighted that a dormancy-breaking agent (hydrogen cyanamide) was applied on Thompson Seedless grapevines to compensate for the lack of chilling temperatures during winter. This could be the main reason for the negative values of ME obtained with Thompson Seedless. Secondly, since field observations of dormancy release cannot readily be made, budburst observations were used to calibrate both the sigmoid function that expresses the plant response to forcing temperatures and the two-parameter bell curve used to describe the response to chilling temperatures. This results in an overparameterization of the budburst model relative to the information content of the data available for calibration and validation.

Additional information regarding irrigation practices and crop evapotranspiration is thus necessary to validate the irrigation management model and increase confidence in future IWR

projections. Better estimates of crop coefficients are notably needed. Using eddy-covariance measurements in a drip-irrigated vineyard of semi-arid Northern Mexico, Er-Raki *et al.* (2003) found that  $K_C$  values recommended by the FAO overestimated evapotranspiration of table grapes by about 46%. Going forward, these modelling weaknesses could be addressed by expressing  $K_C$  as a linear function of the shaded area beneath the canopy (see e.g. Williams & Ayars, 2005).

Finally, the question remains of how climate change could affect the 50-day time lag observed during the 2001–2010 period between the peak irrigation requirement and the peak discharge. Depending on their magnitude, seasonal shifts in the timing of peak flows and phenological events could result in either additive or countervailing effects. For instance, earlier peak flows could lead to an increase in water supply at a time when it is not required or simply compensate for a simultaneous and similar shift in crop phenology. To address these issues, a multidisciplinary agro-hydrological modelling is currently being developed, which will enable assessment of the capacity of the whole upper Elqui River system to satisfy irrigation water needs under climatic and agricultural change scenarios.

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