

Water management under changing climate and land use: Use of simulation modeling

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1. Abstract

Water, that is often the main limiting factor of plant growth, is also the main factor directly or indirectly responsible for soil and land degradation processes. These processes are strongly linked to unfavourable changes in the hydrological processes responsible for the soil water balance and for the soil moisture regime, which are affected by the climate conditions and variations, and by the changes in the use and management of soil and water resources. The soil moisture regime, determined by changes in soil water content with time, is the main single factor conditioning moisture availability, plant growth and crop production. It is mainly conditioned by soil properties affecting the capacity and possibilities of infiltration, retention and drainage of rainwater, and the limitations to root growth under the particular rainfall characteristics. These conditions may be modified by soil, water and plant management practices as tillage, irrigation, drainage, etc. The previewed effects of global climate changes would mainly affect hydrological processes in the land surface, mostly related to the soil water balance. Human activities leading to land degradation processes may affect more the soil hydrological processes than the previewed climate changes, or may increase the influence of those changes. The water balance may be drastically upset by the consequence of inappropriate changes in land use and management, and especially by the consequent land degradation.

For an adequate planning of soil and water management and conservation it is required an adequate understanding and prediction of the interactions between climate characteristics and soil properties, under different scenarios of changing climate and changing land use and management practices and systems. These complex interactions may be integrated over time using simulation modeling based on hydrological processes. Such approach has been applied to the evaluation of the effects on the soil water balance and soil moisture regime, associated to new land and crop management systems, ant to the previewed climate changes, in dry-land and irrigated vineyards for quality wine production in NE Spain. The generated information has been used in planning strategies for land use, and in the selection of the soil and water management practices, based on probabilities of success, levels of risk and long term sustainability. Special attention is given to the water use efficiency, under the semiarid Mediterranean climate, with low and very variable and erratic rainfall, and with scarce availability of water for irrigation, in reation to the production, both in quantity and quality of grapevines and wine.

2. Introduction

Major recent water-related disasters including both floods, landslides and extensive droughts are reminders of both the destructive power of water and the tragic consequences associated to the lack of it in many regions of the World. These extreme events are only the final consequences of changes in land use and management that are affecting the soil and water resources, under very different climate and land conditions. In some cases these effects may be linked, at least partially, to global climate changes. The previewed climate changes may also affect water availability, because there is a strong link among soil degradation, climate change and water resources. Changes in population, both in total number and distribution, are also strongly affecting the quality and quantity of the available freshwater, and the land use and management. To the increased demand of water for agriculture there must be added the demands for urban and industrial uses and for energy generation. Water resources must be managed not only to satisfy people direct needs, but also for nature conservancy (Johnson et al. 2001). The combination of different economic, environmental and social pressures often results in increased water use competition and pollution, generally associated to inefficient water supply practices. As a result, in many parts of the world available quantity of water is decreasing and quality is worsening. About 1/3 of the world population suffer from deficient supply in quantity and quality of water, and about 900 million people do not have enough food and water for a healthy life.

Climate, especially precipitation and temperature, is the primary driver of water resources, interacting with land and topography. Yet, all components of the hydrological cycle (precipitation, infiltration, runoff, evaporation and transpiration) must be taken into account for water management planning. It is very important to understand the role played by each of those components. Changes in land use and management, associated to deforestation, urbanization and increase or abandonment of farmland, all significantly influence the soil and

water resources, moreover than the effects of climate change. Besides, the river regimes are being influenced in many regions of the world through construction of dams and diversions. All these changes makes more difficult to predict the future impacts of climate change. Soil management practices strongly impact quality of surface and ground waters, because chemical characteristics of soils, and the application of chemical fertilizers, manure, and other chemicals affect the quality of water flowing over and through it. In the increasing water scarce regions of the world, the necessity of reuse for irrigation of treated waste, polluted water, also impacts quality of water and soil resources.

With a growing population, the available land and water resources per capita shrink, and higher productivity is required to compensate. On average it takes about 3000 liters of water per person to produce the daily uptake of food (Brown, 2004). Although rain-fed agriculture is still dominating in the world, irrigation is required as a reliable supplement of rainfall where soil moisture is insufficient to satisfy the needs of the crops, especially in areas with excessive climate variability (probably accentuated by the previewed climate changes), or where multiple cropping, looking for increased productivity, requires provision of water outside the rainy season. The amount of water available to agriculture is now being progressively limited by degraded land and water systems, competition from other economic sectors, and by climate change in some regions. While agriculture is the larger user of freshwater, there is growing competition from industrial and urban users (Gleick, 2003). To alleviate the increasing burden on available freshwater resources there are needed prevention strategies and new technologies that increase existing natural water resources, reduce demand and achieve higher use efficiency. Water re-use and desalinization and harvesting rainwater are some of the potential methods to increase the availability of water resources. Soils are complex porous media that are highly relevant for the sustainable use of water resources (Vogel et al. 2008). They are the essential basis for agriculture, but they also act as a filter for clean water, and depending on soil properties, affected by land use and management, they reduce or intensify surface runoff and thus susceptibility to erosion, floods and sedimentation. Additionally, the interaction of soil water with the atmosphere and the related energy flux is an important part of modern weather and climate models. Soil resources will have to be managed to enhance water use efficiency, denature and filter pollutants, enhance aquifer recharge, and improve water quality and yield from protected watersheds.

To improve the strategies and the efficiency in the use of the available water resources there is required a better understanding of the hydrological systems, and of the regional and local water balance estimates. Quantifying the hydrological balance at high temporal resolution is necessary to evaluate field-scale management effects on soil water storage. This requires an accurate modeling and prediction of soil water dynamics, which especially at large spatial scales, is complicated by the heterogeneity of soils and changing topography. It is further limited by a severe decrease of the basic hydrological data collection, owing to economic problems, budget constraints and lack or deficiencies in professional education. As an alternative there have been used empirical models, using pedotransfer functions to estimate the required soil hydraulic parameters from other available or easily measurable soil properties. With a general lack or incomplete set of reliable and consistent data of subjects relevant to soil water balance, large scale simulations of water dynamics in soil may be imprecise to completely wrong.

3. Water management and hydrology

Water, that is often the main limiting factor of plant growth, is also the main factor directly or indirectly responsible for soil and land degradation processes. These processes are strongly linked to unfavourable changes in the hydrological processes responsible for the soil water balance and for the soil moisture regime, which are affected by the climate conditions and variations, and by the changes in the use and management of soil and water resources (Pla, 2002).

The soil moisture regime, determined by the changes in soil water content with time, is the main single factor conditioning moisture availability, plant growth and crop production. It is mainly conditioned by soil properties affecting the capacity and possibilities of infiltration, retention and drainage of rainwater, and the limitations to root growth under the particular rainfall characteristics (Pla, 2002). These conditions may be modified by soil and plant management practices as tillage, irrigation, drainage, etc. Moisture availability is determined both by water gains from precipitation and water losses through runoff and evapotranspiration (Figure 1).

The previewed effects of global climate changes would mainly affect hydrological processes in the land surface, mostly related to the soil water balance. In terms of ecological and social impacts of climate change, changes in moisture availability are more important than changes in precipitation alone. Low levels of moisture availability are associated with droughts and desertification. Reductions in mean annual rainfall leads to drier conditions, but increase in climate variability during the year, or increasing frequency of very dry years, could be equally or more important. Human activities leading to land degradation processes may affect more the soil hydrological processes than the previewed climate changes, or may increase the influence of those changes (Pla,

2001). Forests usually regulate stream flows, protect land from erosion, reduce flooding in adjacent areas, minimize the silting of rivers, canals and dams, and contribute to a stable hydrology essential for providing stable sources of water for human needs and irrigated agriculture. This water balance may be drastically upset by the consequence of inappropriate changes in land use and management, and especially by the resulting land degradation. Supply of available water may decrease irreversibly under unchanged soil properties and stable hydrological soil parameters due to reduced water income, increasing water consumption, or both. Under unchanged water income by rainfall, the hydrological parameters of soils may change irreversibly as a result of soil degradation (sealing, compaction, erosion, decreased water retention capacity, etc), leading to the same effects of decreasing available water supply (Pla, 2006, 2007) (Figure 1).

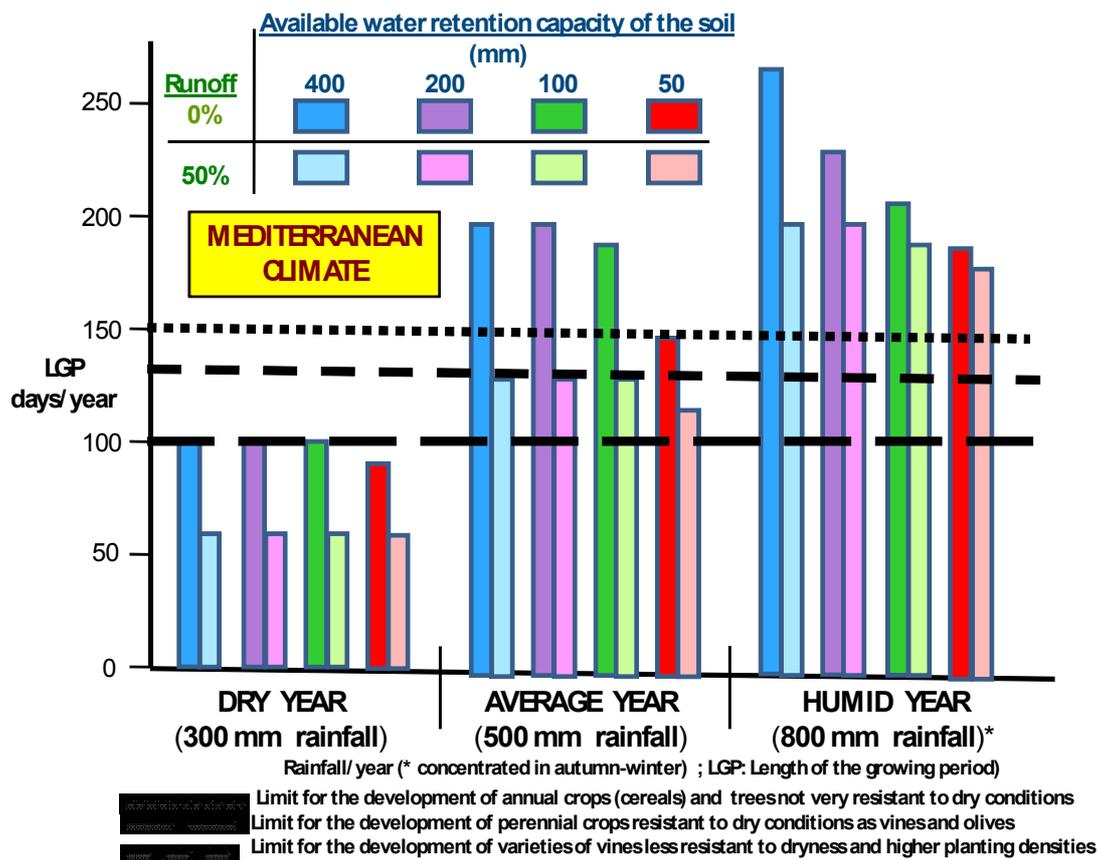


Figure 1 Potential length of the growing period in days/year (LGP) under semi-arid Mediterranean climate conditions, as affected by the main critical factors derived of climate changes, land use & management and soil degradation.

Irrigation causes drastic changes in the regime and balance of water and solutes in the soil profile, which may result in soil salinisation, one of the processes of soil degradation leading to land desertification. The salinity problems are a consequence of salt accumulation in zones and depths where the soil moisture regime is characterized by strong losses of water by evaporation and transpiration, and by reduced leaching of the remaining salts. Inadequate irrigation and drainage water management is the main cause of soil salinisation. The salt accumulation may conduce to a partial or complete loss of soil capacity to provide the required amounts of water to plants, changing fertile lands to deserts (Pla, 1996).

From the previous arguments, it follows that approaches based on water balance models are the more adequate to predict the reliability of the water supply for a plant during its growth. This would be the main basis for determining the suitability of the land for various uses under given conditions of management. There is required research into the basic hydrological processes determinant of the soil water balance, including climate and soil data. Research is also required on the hydrological changes as a result of various alternative land uses and agricultural systems and practices. The soil water balance may be quantitatively determined in terms of certain physical properties and water regime of soils (annual supply of available water in the root zone), using soil hydrological parameters (Pla, 2006).

4. Simulation modelling for soil water management

For an adequate planning of soil and water management it is required a good understanding and prediction of the interaction between climate characteristics and soil properties, under different scenarios of changing climate and changing land use and management practices and systems. These complex interactions may be integrated over time using simulation modeling based on hydrological processes. The generated information may be used in planning strategies for land use, and in the selection of the soil and water management practices, based on probabilities of success, levels of risk and long term sustainability.

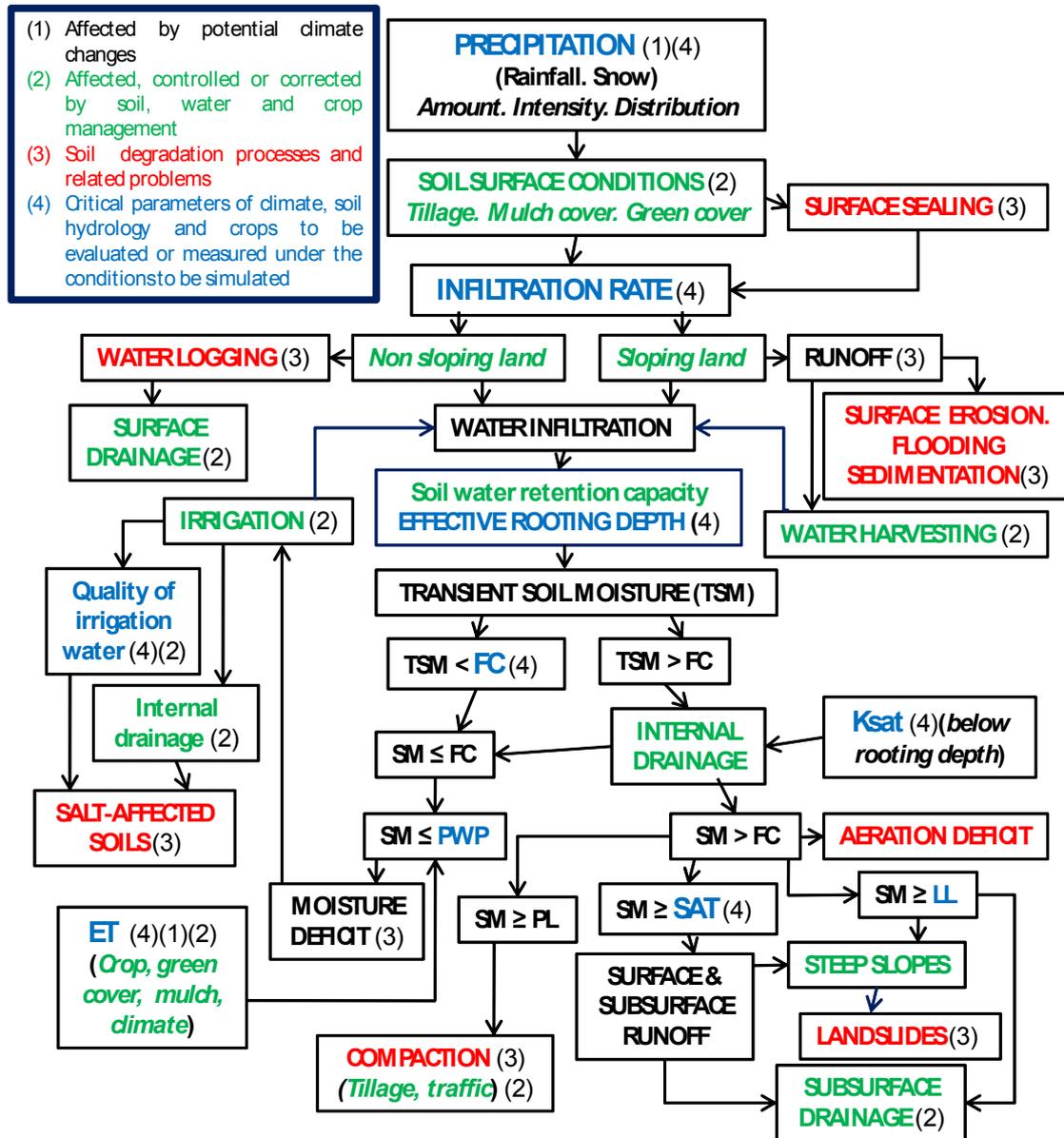


Figure 2 Flow diagram of a simulation model (SOMORE) based on hydrological processes to predict soil water balance, soil moisture regime and derived soil degradation processes under different scenarios of climate, soil and soil and water management (Adapted from Pla, 1997, 2000, 2006) (SM: Soil moisture at root depth; FC: Field capacity; PWP: Permanent wilting point; ET: Evapo-transpiration)

Models must be based on well established cause-effect relationships for prediction, and flexible enough to be able to include the variety of possible soil-climate-use and management situations, and to be constantly improved as more is known about the influence of specific land and climate characteristics on the soil water balance and derived soil and water degradation processes. Simulation modeling requires data collection, updating of information and monitoring. Poor, incomplete and inaccurate basic data on soils and climate give poor qualitative and quantitative evaluations of soil and water use and management. The analysis itself by models does not add any new information, and when it is based on empirical statistical approaches developed for different conditions, using pedotransfer functions to substitute non available local data, it may lead to gross inaccuracies and misinterpretations.

Simulation modelling and prediction of soil water balances must rely on hydraulic parameters of rainfall and runoff generation, using infiltration or storage approaches. The methods and techniques applicable for predicting soil hydrological behavior under field conditions include from simple, straightforward field techniques, usually providing rough estimates of soil hydraulic properties, to rather complicated techniques, generally requiring costly equipment, more accurate under controlled laboratory conditions but difficult to use under the very variable field conditions. Our experience indicate that simple field techniques must be preferred (Pla,1990), because of operational considerations, and because they are more able to be adapted to the required sample volume and spatial variation of soil hydraulic properties under field conditions. Moreover, the models must not be extremely complex, requiring input information which is seldom available, or difficult to determine or non representative, making the simpler models more suitable for practical purposes. Simulation errors derived from estimation errors in soil properties and the sampling costs are generally lower when simple models are used for predicting soil water balance in space (Leenhard et al., 1994). Simpler models require fewer input data, and therefore they allow larger samples and sampling densities for a given field measurement.

Figure 2 shows an adaptation of the flow diagram, which was the basis for the development of the simulation model SOMORE (Pla, 1997), based on hydrological processes. This model simulates the evolution of the soil water balance in the soil profile with a time step of one day, using easily obtainable soil and climate data as input. It may be used to predict the soil moisture regime, including water logging, rainfall losses by surface runoff, and surface and internal drainage, under different conditions of soils, topography, climate, vegetation, crops and management. The predictions may be used for the identification and selection of the best alternatives of soil and water management with more probabilities of success, and for the assessment of environmental impacts, positive or negative, of soil and water conservation practices for each combination of soils, climate and topography.

5. Case studies: Modelling soil water balances in vineyards

The climate in arid and semiarid Mediterranean environments, with highly variable and erratic rainfall amount and distribution, increases the risks of land degradation and desertification. Those risks may have been further increased in the last decades, mainly due to drastic changes in land use and management, with an additional potential negative effect derived of apparent climate changes. There are significant uncertainties in predictions of regional climatic changes, but probably the Mediterranean region will warm significantly, with more precipitation in winter and less in summer, and declining annual precipitation in the southern part (N Africa and SE Spain), increasing the frequency and severity of droughts, and the occurrence of extreme events (Pla, 2006).

Some permanent dry land crops, like grapevines, with great survival capacity under drought conditions, have contributed in the past to decrease the processes and consequences of land desertification in the semiarid regions of the Mediterranean region. But in the last decades, the lands with dry land vineyards in the Mediterranean region have suffered and are increasingly suffering great changes that may seriously affect the conservation of soil and water resources. Some cropped lands have been abandoned, but in others the cropped area has increased, with more intensive and highly mechanized agricultural systems. This has required great changes in the planting and cropping systems, with previously mechanical land conditioning, reducing relief irregularities and decreasing slopes through levelling operations and bench terracing. This has lead to drastic changes in the soil properties, both in surface and subsurface soil, mainly affecting the hydrological properties, the effective rooting depth of the vines, and the drainage system.

The interaction of changes in land use and management, and in climate, with land degradation processes associated to unfavourable changes in hydrological processes has been studied in three different areas (Penedés, Priorat and Costers del Segre) with vineyards for high quality wine production in Catalonia (NE Spain). There were evaluated problems of soil water supply to the plants through the different growing periods in the year, of surface and mass erosion, of runoff, of flooding, and related problems, derived of changes in hydrological behaviour under the new levelling, terracing, planting and management practices (Pla, 2006; Pla and Nacci, 2001, 2003; Pla et al., 2004, 2005).

In the three regions the climate is Mediterranean semiarid, with an average annual rainfall of 500- 600 mm in two of them (Penedés and Priorat), and of 300 mm in Costers del Segre, where drip irrigation is used as a complementary source of water. The rainfall is very irregularly distributed, with the greatest rains in autumn-winter, a very dry summer, and with large variability in totals from one year to another (400-750 mm in Penedés, 300-900 mm in Priorat and 200-500 mm in Costers del Segre). Rainfall is typified by many storms in autumn, and occasionally in spring of high concentration and intensity. Climate change may increase the irregularity of this rainfall, the frequency of dry years and the probability of extreme events, phenomena that have been observed in the last 25 years.

	Slope %	Coarse fraction %	Effective rooting depth cm	AWC mm	Rainfall Infiltration mm/hour		K sat (subsoil) mm/hour
					No cover	Cover	
<u>PENEDÉS</u>							
NON LEVELED	10	<5	20→ 80	200	20	50	3
LEVELED	6	5-10	15→ 60	120	5	20	0,4
<u>PRIORAT</u>							
SLOPES	50	50-60	0→ 40	61	>200	>200	>200
TERRACES	0	30-60	10→ 70	110	>100	>100	>100
<u>COSTERS DEL SEGRE</u>							
SLOPE	10-12	10-15	10→ 100	160	6	18	2,4
LOW LAND	0	8-10	5→ 55	110	1	6	1,3

(AWC: Available water capacity)

Table 1 Some characteristics and hydraulic properties of the soils, under different conditions, in the three regions included in the study

The water use of grapevines through the growing season is characterized by lessened requirements in the periods before bloom and after harvest until fall (autumn), and a maximum consumption in the mid part of the growing season. If the reserve water capacity of the soil in the rooting zone is not enough, reduced amounts of rainfall during the main growing season of grapevines (June-August) may lead to a long term soil water deficit, which can affect growth, production and maturation, in spite of the natural survival capacity of grapevines under drought conditions.

In order to decrease costs of the scarcely available manual labour, to increase production and to speed all operations, the current trend is towards full mechanization of all practices, including harvesting. To proceed to a fully mechanised system there is a need for heavy land levelling or terracing operations, with drastic changes in the surface drainage network and on the effective soil rooting depth and surface soil properties (Pla & Nacci 2003). The main changes in land management in those three regions include:

- leveling and use of green cover in rain-fed vineyards of the Penedés
- terracing and tillage in rain-fed vineyards of the Priorat
- complementary irrigation and use of green covers in vineyards of the Costers del Segre

Soils in Penedés and Costers del Segre, derived of calcareous lutites, are mainly of silty-loam texture. The soils in Priorat, derived of slates, are very stony (>50% coarse fraction), and calcareous only in the deeper horizons, where the clay (smectites) content slightly increases. The main characteristics of the soils in the different studied conditions are shown in table 1.

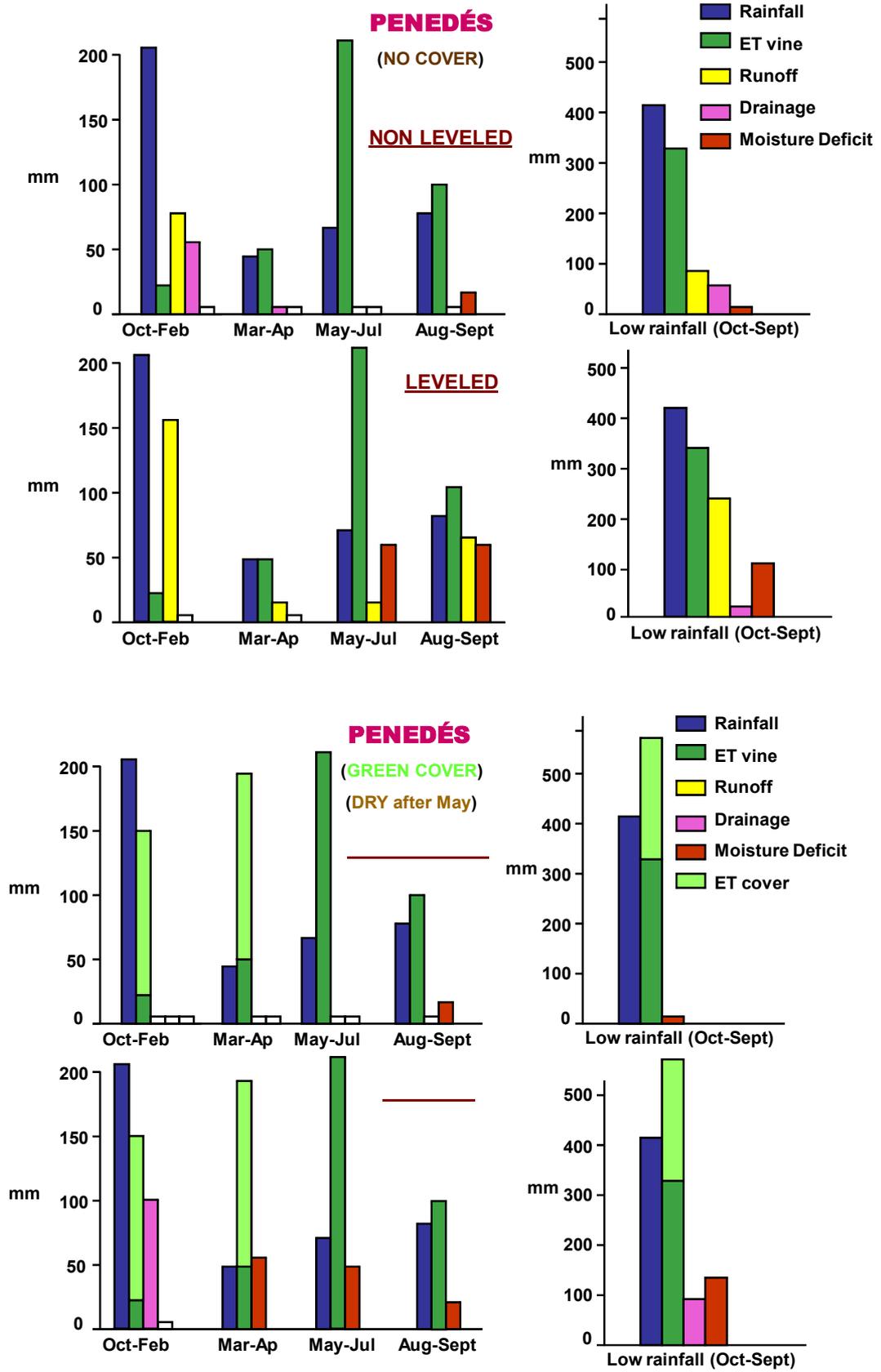


Figure 3 Rainfall and soil water balance components in rainfed vineyards of the Penedés region in years with low rainfall (Return period:5 years) in non levelled and levelled land, with or without use of green cover

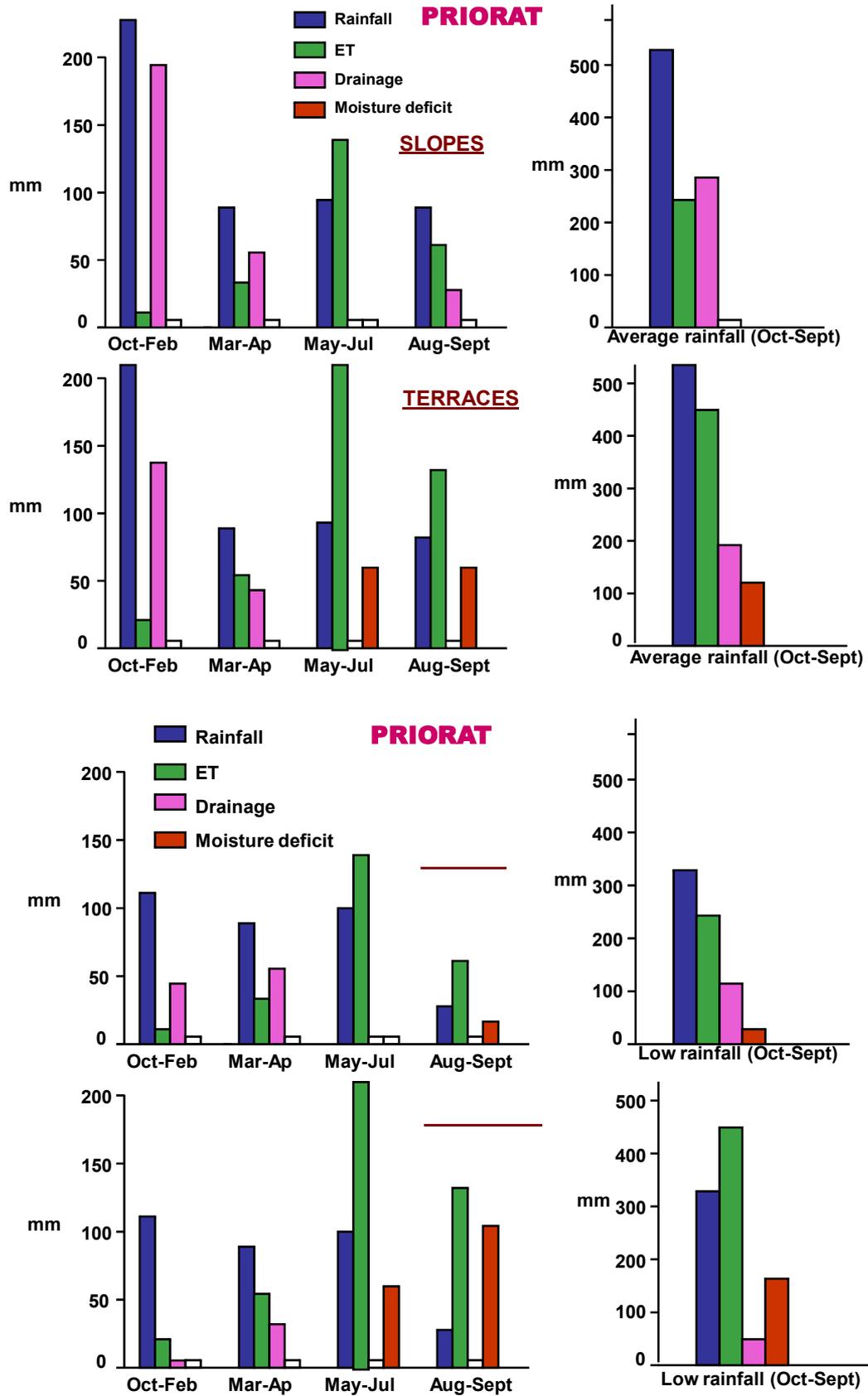


Figure 4 Rainfall and soil water balance components in rainfed vineyards of the Priorat region in years with average rainfall (Return period : 2 years) or low rainfall (Return period:5 years) in sloping (no tilled) and terraced (tilled) land



Figure 5 Rainfall and soil water balance components in irrigated vineyards of the Costers del Segre region in years with average rainfall (Return period : 2 years) in sloping and flat land, with or without green cover

The effects of these changes on the relief and soils for new plantations, and of the changes in land management in the traditional plantations were studied under different field and laboratory conditions. Measurements and continuous monitoring of appropriate soil hydrological parameters and rainfall characteristics have been conducted at field sites, complemented with laboratory measurements. These have been used as a basis for the application and validation of the model SOMORE (Pla, 1997, 2002, 2006), based on hydrological processes, which allows the simulation and prediction of the soil water balances, soil moisture regimes and of the associated potential problems of soil erosion and of water supply to the grapevines at different growth stages (Pla 1997; Pla, 2002; Pla and Nacci 2001), under different actual or potential climate conditions (Figures 3, 4, 5).

Continuous field monitoring during several years, have shown that the soil water regime under the different and variable climate, soils and land management of the study sites could be reasonably well predicted with the adequate simulation of the hydrological processes, based on climate information and on changes in the soil water balance derived from the soil hydrological properties properly evaluated under field conditions. It may be observed that the recent changes in land and crop management in dry-land vineyards for wine production in the Mediterranean regions of NE Spain have mainly affected the hydrology of the cropped lands. These effects could be increased under the previewed future climate changes in the Mediterranean region.

The main effects are changes in the soil moisture regime, which under Mediterranean climate is the main factor affecting the quantity and quality of grape and wine production. Therefore, the previewed influences of the different land and crop management practices on the soil water regime are required to rationally establish the basis for a more effective soil and water management and conservation, leading to a more efficient use of the scarce available water resources and to a more sustainable and regular production of high quality wines.

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