REVIEW

IRRIGATION WATER MANAGEMENT IN LATIN AMERICA

Aureo S. de Oliveira[1], Ricardo Trezza[2], Eduardo A. Holzapfel[3], Ignacio Lorite[4], and Vital Pedro S. Paz[5]

ABSTRACT

Latin American countries show a great potential for expanding their irrigated areas. Irrigation is important for strengthening local and regional economy and for enhancing food security. The present paper aimed at providing a brief review on key aspects of irrigation management in Latin America. Poor irrigation management can have great impact on crop production and on environment while good management reduces the waste of soil and water and help farmers maximizing their profits. It was found that additional research is needed to allow a better understanding of crop water requirements under Latin American conditions as well as to provide farmers with local derived information for irrigation scheduling. The advantages of deficit irrigation practices and the present and future opportunities with the application of remote sensing tools for water management were also considered. It is clear that due to the importance of irrigated agriculture, collaborative work among Latin American researchers and institutions is of paramount importance to face the challenges imposed by a growing population, environment degradation, and competition in the global market.

Key words: irrigation, evapotranspiration, deficit irrigation, remote sensing.

INTRODUCTION

Food security is becoming a major issue in today's society and irrigated agriculture is in the center of this discussion not only because it constitutes approximately 20% of the world's total cultivated farmland, but mainly because it responds for 40% of the food and fiber production (Hoffman and Evans, 2007). In the 20th century, worldwide irrigated area experienced a huge expansion of more than 500% with an increasing from 40 million to 270 million ha of irrigated land. Such numbers are part of the ability of humankind to produce food fast enough to meet population growth. But that remarkable ability, on the other hand, has its cost – a water crisis, characterized by water scarcity and competition, pollution and malnutrition (Molden, 2003). Three basic approaches (supply side, conservation, and unit productivity) were pointed out by Molden (2003) to increase food production. The 'supply side' approach suggests the development of more infrastructures and more rain-fed and irrigated land to supply more water for more agriculture. The "conservation" approach establishes the importance on reducing wastage and loss of water by agriculture; and the "unit productivity" calls for increasing in the productivity of water for each drop consumed by agriculture.

The rate of increase in irrigated land reached a peak of about 2.2% per year in the mid-1970s (Jensen, 2007) but the annual rate of increase has decreased since the mid-1990s to less than 0.5% per year at the beginning of the 21st century. This reduction has largely been the result of diminishing water supplies and increased demands from other sectors (Hoffman and Evans, 2007). The higher annual growth rate of irrigation in the 70s and 80s was directly related to massive investments by international financing institutions, like World Bank (Comprehensive Assessment of Water Management in Agriculture, 2007).

While the population grew from 2.5 billion people in 1950 to 6.5 billion today, the irrigated area doubled and the water withdrawals tripled. Global food prices declined markedly. And the greater use of water for irrigated

[1]Universidade Federal do Recôncavo da Bahia (UFRB), Núcleo de Engenharia de Água e Solo (NEAS), 44380-000 Cruz das Almas, Bahia, Brasil (aureo@ufrb.edu.br).
[2]Universidad de Los Andes, Núcleo Rafael Rangel (NURR), Mérida, Venezuela (rtrezza@ula.ve).
[3]Universidad de Concepción, Facultad de Ingeniería Agrícola, Chillán, Chile (eholzapf@udec.cl).
[4]Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (IFAPA), Centro de Investigación y Formación Agraria Alameda del Obispo, Consejería de Agricultura y Pesca, Junta de Andalucía, Córdoba, España (ignacioj.lorite@juntadeandalucia.es).
[5]Universidade Federal do Recôncavo da Bahia (UFRB), Núcleo de Engenharia de Água e Solo (NEAS), 44380-000 Cruz das Almas, Bahia, Brasil (vpaz@ufrb.edu.br).

agriculture benefited farmers and poor people, propelling economies, improving livelihoods, and fighting hunger (Comprehensive Assessment of Water Management in Agriculture, 2007). But much work still remains to be done. In 2003, 850 million people in the world were food insecure, 60% of them living in South Asia and Sub-Saharan Africa. In Africa, a continent desperate for food, only 7% of the arable land is irrigated (Hoffman and Evans, 2007).

Focusing on South America (SA), recent statistics by FAO (Hoffman and Evans, 2007) have shown that the total irrigated area is around 10.5 million ha, corresponding to only 9% of the estimated world's total irrigated area. For comparison purposes, the irrigated area in the whole SA is only half of that in the United States, which is around 22.5 million ha (Hoffman and Evans, 2007). Brazil has the largest irrigated area in SA, with 3.5 million ha (5% of the world's total), followed by Chile, Argentina and Bolivia. But, in Brazil, for example, just over 500 000 ha are located in the Brazilian Semi-Arid Region, the one with the lowest social and economic indicators (World Bank, 2004).

Agriculture is by far the largest water-use sector, accounting for about 70% of all water withdrawn worldwide from rivers and aquifers compared to the industry (20%) and municipality (10%) (Comprehensive Assessment of Water Management in Agriculture, 2007). In several developing countries irrigation represents up to 95% of all water withdrawn, and it plays a major role in food production and food security. The agriculture development strategies of most of these countries depend on the possibility of maintaining, improving and expanding irrigated agriculture (Siebert *et al*., 2006). However, as the pressure on water resources increases, irrigation is facing growing competition from other water-use sectors and becoming a threat to the environment in an increasing number of regions. Despite the current problems and negative perceptions in many sectors of society (Hoffman and Evans, 2007), it is certain that irrigation will continue to be a necessary and important component of the world's well-being and growth.

All these issues call for the implementation of sustainable irrigation in order to preserve the environment while keeping the actual levels of food production. On this, Oster and Wichelns (2003) defined sustainability as the likelihood that an irrigation system will continue to generate desirable outputs and amenities at reasonable costs in future. They pointed out that in order to reach sustainability, irrigation and drainage systems should be managed in a manner that does not degrade the quality of land, water, and other natural resources that contribute to agricultural production and environmental quality. Scientists agree that one of the biggest threats to the sustainability of irrigated agriculture is salinity (Khan *et al*., 2006; Hoffman and Shalhevet, 2007).

To make irrigation sustainable, both environmentally and economically, society will need to improve agricultural productivity, change institutional structures, modify water policies, improve delivery and on-farm systems, improve management of degraded soils, enhance water reuse, improve crop water management, and address rising energy prices (Howell, 2001; Hoffman and Evans, 2007). Therefore, a better management of water in irrigated agriculture it is necessary to enhance crop production and preserve soil and water quality. Irrigation management should focus in the adoption of practices that enhance the efficient use of water so that other sectors can have more water for economic use (Comprehensive Assessment of Water Management in Agriculture, 2007). On this, Howell (2001) suggested three paths that can be taken to improve water use efficiency on irrigated agriculture: (a) increase the output per unit of water; (b) reduce loss of water to unusable sinks and reduce water degradation; and (c) reallocate water to higher priority uses.

The main objective of this paper is to address some issues related to the management of irrigation water in the semiarid and dry areas of SA countries. The paper emphasizes the water demand of the major crops grown in the region as well as some recent developments on regulated deficit irrigation. Application of remote sensing techniques with high potential for planning and management of the water resources at both regional and farm levels area also addressed.

Water requirements for South American crops

The contribution of natural precipitation to the total amount of water required for irrigation varies from climate to climate. In arid climates (precipitation, < 200 mm yr^{-1}) crop growth and yield are not possible without irrigation (Martin and Gilley, 1993). In semiarid climates (200-600 mm yr^{-1}), irrigation is necessary to avoid crop failure. In subhumid climates (600-1000 mm yr^{-1}) irrigation is important to guarantee crop growth and development during the drought periods that might occur during the crop season. In humid climates (> 1000 mm yr^{-1}), depending on soil water holding capacity and crop root depth, irrigation might be necessary to avoid significant yield reduction during short drought periods.

Due to climate diversity across the continent from dry to temperate climates (FAO, 2009a) all the above scenarios are possible in SA countries. In arid and semiarid areas of Chile, Argentina, and Brazil, crop production relies totally on water supply by irrigation for plant growth and development, while in other areas, like the southeastern of Brazil, irrigation is supplemental to natural precipitation (Paz *et al*., 2000).

Crop evapotranspiration (ET_c) accounts for the water transferred to the atmosphere by soil evaporation (E) and plant transpiration (T). Evapotranspiration from irrigated agriculture is an important issue in arid and semi-arid regions where it has large impact on water resources depletion and water management (Tasumi and Allen, 2007). Accurate determination of crop ET is essential for designing irrigation systems and for irrigation scheduling. A traditional method for quantification of crop water demand was first proposed by Doorenbos and Pruitt (1977). The method is based on the premise that no single equation can estimate actual ET for various crops under different conditions due to the interdependence among the weather, soil, plant, and environmental factors that affect ET and their spatial and temporal variability. They proposed to estimate actual ET by multiplying the ET of a reference crop (ET_o) by a conversion factor, called crop coefficient (K_c) (Equation [1]), which incorporates those characteristics of a particular crop that affects ET:

$$ET_c = K_c \, ET_o \qquad [1]$$

The methodology proposed by Doorenbos and Pruitt (1977) was widely accepted and exhaustibly applied in different conditions worldwide. Reference crop ET was defined as the ET rate from well-watered grass, actively growing and completely shading the ground and among other methods, the authors suggested a modified form of the original Penman equation for its estimation. Allen *et al.* (1998) reviewed the original work to propose a modified form of the Penman-Monteith equation as the standard method to estimate ET_o, followed by updated K_c values to be used with this modified form. Additionally and based on the works by Wright (1982) a procedure was proposed to estimate actual ET that allow for predicting the effects of specific wetting events on the value of K_c as follows (Equation [2]):

$$ET_c = (K_{cb}+K_e) \, ET_o \qquad [2]$$

where K_{cb} is basal crop coefficient and K_e is soil evaporation coefficient.

As pointed out by Allen *et al.* (1998) the differences in evaporation and transpiration between field crops and the reference crop surface can be incorporated in a single K_c (Equation [1]) or separated into two coefficients as shown by Equation [2]. The single K_c approach is basically indicated to irrigation planning and design and the dual K_c approach is recommended for real time irrigation scheduling. This second approach has been also extensively evaluated (Allen, 2000; Suleiman *et al.*, 2007; Hunsaker *et al.*, 2007).

In SA, many crops are cultivated under irrigation. The gross production supplies the internal as well the international market. Fruit crops (temperate and tropical species), grain crops e.g., wheat (*Triticum aestivum*), corn (*Zea mays*), soybean (*Glicine max*), vegetable crops, sugar cane (*Saccharum officinarum*), and coffee (*Coffea arabica*), are among the most important for the economy of SA countries. Local derived information about water requirements of these crops are important to give farmers and irrigation scheme administrators the necessary information for maximizing crop yield while saving water and energy (Paz *et al.*, 2000).

The response of some crops to irrigation in SA conditions has been widely investigated as is the case for grapes (table and wine) (*Vitis* sp.) (Ferreyra *et al.*, 2002; 2003; Ortega-Farías *et al.*, 2007; Azevedo *et al.*, 2008). But for other equally important crops there is a lack of information that has to be filled by agricultural research which seems to be the case of fruit crops. The gap on local derived information inevitably leads to the data transferability from other parts of the world. Just as an example, Pannunzio (2009) reported that irrigation management in blueberry in Argentina is made with crop coefficients derived in Oregon, USA. It is understood that water requirements for fruit crops should be better evaluated especially because these crops are at the base of the regional economy as important products for exportation. Even for grapes, water requirement data from orchards in California have been used in Chile as reported by López Ríos (2005). Crop coefficients for olives derived in California were used by Sellés *et al.* (2006) in Chile to evaluate crop yield responses to different irrigation levels.

For illustration purposes, data on water requirements for some crops are shown in Table 1 based on research results conducted under SA conditions. Table 1 can help to give an idea on the need for additional researches to be done. We identified that little information about irrigated SA crops is available on peer-reviewed journals, which essentially contrasts with the large number of crops grown in the continent. The majority of the papers found and that have been published in the last 10 years deal with the effects of irrigation depths on crop development and production without providing more details on the amount of water used by the crop. Knowing such effects is important to evaluate plant physiological responses to shortage and excess of water but only the knowledge on the amount of water effectively used by the crop can provide the necessary tools for irrigation system design and real time management of irrigation under field conditions.

Improving irrigation water management in South America

The rapid increase in population in SA demands an

Table 1. Water requirements and crop coefficient derived from experimental research for some important South American crops.

Crop	Location	Seasonal water use (mm)	Crop coefficient		Remarks	Reference
			Stage	Value		
Mango	Petrolina, Pernambuco, Brazil	553	All	K_c = f(DAF), DAF = days after flowering	Seven-year old drip-irrigated mango orchard var. Tommy Atkins. Energy (Bowen ratio) and soil water balance (SWB) methods used for crop ET. ET_o by FAO-56 Penman-Monteith model. Season: flowering to fruit harvest.	Azevedo *et al.,* 2003.
Table grape	Petrolina, Pernambuco, Brazil	445 to 517 (dry season) 259 to 462 (rainy season)	All	K_c = f(DAP), DAP = days after pruning	Five-year old drip-irrigated grape orchard var. Superior. Four treatments per season as intermittent irrigation times. Drainage lysimeter for crop ET. Season: bud break to fruit harvesting.	Azevedo *et al.,* 2008.
Sugarcane	Lara, Venezuela	1418	-	-	Sprinker-irrigated sugarcane. Reference ET by FAO-56 Penman-Monteith model.	Trezza *et al.,* 2008.
Banana	Petrolina, Pernambuco, Brazil	1700 (1st season) 860 (2nd season) 950 (3rd season)	Vegetative growth	0.8	Micro-sprinkler irrigated banana field cv. Pacovan. Soil water balance method used for crop ET determination. Reference ET by FAO-56 Penman-Monteith model. Variable irrigation frequency based on soil water tension.	Bassoi *et al.,* 2004.
			Flowering to harvest	1.1		
Pineapple	Paraíba, Brazil	1420	Vegetative growth	0.90	Sprinkler-irrigated pineapple field. Crop ET evaluated with a Bowen ratio system. Reference ET by FAO-56 Penman-Monteith model. Considerable amount of precipitation during the season.	Azevedo *et al.,* 2007.
			Flowering	0.88		
			Fruit formation	0.87		
			Fruit harvesting	0.89		
			Full season	0.88		
Papaya	Ceará, Brazil	994	Vegetative growth	0.54	Micro-sprinkler irrigated papaya orchard cv. Sunrise. Soil water balance method for crop ET. Reference ET by FAO-56 Penman-Monteith model.	Montenegro *et al*., 2004.
			Flowering/ fruit growth	0.87		
			Fruit growth and ripening	0.91		

Mango (*Mangifera indica*), table grape (*Vitis* sp.), sugarcane (*Saccharum officinarum*), banana (*Musa* sp.), pineapple (*Ananas comosus*), papaya (*Carica papaya*).

increase in agricultural production. However, availability of fresh water for agriculture is decreasing (Howell, 2001) so that methods that guarantee a more efficient water use are necessary to sustain irrigated agriculture.

In most arid and semiarid zones of SA increase in the irrigated land will require efficiency improvement in conveyance, distribution and application, as well as more efficient use of water by plants. This can be achieved through improvement of designs, rehabilitation and modernization of irrigation schemes and the adoption of more efficient irrigation techniques. A better knowledge of crop water requirements is essential to distribute water efficiently. In addition, improvement in operation and maintenance is necessary, essentially through larger participation of users for public irrigation systems, and improvement in water measurement and control (FAO, 2009b).

Improvement of irrigation system operation and maintenance

With a few exceptions, water management in large irrigation areas of SA has been inefficient due to the lack of policies and technologies that will assure a sustainable irrigated agriculture. A major weakness in many water resource plans in SA is the failure to provide adequately for the operation and maintenance once construction or installation is completed. In cases where projects are funded by loans or grants from international development banks, funds are provided only for construction, leaving the operation of the irrigation system to the project sponsor that is usually a national or state water resource agency. These governmental irrigation agencies (usually constrained by bureaucratic procedures, insufficient budgets and rigid policies) became inefficient and had unmotivated personnel and low system performance (Garcez-Restrepo *et al*., 2007).

Therefore, an important strategic approach would be to adapt water resource management tools to existing institutions and organizations that allow them to make a better use of water resources in irrigation. Important tools that needed to be implemented or improved in SA irrigation areas are related with the measurement of delivered water and the estimation of crop water requirements (irrigation scheduling) as well as crop water use monitoring. With regard to measurements, water cannot be efficiently controlled and distributed without an adequate network of measurement devices positioned along channels and pipes.

One strategy used to improve operation, maintenance and water management in medium to large irrigation systems is the transfer of irrigation management to the users. The concept of irrigation water transfer (IMT) refers to the process that seeks the relocation of responsibility and authority from the controlling government agencies managing irrigation systems (under the public sector) into the hands of non-governmental organizations, such as Water Users Associations (WUAs), or other private-sector entities. One of the most common reasons for governments to start considering the possibility of turning the management of irrigation schemes over to users is the lack of public funds to cover the Operation and Maintenance (O&M) costs of the scheme (Garcez-Restrepo *et al*., 2007). For example, many governments have made efforts to collect irrigation service fees to invest on operation and maintenance, but few were successful.

The perception that increased ownership, decision-making authority and active participation in the operation and maintenance of irrigation systems would create a commitment from water users to be more effective and responsible towards their obligations within the irrigation system. Therefore, IMT is the process of transfer authority and responsibility from government agencies managing irrigation systems to farmers' organizations, and has been utilized as a tool for irrigation sector reform in more than 60 countries. In SA, the level of transfer in the management of Irrigation Districts varies according to country. In some countries, it was completed several years ago, as in the case of Chile; in others, it is at several evolutionary stages such as in Peru, Ecuador, Bolivia, Colombia, Brazil, and Argentina. Prior to this transfer, a process of rehabilitation and modernization of the Irrigation Districts was performed in most of the countries so that they could be transferred to the users in conditions that permit them to take over management and maintenance tasks. The final impact of the strategy over the performance of the transferred irrigation systems is still inconclusive (Garcez-Restrepo *et al*., 2007).

Implementation of more efficient irrigation methods

Surface irrigation is the dominant method to irrigate crops in SA. FAO (2009b) reports that 95.6% of irrigated lands in SA are surface irrigated; 2.7% use sprinklers and just 1.7% used localized irrigation (drip and micro-sprinkler). These percentages indicate that there is a high potential of increasing water productivity in the region by switching to more efficient water application methods. Brazil, as the country with more land under irrigation in the region, shows progress toward a better application of water with 59% of irrigated lands under surface irrigation, 35% with sprinkler irrigation, and 6% with localized irrigation; here water scarcity and farm characteristics have induced the use of more efficient irrigation methods.

Deficit irrigation as a water saving practice

The increasing scarcity of fresh water in arid and semi-arid regions has driven the necessity of the application of strategies that can save water, but without impacting the crop yields. Within this concept, deficit irrigation (DI) is now being extensively researched as an agricultural practice (Fereres and Soriano, 2007). Some research results confirm that DI might be successful in increasing water productivity for various crops without causing severe yield reductions. According to Geerts and Raes (2009), deficit irrigation is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop. Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum amount of water. The objective of this strategy is to save water by subjecting crops to periods of moisture stress with minimal effects on yields. The water stress results in less ET by closure of the stomata, reduced assimilation of carbon, and decreased biomass production. The reduced biomass production has little effect on ultimate yields where the crop is able to compensate in terms of reproductive capacity. In some cases, periods of reduced growth may trigger physiological processes that actually increase yield and/or income, such as the case of sugarcane, where irrigation is stopped during the last stage of growth to stimulate sugar concentration, practice commonly applied in Brazil and Venezuela (Trezza *et al*., 2008).

To obtain satisfactory yields with DI, water restriction should be limited to drought-tolerant phenological stages, often the vegetative stages and the late ripening period. Since drought tolerance varies considerably by genotype and by phenological stage, DI requires precise knowledge of crop response to drought stress for each of the growth stages. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. The grower must have prior knowledge of crop yield responses to deficit irrigation. Therefore, both extensive research and the help of extension services to farmers are essential.

Deficit irrigation has been applied to many crops such as wheat, corn, potato (*Solanum tuberosum*), onion (*Allium cepa*), garlic (*Allium sativum*), tomato (*Licopersicon esculentum*), cotton (*Gossypium hirsutum*), soybean, sugar cane, sugar beet (*Beta vulgaris*), alfalfa (*Medicago sativa*), grapevine (*Vitis vinifera*), quinoa (*Chenopodium quinoa*) (Geerts and Raes, 2009). FAO (2000) reported many cases where DI was a beneficial impact on water savings. In SA, deficit irrigation techniques has been investigated for olives (Sellés *et al*., 2006), grapevine (Ferreyra *et al*., 2003), Chilean tomato (Maldonado *et al*., 2003) in Chile; maize (Bergamaschi *et al*., 2006), sugarcane (Silva *et al*., 2008), irrigated coffee (Fernandes *et al*., 2000), sorghum (Peiter and Carlesso, 1996), beans (*Phaseolus vulgaris*) (Calvache *et al*., 1997; Guimarães *et al*., 2006), garlic (Macêdo *et al*., 2006), watermelon (*Citrullus lanatus*) (Andrade Júnior *et al*., 2001) in Brazil; quinoa in Bolivia (Geerts *et al*., 2006); sugar cane in Argentina (Romero *et al*., 2006).

In areas where the available water supply limits agricultural production, deficit irrigation will gain importance over time as farmers fight to increase the productivity of their limited land and water resources. Farmers must choose crops and irrigation strategies carefully to maximize the value of their crop, save water, while ensuring the sustainability of agriculture. According to FAO (2000), DI will play an important role in farm-level water management strategies, with consequent increases in the output generated per unit of water used in agriculture. However in SA this practice will require more research and experimentation to make sure that DI will not have a negative impact on crop yield and water productivity.

Water management assisted by remote sensing tools

In SA, irrigated agriculture generally uses large volumes of water compared to cities and industries, and competition for good water quality is really high in many regions. It is recognized that improved water management practices in agriculture can lead to important benefits in terms of water availability for expanded agricultural activity and for other uses, and can reduce many environmental problems. However, it is difficult to successfully implement efficient practices without field measurements and analytical tools that allow water managers to have a good estimation of crop water use, situation which is constraining water management in SA countries. Regular feedback of information from the field into water management decision making can substantially improve the performance of water delivery services. However, obtaining repeated objective evaluations about actual field conditions is difficult so that operational tools are needed to facilitate water managers to take right decisions about crop water use and water deliveries.

Within the new technologies currently used for irrigation scheduling and crop water use is remote sensing (RS). The potentiality of remote sensing techniques in irrigation and water resources management is now widely acknowledged (Allen *et al*., 2007). Remotely sensed information on irrigated areas can be obtained with satisfactory accuracy and in a cost-effective way by means of several on-board satellite sensors, such as LANDSAT, SPOT, and MODIS. These remote sensing platforms allow for efficiently monitoring crop water requirements of each field in extended areas and make information readily available to decision makers. While traditional ground data collection relies on sample areas, being extremely costly and many times inefficient, RS can be used to retrieve information over an entire area. Combined with ground information and geographic information systems, RS can be an extremely effective tool to analyze the performance of large irrigated areas and to monitor water use (Bastiaanssen *et al*., 1998; Teixeira *et al*., 2009).

Remote sensing has the possibility of offering important water resource-related information to policy makers, managers, consultants, researchers and to the general public. This information is potentially useful in legislation, planning, water allocation, performance assessment, impact assessment, research, and in health and environment-related fields. Remote sensing has been able to provide information on land use, irrigated area, crop type, biomass development, crop yield, crop water requirements, crop ET, salinity, water logging and river runoff (Bastiaanssen *et al*., 2000).

This information when presented in the context of management can be extremely valuable for planning and evaluation purposes. Ideally, managers of irrigation systems should include regular performance monitoring in their management techniques. Strategic water use requires good information on irrigated areas, cropping patterns, evaporative use and historic use of water. This information can be achieved by using remote sensing techniques on a regular basis as demonstrated in many applications (Courault *et al*., 2005). Remote sensing can provide decision makers and water managers with a useful diagnostic tool to monitor and evaluate the improvement or inefficiency in irrigation projects in SA.

Applications of RS in irrigated agriculture have been extensively reported in the last three decades (Courault *et al*., 2005). In SA some efforts have been made to apply RS techniques for the management of water resources in public irrigation schemes and private farms. Bastiaanssen *et al*. (2001) used SEBAL to monitor irrigation performance in Nilo Coelho, Brazil; Teixeira *et al*., 2007 and 2008 performed water productivity analysis via RS; Folhes *et al*. (2009) applied the RS model METRIC (Allen *et al*., 2007) for irrigation water management in the semiarid northeast of Brazil. Trezza (2006) applied the RS models SEBAL and METRIC to estimate water use in a large irrigation system in Venezuela and employ results for water management; Schipper (2005) determined crop water use in Santiago del Estero, Argentina. In all applications, RS tools demonstrated to have a lot of potential on improvement of scheduled deliveries of water. These applications performed a complete energy balance of the surface to estimate ET and subsequently water use.

In SA, simpler applications of RS are also recommended for operational use, like RS methods based on vegetation indices. A good example is the Irrigation Advisory Service (IAS) in Europe (Olalla *et al*., 2003), where remotely sensed data is used for irrigation scheduling. The IAS provides the farmers with irrigation scheduling information, based on crop water requirements for different crops, and thus, help farmers to optimize production and cost-effectiveness. The IAS uses the following equation (Belmonte *et al*., 2005) to estimate crop coefficients for irrigation scheduling in agricultural areas of Portugal, Italy, Spain, and Greece:

$$K_C = 1.25\ NDVI + 0.2 \qquad [3]$$

where K_C is crop coefficient and *NDVI* is vegetation index, calculated from red and near infrared surface reflectance obtained from satellite images. The value of K_C is used in Equation [3] to estimate crop water use and irrigation requirements.

Even though considerable progress has been made over the past 20 years in research applications, remotely sensed data remain underutilized by practicing water resource managers (Bastiaanssen *et al*., 2000), especially in developing countries. Discussions with water managers and policy makers have revealed that this community is quite often unaware of the new technical possibilities, partly because the discussion about the possibilities of RS remains within the remote sensing community (Bastiaanssen *et al*., 2000). Therefore, important efforts are required to make remote sensing algorithms available for operational use in SA.

CONCLUSIONS

Improving water management in SA is becoming a real need to guarantee food supplies for the continent's growing population and to preserve fresh water resources. In most of countries of SA, irrigation is seen as an important means to increment productivity and foment crop diversification, an objective of most agricultural policies of governments in the region. Water scarcity in certain zones of the continent is, in general, a source of conflict among sectors. Efficient water management in medium to large irrigation schemes has encountered many obstacles due to political and social issues as well as technological constraints. Some of the technological topics that need to be address in the future, to keep irrigated agricultural at sustainable levels in SA, were discussed in this paper. Large amounts of water are inefficiently supplied to farmers because the right tools are not available for irrigation managers that allow them to schedule water deliveries and satisfy crop water requirements in an effective way.

There is a preoccupant lack of published and available information about crop water requirements for SA in the literature; this fact can drag to the conclusion that information generated from research by government entities, universities, and scientists is not being efficiently share and distributed. Within the strategies that can provide tools for irrigation managers are the remote sensing of crop water use and the improvement of operation and maintenance (O&M) activities. Particularly, the improvement of water measurement in the delivery system is of the paramount importance. Managers cannot control water supplies and deliveries if water flow is not correctly measured in canals and pipes. Within the O&M strategies, the transfer or irrigation management to users was discussed as a way to improve water management by increasing the commitment of the farmers with irrigation systems.

Other important issue treated in this paper was the need to save fresh water and increment water productivity. A change from surface irrigation to more efficient pressurized methods can save water and allow agricultural expansion. Deficit irrigation (DI) was discussed as a strategy to save water in arid and semiarid areas; however, the implementation of DI requires extensive research work to make sure that the practice will keep economically sustainable yield levels in local crops for SA.

RESUMEN

Manejo del agua de riego en América latina. Los países sudamericanos tienen un gran potencial para aumentar sus áreas regadas. El riego es importante para fortalecer las economías locales y regionales y para mejorar la seguridad alimentaria. Esta revisión tiene por objeto proporcionar un resumen de los aspectos más importantes del manejo del riego en Sudamérica. Un manejo pobre del riego puede tener un alto impacto en la producción de cultivos y en el ambiente, en tanto que un buen manejo reduce las pérdidas de suelo y agua, y ayuda a los productores a maximizar sus ingresos. Se encontró que se requiere investigación adicional que permita una mejor comprensión de los requerimientos de agua de los cultivos en las condiciones sudamericanas, y también para proporcionar a los agricultores información local que permita hacer programación de riego. También se consideraron las ventajas del riego deficitario y las oportunidades presentes y futuras de la aplicación de los sensores remotos para el manejo del agua. Está claro que dada la importancia de la agricultura de riego se requiere realizar trabajos colaborativos entre investigadores e instituciones de Sudamérica, para enfrentar los desafíos que imponen el crecimiento de la población, la degradación del ambiente y la competencia en los mercados globales.

Palabras clave: riego, evapotranspiración, riego deficitario, sensores remotos.

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