Water Resources and Irrigation Management
Universidade Federal do Recôncavo da Bahia, Cruz das Almas, BA
Instituto Nacional do Semiárido, Campina Grande, PB
v.1, n.1, p.7-14, Sept-Dec, 2012

ISSN 2316-6886
WRIM
www.wrim.com.br

Geographic information system supported farm irrigation system design and planning

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Protocol 07.2012 - Received: September 26, 2012 - Accepted: October 30, 2012

Abstract: A methodology was developed using a Geographic Information System (GIS) to select, design, install and manage an irrigation system for a farm. GIS was used to develop different thematic layers, each consisting of a particular attribute required for analysis of alternative irrigation system types. These layers included data such as: topography, soil texture, soil water retention, bulk density, infiltration rate of water and field drainage system. These layers were used with water availability and water demand to design and plan the farm irrigation systems. A case study for blueberry orchards with drip irrigation was developed. The GIS facilitated irrigation planning, although additionally AUTOCAD was used to design the irrigation method. GIS was found to be a useful tool for a general farm planning analysis.

Key words: GIS, irrigation design, irrigation management

Sistema de informação geográfica como suporte para projeto e planejamento de sistema de irrigação

Resumo: Uma metodologia foi desenvolvida utilizando um Sistema de Informação Geográfica (SIG) para selecionar, desenvolver, instalar e manejar um sistema de irrigação em uma área. O SIG foi utilizado para definir diferentes camadas, cada um consistindo de determinado atributo necessário para a análise de tipos de sistemas alternativos de irrigação. Estes cenários incluem dados, tais como: topografia, textura do solo, retenção de água do solo, densidade, taxa de infiltração de água no solo e sistema de drenagem no campo. Os cenários foram utilizados de acordo com a disponibilidade e demanda de água para projetar e planejar sistemas de irrigação. Foi desenvolvido um estudo de caso para pomares de arándano com irrigação por gotejamento. O SIG facilitou o planejamento da irrigação, no entanto, adicionalmente utiliza-se o AUTOCAD para projetar o método de irrigação. O SIG mostrou-se ser um instrumento útil para uma análise de planejamento da fazenda.

Palavras-chave: SIG, projeto de irrigação, manejo de irrigação

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Introduction

In the near future, irrigated agriculture will need to produce two-thirds of the increase in food products required by a large population increase (English et al., 2002). The growing dependence on irrigated agriculture coincides with an accelerated competition for water and increased awareness of unintended negative consequences of poor design and management.

Irrigation systems are selected, designed and operated to supply the individual irrigation requirements of each crop field on the farm while controlling deep percolation, runoff, evaporation and operational losses to establish a sustainable production process.

Considering the stupendous task and constraint of time in developing the ultimate irrigation potential, it is necessary to use the modern methods of surveying and analysis tools. Remote sensing and Geographic Information System (GIS) with their capability of data collection and analysis are now viewed as efficient and effective tools for irrigation water management. The capability of GIS to analyze the information across space and time would help in managing such dynamic systems as irrigation systems.

Soil survey data and GIS are important tools in land use planning. Intertwined, they represent an invaluable and underutilized resource. Hazrat et al. (2003) found that the GIS is an important tool that can be used for optimal allocation of water resources of an irrigation project. Mean water balance components results for different months were stored in GIS databases, analyzed and displayed as the monthly crop water requirements maps.

Chowdary et al. (2008) showed that satellite remote sensing coupled with GIS offers an excellent alternative to conventional mapping techniques in monitoring and mapping of surface and sub-surface waterlogged areas. El Nahry et al. (2011) found that for center pivot irrigation under precision farming, remote sensing and GIS techniques have played a vital role in the variable rate of water applications that were defined due to management zone requirements. Fertilizers were added at variable rates. Crop water requirements were determined in variable rate according to the actual plant requirements using SEBAL model with the aid of FAO CROPWAT model. Hatzios & Kriton (2000) used the soils information recompiled from an uncorrected aerial photographic base to a USGS topographic base map. Soils data were added to numerous other data layers and images. Interpretation maps flooding frequency maps, and runoff maps were created from map unit interpretive records. Utset & Borroto (2001) used the GIS to create raster layers with soil electrical conductivity and topographical altitudes to determine the border of saline effect zones. Szalai et al. (2004) analysed several applications of the GIS in climatology, meteorology and regional evapotranspiration, as well as, to determine irrigation requirements. Xiaopveng et al. (2011) developed an irrigation scheduling method by integrating the 'checkbook irrigation method' into a GIS-coupled soil water and nitrogen management model. The soil water and crop information required by the checkbook method and previously collected from field observations, was estimated by the soil water and nitrogen management model.

Geographic Information Systems has been used to improve the irrigation water management (Calera et al., 1999; Todorovic & Steduto, 2003; Satti & Jacobs, 2004; and Singh et al., 2006) and for irrigation scheduling (George et al., 2004 ; Fortes et al., 2005). Playán et al. (2007) have built a database program for enhancing irrigation district management to manage detailed information about district water management and to promote better on-farm irrigation practices.

The application of GIS has become popular in water resources management due to its dynamic process to incorporate data and display results. GIS techniques are more time and cost efficient than the conventional field techniques and can be used to formulate a management plan much more efficiently and link land cover data to topographic data and to other information concerning processes and properties related to geographic location.

Information about a farm is needed to plan and implement an optimized farm practice that leads to effective and efficient water use. This information must be based on detailed spatial and temporal data. Amongst the most relevant are soil properties, topography, crops, water supply and weather (historical and real-time).

Good planning is essential for successful irrigation, including: 1) The selection of an irrigation system that provides the best practical and economical irrigation system alternative, 2) the design and installation of a system according to standards and accepted engineering practice and 3) system management that ensures a correct and timely application of water that is based on crop requirements and avoids unnecessary water use (Holzapfel et al., 1985a).

Furthermore, to increase production efficiency and to diminish environmental impacts, agricultural problem-solving should incorporate technologies that can improve the quality and timeliness of data relevant to the management of the system, including technologies that can be used to measure and manage variability from a spatial perspective (Holzapfel & Arumi, 2006).

The GIS has not been used in selection, design and management of surface and pressurized irrigation systems. For these reasons, the objective of the present study was to develop a GIS-supported irrigation design and planning methodologies at the farm level and to apply it in a case study.

The specific objectives were to: 1) evaluate GIS as a tool for farm-level irrigation system design and planning, 2) analyze the spatial variability of the parameters that affect design and management of irrigation systems, 3) develop a procedure for optimal design of irrigation systems taking into account spatial variability, and 4) develop a support for a water distribution system planning.

Materials and Methods

Methodology development

The use of GIS to design and plan irrigation systems requires a procedure for adequate analysis as is shown in the chart flow (Figure 1). The methodology developed and applied to this study consists of the following steps:

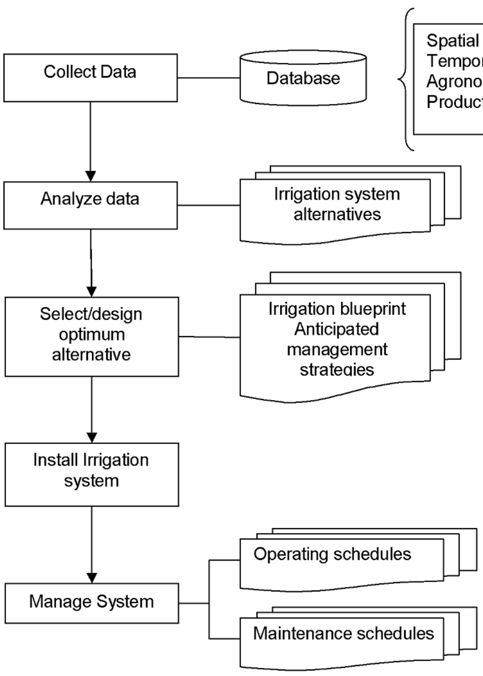

Figure 1. Methodology implemented in this work

1. Data collection

In this step the soil data as texture, water holding capacity, infiltration rate, bulk density; must be collected. In addition, topography, actual plots, constructions, irrigation network, drainage network georeferenced basic information, which requires the coordinates of each sampling point for the different information, as well as to develop the thematic layers for each parameter must be obtained.

2. Analysis

On the basis of the data, the spatial distribution for each parameter, considering the most restrictive areas and their weight in the total study area must be evaluated, for the design and management of the irrigation systems and the pipe distribution network. A thematic layer with the established irrigation system is incorporated.

The design system is done taking into account the procedure given by Holzapfel et al. (1984) for surface irrigation and for pressurized irrigation on the basis of Holzapfel et al. (1990) and Abarca (2002).

For the optimal design of surface irrigation the length, time of cutoff and discharge must be considered (Holzapfel et al., 1985a; Walker & Skogerboe, 1987, Holzapfel et al., 2010). The optimal design of pressurized irrigation system takes into account, the selection of emitters (Holzapfel et al., 2007a, b), optimal design of sub-units and optimal pipe diameter (Pizarro, 1996; Stuardo, 2006).

It is important to mention that all the thematic layers are dynamic and can improve as a greater quantity of new information is incorporated. This dynamic nature permits adaptation of irrigation system management to real-time conditions and even system design modification is permitted.

The use of this tool is also of great use in farm management and planning since it can also help in other activities necessary for the production process, such as crop rotation, changes in farm structures or their location, implementation of new crops with new irrigation systems.

General farm information

Los Crisoles farm is located in San Ignacio County, VIII Region, Chile (Latitude 36° 50' 7" S, Longitude 72° 6' 17" W). The farm surface area is 110 ha., crops most often grown include wheat, sugar beet and grasses. A reliable water supply for irrigation is available at a sustained flow rate of 42 L s^{-1}, in addition to other non-quantifiable sources. The area has a large potential for berries and apple orchards.

Topographic map

An existing topographic map (scale 1: 5000), with 0.5 m equidistance contour level curves is available. The map includes cultivated plots, internal roads, construction, drains and water sources. This map was digitalized, forming an independent thematic layer.

Farm georeferencing

Using the previously described topographic map, characteristic points on the farm were selected for georeferencing using a GPS model GARMIN 12. These points were site vertexes, constructions, plot borders and other structures.

Georeferencing was performed at several key points, at three different times and with three replications. This was done to minimize distortion errors and ensure good map adjustment.

Determination of physical characteristics of the soil

For irrigation design and management purposes the following soil information is required: texture, bulk density and water holding capacity. To obtain these soil data, initially ten one meter soil test pits (profiles) were distributed following three transects, to assure good representation of the area. Given GIS's dynamic characteristic, a new soil characteristic sampled with additional test profiles were incorporated according to the field digital model data results for each of the parameters were analyzed. Simultaneously, these test profile were georeferenced in their spatial location in the map, including soil texture, water holding capacity and depth. In addition, close to the soil test profiles water infiltration rate were determined with double ring cylinder infiltrometer.

Results and Discussion

Basic Map

The GIS was used to create basic digitalized information, as presented in Figure 2, with four thematic layers: 0.5 m equidistance contour level curves, plots, drains and location of soil test profiles.

From Figure 2 it can be observed that the study area does not present great topographic variations in the northern sector, where the dominant slope goes from east to west with a mean value of 0.73%. In the southern sector, the slope value is 1.12% in the same direction

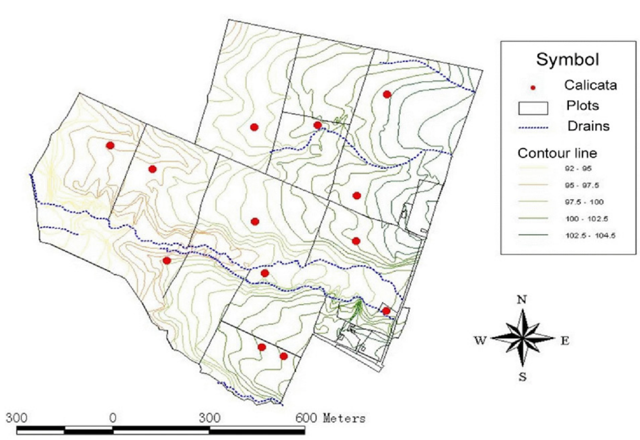

Figure 2. Basic thematic map of Crisoles Farm that includes topography, drains, plots and location of test pits

Texture

To digitalize a soil texture information a numeric code was used as shown in Table 1.

Table 1. Values of the different soil textures according to the international classification system

Texture	Code
Heavy Clay	11
Clay	10
Silty Clay	9
Clay Loam	8
Silty Clay Loam	7
Silty Loam	6
Sandy Clay	5
Loam	4
Sandy Clay Loam	3
Sandy Loam	2
Sand	1

Based on the proposed classification and the textural information from the test pits, thematic maps were constructed for each soil strata, which were differentiated by texture. Figure 3 presents the thematic layer for the first soil strata because this stratum is the most important for crop development.

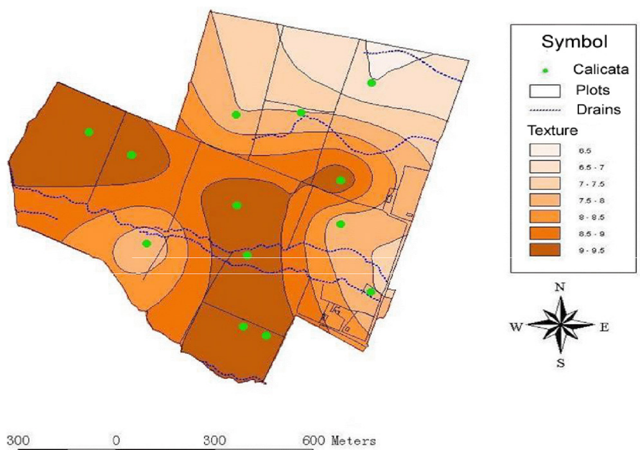

Figure 3. Thematic map of Crisoles Farm of texture for the first soil strata

In general, from the texture thematic level, with a range between 7 and 10, it can be established that the soil is principally clayey (silty clay, clay loam and low density clay). This layer corresponds to the first soil profile strata analyzed.

The origin of the studied soil is volcanic ash and it presents the characteristics of the Arrayán series (Molina, 1966). This type of soil generally presents high retention capacity and high infiltration velocity in the first few minutes.

Soil water retention

Soil water retention capacity is very important for irrigation system design and planning due to its relation with irrigation frequency and application times. The spatial distribution of this parameter is shown in Figure 4.

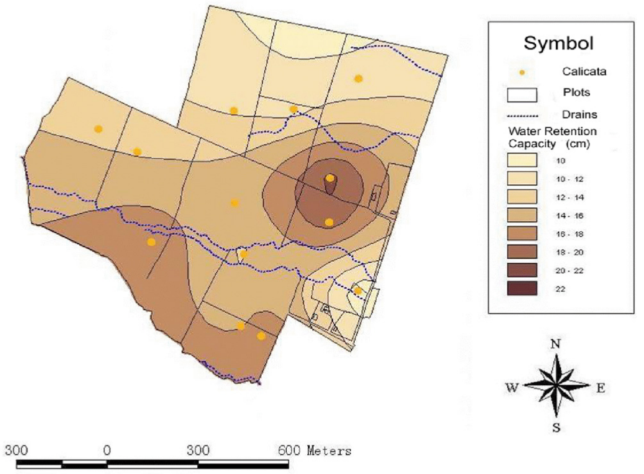

Figure 4. Thematic map of Crisoles Farm of soil water retention up to 1 m depth

It can be deduced that a large part of the farm has soil with high water retention up to 1 m depth with values that fluctuate between 12 cm m^{-1} occupying a surface of 16.4% of the farm, 33.7% present a value of 18 cm m^{-1}, reaching 22 cm m^{-1} at certain points, although in only 0.2% of the farm area. These values are within the range cited by Molina (1966) for this type of soil. Additionally, it is important to establish that there is no great spatial variability in the water retention capacity of soil.

Water retention capacity is affected not only by the soil texture but by other factors, such as organic matter content, structure, compaction, which act in complex ways.

When the infiltration and the water retention thematic maps are analyzed, it can be established that the sectors with greater retention capacity are those with the lowest infiltration. This result can be attributed to the smaller soil particle size in these sectors, retaining a greater quantity of water and impeding infiltration of water in the soil profile. When these thematic maps are compared with the texture thematic map, it can be observed that there is a certain concordance with the clayey sectors.

Analysis of this thematic map provides the information to determine irrigation frequency for the design, tasking in to consideration factors such as the percentage of surface area under a determined water retention level. Additionally, different types of operation and management can be identified for sectors that present characteristics different from those established for the design.

Infiltration rate

Furthermore, the points used to determine the infiltration rate of water in soil, are the same as for the previously described profiles, and consequently other soil information could be related with this parameter.

The infiltration rate curves obtained in each point indicate a similar tendency, decreasing abruptly in the first 30 min, characteristic that is generally presented in sandy soils and which is quite normal in this type of soils, derived from volcanic ash (Holzapfel et al., 1985b).

In general, the infiltration rate was observed to stabilize at 120 min in most of the performed tests. However, it is important to consider that the soil infiltration rate did not greatly vary and that the values of 120 min are within the range of 0.03 and 0.08 cm min^{-1}.

In Figure 5 the soil infiltration rate thematic map corresponds to an infiltration time of 120 min. Other maps for different infiltration times can be incorporated if necessary, depending on the irrigation systems that can be feasibly implemented in the study area.

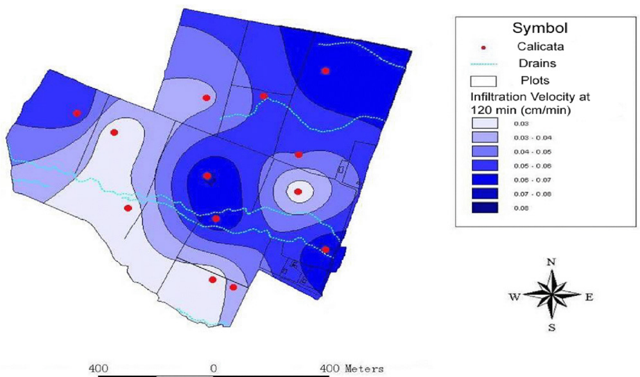

Figure 5. Thematic map of Crisoles Farm of soil infiltration rate at 120 minutes

The infiltration rate of water in soil is a very important parameter for irrigation design and operation and is highly relevant in irrigation planning of a farm. Infiltration velocity has direct influence on the selection of pressurized irrigation emitters as well as on the operation of irrigation sectors since this should be performed in differentiated form depending on eache points infiltration value. In the case of surface irrigation, this will affect the design variables such as furrow length, irrigation time, and discharge.

The results indicate that there is little variability in infiltration rate, which can be attributed to the lack of soil variability presented in the thematic map of texture. The infiltration values to be considered should be in accordance with the irrigation methods to be implemented, associated to problems that could result, such as water buildup, surface runoff, or poor water storage for the crop or plant.

Irrigation methods

The operation, design, and selection of irrigation methods require a variety of information, where the previously described GIS thematic maps provide a global vision of the design information. Another important factor is the crop type, which can continuously vary if these are annual crops. In the case study, sugar beet has been considered, however, blueberry orchard was selected as the fruit due to its future projection and establishment conditions in the area.

The topography of the area (Figure 2) presents certain limitations for the implementation of surface irrigation considering the soil characteristics. The slope in the middle sector of farm is 0.67 % in the east-west direction. However, from an irrigation planning perspective, this is an area with quite irregular topography since it has a very abrupt slope in the north-south direction, which creates certain limitations for surface irrigation.

According to Holzapfel et al. (1985a), the pressurized irrigation methods are the best systems adapted to the selected farm requires analysis and evaluation of information on soil, infiltration velocity, water availability, topography and crop.

The case study carried out consisted in the design of a micro-irrigation system for a small-fruit crop (blueberry).

Case Study

Based on the information collected, basic feasible irrigation method selection criteria were established. Additionally, as the study advanced, decisions were continuously made, assuring a dynamic process.

Drip irrigation for small fruit

Drip irrigation is a method that eliminates conduction losses and minimizes evaporation and percolation losses as well as controls the pattern with which water is distributed in the soil. Under adequate design, operation, and management conditions, it generates an environment with optimal physical, chemical and biological characteristics in the root area as required to achieve a production of greater quantity and quality.

From an engineering and agronomic perspective, the fundamental objective of drip irrigation system design is to maintain water content in the soil, close to the field capacity in the root area for plants with high water extraction. The distribution and level of soil water should be such that the relation between the water-soil-plant factors optimizes water use and plant production performance.

Design information

Since drip irrigation is a high frequency system, the existing water deficit and height differences between the water source and distribution points need to be defined to assure the correct pump capacity.

As in the earlier cases, drip irrigation system design also requires analysis of the thematic maps of topography, infiltration rate, soil water storage capacity and soil texture, considered in the order of decreasing importance.

Infiltration rate, even though it is less relevant in drip irrigation than in sprinkler irrigation, is used to determine the emitter discharge to avoid water accumulation or surface runoff. Additionally, soil water storage capacity and soil texture can be used as management tools since water application can be more or less frequent depending on soil type of each sector. For example, if a sector has the high retention capacity and clayey soil, then more water should be applied at a lower frequency (every two days), producing better aeration in the rooting depth. The soil water storage capacity and the rate of infiltration in the design process will be 12 cm m^{-1}, and 0.03 cm min^{-1}, respectively (Figures 4 and 5).

To locate the drip irrigation sub-units, site sectors with the best conditions for blueberry development were selected. Additionally, the dimension of the sub-units was defined considering a plantation plot of 3 x 1 m under daily irrigation conditions. For the studied plot, 20 sub-units of 2.8 ha were established according to the thematic map characteristics, selecting their optimal location. Simultaneously, two sub-units were irrigated for a period of 1.6 hours, for a total irrigated surface area of 56 ha.

Irrigation sub-unit distribution and the principal piping are presented in Figure 6.

Drip irrigation design information and results for small orchards (blueberry) are presented in Table 2.

Farm irrigation planning

Farm irrigation planning considers the establishment of irrigation methods, water distribution, a control center, irrigated area, crop distribution, water demand and irrigation frequency. Planning can be influenced by diverse factors, such as: water availability, crop,

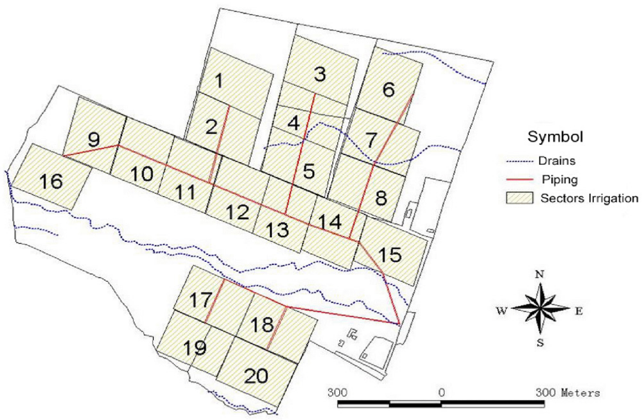

Figure 6. Irrigation sectors and principal pipe distribution for drip irrigation system at Crisoles Farm

Table 2. Drip irrigation data for design of irrigation systems

Item	Unit	Magnitude
Irrigation Frequency	Day	1
Plant spacing	m	3 x 1
ETa	mm day^{-1}	6.05
Volume of waterplant^{1} day^{-1}	L	19,1
No. of emittersplant^{1}	Units	2
Emitter discharge	L hr^{-1}	4
Drip pressure	mca	12
Irrigation hours per set	hr	2.38
Irrigation hours available daily	hr	24
Water availability	L s^{-1}	42
System capacity	L s^{-1}	42
No. of plants per set	plants	18,900
Area simultaneously irrigated	m^2	56,000
No. of set per day	units	10
Maximum irrigated area	ha	56
Pump	HP	30

climate and physical characteristics of the soil. The objective of planning is to achieve greater efficacy in water management, which means in practice water savings without diminished crop performance (Holzapfel et al., 2009).

Planning for the Crisoles Farm began with the identification of the feasible irrigation methods by studying the topographic conditions, water availability and crop requirements. Since water availability is restricted and the topography of farm is irregular, the use of the available water resources needs to be maximized by reducing the losses by surface runoff and consequently pressurized irrigation is required. Specifically, this study considers three possibilities: aspersion irrigation by a central pivot, sprinkler irrigation and drip irrigation.

In the case of sprinkler irrigation, the maximum irrigation frequency was considered important in planning. Irrigation frequency is related with the crop water requirement and the water retention capacity of the soil and in the case study was calculated at 10 days.

For localized irrigation, a daily irrigation frequency was considered given soil characteristics and crop demand.

Another important factor is flexibility in management of irrigation frequency and times, considering the specific site characteristics of each sector. When an irrigation sector has a higher infiltration velocity and good retention capacity, this sector can support a higher application velocity and less frequent irrigation.

The water reservoir and the distribution and water evacuation systems (pipes, canals, and drains) should be considered when planning. This information is easily managed in the map using a GIS because it can be used to locate structures and evaluate different operational scenarios. Furthermore, a GIS can rapidly identify structural dimensions. In the case study, the GIS identified the location of the control center between the two principal drains, a point where water from the two drains and from irrigation overflows can be captured. The pipe distribution system begins at this point.

Conclusions

1. A geographic information system (GIS) is a highly useful tool for farm irrigation design and planning.

2. The information incorporated in the thematic maps establish a dynamic system useful for farm irrigation system management.

3. Soil, crop, and topographic information can be spatially observed and analysed and basic design criteria, such as water application, irrigation frequency, and operation restrictions can be more easily established.

4. Considering design and optimization criteria, with support of GIS, the feasible irrigation method for the Crisoles Farm was drip irrigation for small fruits.

5. The location of the central control system and water distribution system was determined using the general vision of the farm provided by the GIS.

6. A general criterion for irrigation system planning and design is to base decisions in tools that help make real-time decisions for site specific conditions.

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