Integrating biophysical and economic data using GIS/ DSS to assess irrigation suitability for specific crops

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Abstract

Economic and environmental sustainability are of great importance in the planning and development of new irrigation schemes in order to underpin their long-term viability. In San Luis Province, Argentina, a novel approach has been used to produce irrigation suitability maps for specific crops using the combination of two decision support systems (DSS) with a geographic information system (GIS) in order to select areas suitable for irrigation development using groundwater. This approach has enabled spatial data on soils, groundwater and climate to be integrated with crop agronomic data and economic analysis to produce maps of physical and economic suitability for specific crops. The methodology initially involved land suitability classification based on FAO methodology and hydrogeological mapping of depth to groundwater, potential yield and groundwater quality (salinity and toxic trace elements). These datasets were analysed within the ASSESS (A System for SElecting Suitable Sites) decision support system using both the Law of the Minimum and Addition methodologies to exclude areas and to rank the remainder with potential for irrigation suitability. More detailed investigations were undertaken using the ALES (Automated Land Evaluation System) decision support system that provided the framework for the integration of biophysical data with crop suitability and economics. This facilitated the comparison of alternative crops in terms of biophysical and economic feasibility. Specifically, a modelled long-term annual rainfall surface was combined in the GIS with the soil and groundwater data as the basis for estimating soil-crop-water relations within the ALES land map units. Crop water requirements and potential yields were modelled based on field and laboratory data. This information was used to define land utilisation types, which were combined within ALES with the land characteristics of each land map unit and economic data to determine physical suitability and economic returns in terms of internal rates of return, gross margins and net present value. Definitions of the sustainable aquifer yield further refined the model allowing for the estimation of the potential irrigable area for any given combination of crop types. The results provide a spatial context for the sustainable development of groundwater based irrigation areas in San Luis Province, together with an economic basis for the selection of alternative cropping systems, and a methodology which has great potential for use elsewhere.

Keywords: irrigation suitability, ALES, ASSESS, GIS, San Luis Province Argentina

Introduction

In San Luis Province, Argentina, irrigation development using groundwater offers the potential for many new agricultural opportunities. The key objective of the San Luis Irrigation Feasibility Study was to identify areas that could be sustainably irrigated using groundwater. The project was conducted in two phases. The initial phase involved a province-wide reconnaissance level investigation at 1:500,000 scale to identify areas with the greatest potential for irrigation development using groundwater. The second phase, which is ongoing, involves more detailed mapping at 1:250,000 scale to determine irrigation suitability for specific crops.

Irrigation developments have frequently been unsustainable, because of poor planning, poor management, or deteriorating water resource quality. This is not surprising because the number of physical and economic variables that must be considered by planners and developers is large and taxes the ability of the human mind to integrate them and thus determine sustainable solutions. The current project had the option of being able to use both geographic information systems and decision support systems to facilitate the making of choices and decisions with respect to both physical and economic suitability of numerous land/water/crop options. It is believed that this process removes subjectivity and increases objectivity when decision making is complex. This paper presents the framework that enabled the integration of biophysical and economic data with ultimate results being presented in comparative terms of economic feasibility for different cropping systems.

Study Area

San Luis Province is located in central western Argentina, approximately 750 km west of Buenos Aires and 300 km east of the Andes (Figure 1). The topography in the north of the province is characterised by block-faulted mountain ranges of more than 2,000 m elevation. These are interspersed by wide basins filled with Tertiary and Quaternary sediments. In the south, relief is flat to undulating and a thick mantle of aeolian sand blankets the landscape.

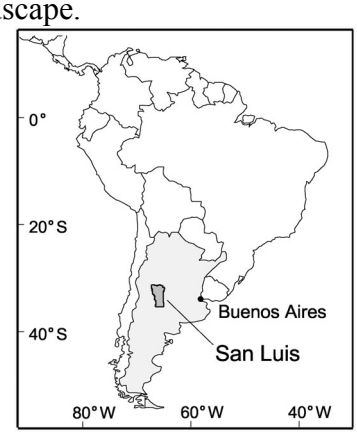

Figure 1 Location of San Luis Province, Argentina.

The soils in San Luis Province are generally young and sandy in texture. They have been classified according to US soil taxonomy (Soil Survey Staff, 1998) as entisols, mollisols and aridisols (INTA, 1998) .The spatial distribution of soils can be

summarised by the following. Shallow stony soils (ortents) are found in the ranges, and dominate the alluvial fans that occur on the western scarps of these ranges. Mixed fluvial and aeolian deposits (ortents/ortids) occur to the west of the ranges, whilst finer textured soils are associated with the river terraces and alluvial plains (ustols). Sand plains and sand dunes (psamments) with deflation basins dominate the landscape in the south of the province, with fine sandy loess deposits (ustols) found southeast of the main range of the Sierras de San Luis.

Rainfall in San Luis Province is summer dominant with long-term mean annual averages of up to 720 mm occurring in the mountain ranges. A strong rainfall gradient is evident across the plains, decreasing from 600 mm y^{-1} in the east to 250 mm y^{-1} only 250 km further west.

The hydrogeological setting comprises Precambrian-Cretaceous block-faulted mountain ranges and Tertiary volcanics in the central-north of the province, and flat to undulating Quaternary aeolian sands overlying basement rock in the south. The mountain ranges are interspersed by wide basins that have been in-filled with Tertiary and Quaternary alluvial sediments up to 2,000 m thick. The heterogeneous basin fill ranges from clay to coarse-grained sands with the coarser grained materials acting as discontinuous unconfined to confined aquifers. The sediments generally become finer and more consolidated with depth and can be loosely classified into an "upper", coarser and more permeable, and "lower", finer and more consolidated, basin fill. Groundwater depths range from 200 m or more to close to the land's surface. Elevated levels of groundwater salinity and high concentrations of boron, fluoride and arsenic exist throughout parts of the San Luis Province, and represent potentially serious limitations to irrigation development using groundwater.

Methodology

An objective methodology was initially required to integrate the soil and groundwater datasets compiled during the reconnaissance level phase of the project in order to identify areas with the greatest potential for irrigation development using groundwater. During the second phase of the project, it was recognised that more sophisticated methods were required to integrate biophysical and economic data to produce irrigation suitability for specific crops.

Data Integration in ASSESS (phase 1)

The ASSESS (A System for SElecting Suitable Sites) decision support system (Veitch, 1997) was selected to integrate the land evaluation and groundwater data collected during phase 1. ASSESS is a grid-based geographic information system (GIS) configured with a graphical user interface to enable the integration of expert analysis with public perceptions of information in a scenario-based decision framework. It was designed to integrate and spatially analyse biophysical datasets such as groundwater and soils and display the resulting suitability in a GIS.

Nine data themes pertaining to groundwater quality, quantity and land capability were combined in ASSESS to determine the most suitable areas for irrigation with groundwater. Groundwater themes used were concentrations of arsenic, boron, fluoride and total dissolved solids (TDS); the sodium adsorption ratio (SAR), depth to groundwater, Darcy flow (TDS <3,000 mg L^{-1}) and storage (TDS <3,000 mg L^{-1}). Land

capability factors incorporated were soil texture, surface pH, erosion hazard, permeability, topography, soil depth, salinity and limiting horizons.

The ASSESS methodology is described in detail in Ivkovic *et al.,* (2000) and is briefly summarised as follows. The methodology comprises two parts. Initially a Law of the Minimum approach was followed whereby critical irrigation limits were determined from established irrigation guideline values (FAO, 1985; Landon, 1984; Richards, 1954) with the inclusion of local knowledge where appropriate. Areas where any one or more of the data themes exceeded the critical irrigation limits were classified as being unsuitable for irrigation development and excluded from further consideration.

The second part of the ASSESS procedure involved an Addition methodology which was applied to the remaining suitable areas. In this process, a ranking of 1 to 5 (from highly suitable through to unsuitable) was assigned to each of the ranges in data values comprising themes. All the ranked themes were combined by a process of addition and then reallocated to five equal interval suitability categories.

The resulting output from the ASSESS methodology was a reconnaissance-level irrigation suitability map of San Luis Province (Figure 2). This map was used to select priority areas for more detailed investigation of irrigation suitability using groundwater during the second phase of the project.

Data Integration in ALES (phase 2)

During the second phase of the project, a more sophisticated decision support tool was required to determine irrigation suitability for specific crops. This was achieved using the Automated Land Evaluation System (ALES) decision support system, developed by Rossiter (1990), which is based on the FAO 'Framework for Land Evaluation' (FAO, 1976). The ALES program allows land evaluators to build expert systems at a project or regional scale to enable the comparison of land use options both in terms of physical and economic suitability (Rossiter, 1990). In the broad terms of this project, ALES provided a framework for matching the soil/land/climate/groundwater qualities of map unit data with the requirements of specific land utilisation types (crops) and economic factors. An ALES model was constructed using the datasets outlined in Figure 3 to determine irrigation suitability. The flexible framework provided by the ALES program allowed for the extension beyond pure land evaluation to encompass groundwater data themes, thus providing results in terms of irrigation suitability using groundwater.

Climate modelling was undertaken in order to more accurately quantify the spatial and seasonal variation in rainfall within San Luis Province. Long term mean monthly rainfall records from all available sites within and immediately adjacent to the province were collated. Climate surfaces were generated using the ANUSPLIN software package (Hutchinson 1989; 1998). Two- and three-dimensional analyses of the rainfall data were undertaken, using thin plate smoothing splines. The climate modelling produced monthly and annual precipitation surfaces of the San Luis Province that were incorporated into the GIS as growing season rainfall (Figure 3a).

Climate modelling results together with field and laboratory measurements of soil hydraulic conductivity were input into soil water balance and crop water use modelling (Kirby and Kingham, 2001) (Figure 3b).

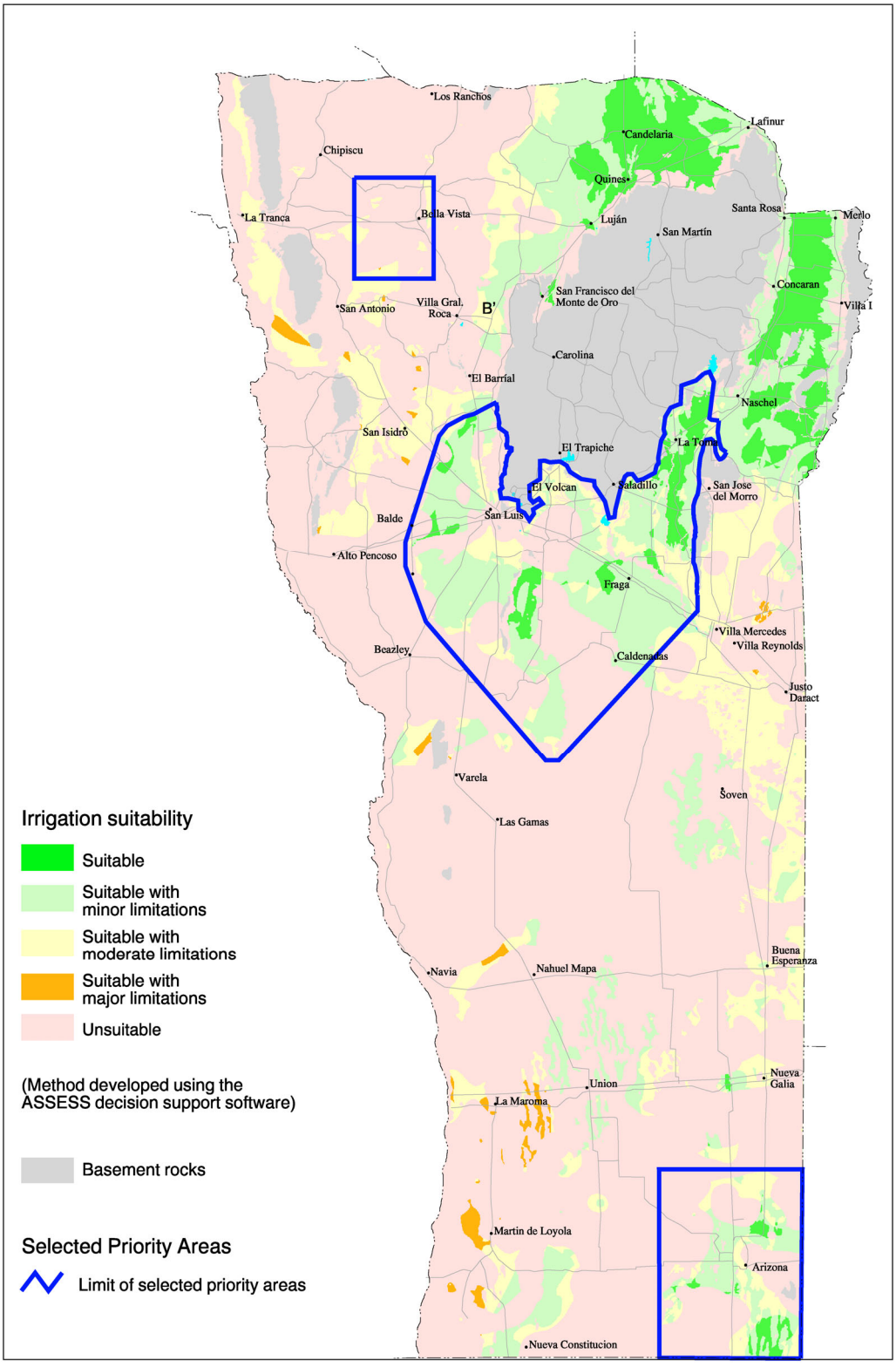

Figure 2 Phase 1 map of suitability for irrigation development using groundwater.

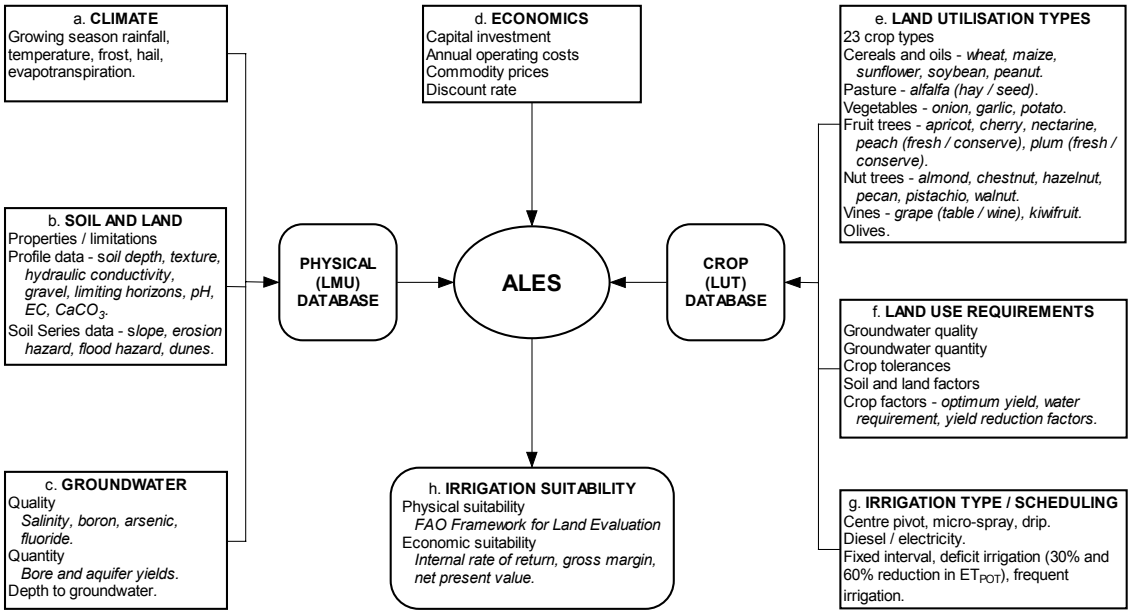

Figure 3 Phase 2 datasets integrated within the ALES decision support system.

This provided estimates of the irrigation requirement and crop yield for seven representative crop types (winter wheat, maize, grapes, citrus, perennial pasture, vegetables, and deciduous fruit) on the major irrigable soils in San Luis Province. Yields were modelled for the median rainfall year, the one-in-ten wet and one-in-ten dry years. The yield results and crop water requirements for the median rainfall year for the major irrigable soils were extrapolated to the soil series mapping to provide a spatial context. Crop water requirements for the seven representative crops were also expanded to the selected land utilisation types based on a ratio of the crop water requirement identified in the agronomic study to the results from the crop water use modelling.

Groundwater chemistry maps of salinity (TDS), boron, fluoride and arsenic were prepared from bore data using point-based interpolation techniques from Topogrid in ArcInfo. Depth to groundwater, bore and aquifer yield were also used to exclude areas where low yields and large depths to groundwater proved to be uneconomical (Figure 3c).

The climate, soil, land and groundwater data themes were intersected using the ArcInfo GIS to form the land map unit (LMU) database (Figure 3).

Agronomic studies (Di Benedetto and Murphy, 2001) provided information on the climate, soil, water and fertilizer requirements, pest and disease control and other management needs for forty-seven crops that were identified as being suitable for irrigation in San Luis Province. Of these, twenty-three crops were selected for inclusion as land utilisation types (LUT's) (Figure 3e) in the irrigation suitability model following an economic assessment of their production and market possibilities. Detailed microeconomic analysis followed (Zavalía and Asociados, 2001), providing information on the capital investment costs, annual operating costs and overhead expenses, historic and current commodity prices and an appropriate discount rate (Figure 3d) (prior to the devaluation of the Argentine peso in December 2001).

Land use requirements, in the context of this integrative project, include those climate, soil, land, groundwater and agronomic factors that impacted on the potential for a crop to be produced (Figure 3f). These factors were included in the irrigation suitability modelling to exclude crops from production where critical irrigation guidelines were exceeded, to reduce yield or increase production costs based on sub-optimal conditions. Analysis of the crop yield response to salinity (Maas, 1990; Maas and Hoffman, 1977) provided information on the critical threshold values at which yield is affected and also yield decline functions that occur with increasing salinity concentrations. Limited data was available for crop yield response to boron (FAO, 1985; Francois, 1991; Gupta *et al.,* 1985; Maas, 1990; Sotiropolous *et al.,* 1999), and as such the crop-specific critical threshold value was used as the irrigation limit.

Two alternative methods of energy supply for groundwater extraction were considered for the irrigation suitability modelling. Electricity infrastructure costs for several distances as well as the power usage and electricity costs were applied to compare with diesel pumping costs (Figure 3g). A matrix of groundwater diesel pumping costs was established based on the dynamic level of groundwater, bore yield and pump size. This allowed for the calculation of the diesel energy cost for pumped groundwater. Several irrigation regimes were also applied. These were fixed interval irrigation, deficit irrigation using a 30% and 60% reduction in potential evapotranspiration, and frequent irrigation (Figure 3g). These incorporated the yield and crop irrigation trade-offs established during the soil water balance and crop water use modelling.

Land use requirement and economic data were entered manually into ALES and land utilisation types were then constructed within the ALES model. Results were output in terms of physical suitability based on the map unit characteristics and land use requirements, and also economic suitability in terms of internal rates of return, gross margins and net present values (Figure 3h).

One of the main objectives of this project was to consider the sustainable development of groundwater irrigation. Fundamental to this objective is the need to determine the sustainable yields of aquifers within prospective irrigation areas. Three methodologies for estimating sustainable yields were employed during this study:

(1) Darcy "through flow" estimations representative of recharge under natural conditions;

(2) Water balance and recharge calculations to estimate the available volume of the groundwater resources; and

(3) Groundwater modelling, including simulation of well-field scenarios.

The analysis and comparison of these methodologies for estimating sustainable groundwater yields is currently ongoing and will underpin planning for future irrigation development.

Results and Discussion

The economic data were integrated with the biophysical data within the ALES DSS to determine the economic suitability, in terms of internal rates of return, gross margins and net present values (Figure 3h). The ALES outputs were linked to the project GIS to spatially represent both the biophysical and economic suitability classes.

The economic suitability for groundwater irrigation is presented within this study as classes of internal rates of return (IRR). At the time of this study, an IRR of >15% was

considered to be a very good return and an IRR of 8-15% a reasonable investment (December 2001, prior to the devaluation of the Argentine peso).

Figures 4 shows the result of the ALES irrigation suitability modelling for kiwifruit production within the central zone priority area of San Luis Province. Kiwifruit is a high value crop with very specific agronomic requirements, being highly sensitive to both salinity (Di Benedetto y Murphy, 2001) and boron (Sotiropolous *et al.,* 1999).

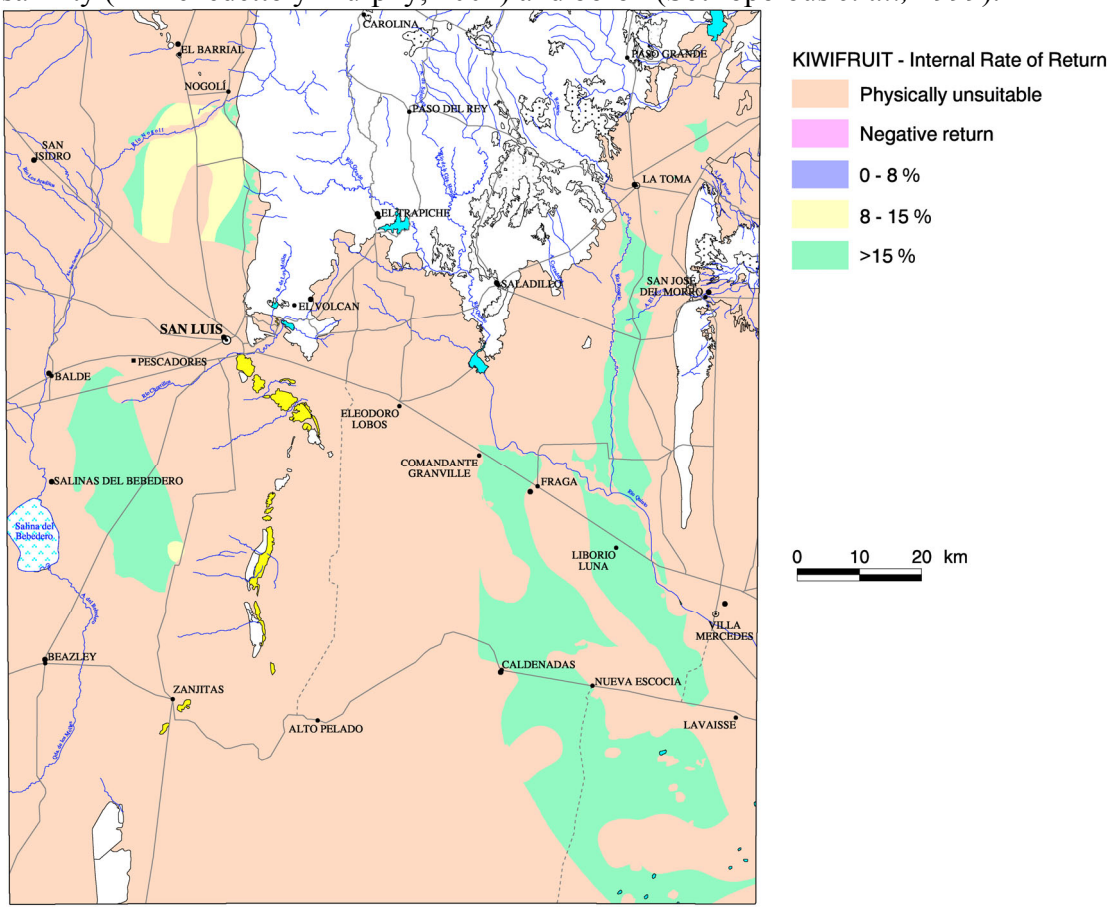

Figure 4 Physical and economic suitability for Kiwifruit production using groundwater.

The areas coloured in green were the most highly suited for production and provided the highest IRR (>15%). The areas in yellow were physically suited for kiwifruit production, but because of elevated groundwater salinity and or boron concentrations, crops grown in these areas would experience a decline in yield, and hence a lower IRR is be expected.

Using ALES it was possible to provide an overview of the most economic cropping options for each of the priority areas within San Luis Province. In general high-value horticultural crops offered the best economic potential whilst the extensive crops were not found to be economical under current market conditions using groundwater irrigation.

Conclusions

The results of this study provide a spatial context for the integration of datasets to facilitate the sustainable development of groundwater-based irrigation in San Luis Province. The combination of GIS and DSS's provided an objective methodology for the integration of the diverse datasets. The flexible framework provided by the ALES DSS was critical in enabling for the inclusion of the groundwater datasets to produce maps of irrigation suitability using groundwater.

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