Development of an integrated computational tool to improve performance of irrigation districts

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ABSTRACT

Nowadays irrigation district managers require several tools to assess irrigation networks' performance such as hydraulic models, geographic information systems (GIS) or decision support systems (DSS) which are available but as independent elements. Thus, simplifying the use of these tools by means of applications that integrate all these components would be helpful for irrigation district managers. In this paper, a computer tool combining a GIS, a hydraulic model and performance indicators (PIs) has been developed creating a database to deal with most information required in an irritation district. MapObjects Java Edition was used for the GIS integration and EPANET calculation module for the hydraulic modeling. This tool enables the study of the network performance, taking into account real measures (data from the remote control system) and simulated measures (obtained when running the hydraulic model) which are stored in a database and used to calculate different indicators that can be represented in the GIS. The PIs calculated with this tool give important information regarding the network response to different conditions, malfunction problems and failures in supply. Therefore, this tool is also useful to study the effects of improvements and the quality of service provided to farmers.

Key words | GIS, hydraulic model, performance indicators, Spain, water distribution systems

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NOTATION

A_f	area of the field supplied
AS	area supplied per outlet
DE	distribution efficiency
D_i	duration of interruptions in supply
D_s	total duration of the service
Ef	irrigation efficiency
ET_c	crop evapotranspiration
F	real flow measured in the outlet
F_a	flow assigned in the outlet
$F_{r/a}$	real/assigned flow ratio
$F_{r/s}$	real/simulated flow ratio
F_s	simulated flow in the outlet
FA	flow adequacy
L	longitude of tubes
NC	network coverage
Nd	number of days with the system working
Nd_o	number of days in which the outlet is open
Nd_p	number of days with a pressure below required at the checkpoint
nFS	number of fields supplied
nO	number of outlets in each field
$n\mathrm{O}_n$	number of outlets of the network
$n\mathrm{O}_p$	number of outlets with a daily average pressure below required
O_a	output per unit irrigated area
O_s	output per unit irrigation supply
OR	outlet operation ratio
P	real pressure measured in the checkpoint
P_a	pressure assigned in the checkpoint
$\bar{P}_{bq}$	pressure average in the best quartile

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$\bar{P}_{pq}$	pressure average in the poorest quartile
$P_{r/a}$	real/assigned pressure ratio
$P_{r/s}$	real/simulated pressure ratio
P_s	simulated pressure
PE	pressure equity
PR_c	pressure reliability at checkpoints
PR_n	pressure reliability in the network
Q_a	allocated flow
RWS	relative water supply
R_{ef}	effective rainfall
SR	supply reliability
t_i	irrigation time
VAP	value of agricultural production (€)
V_{ws}	volume of water supplied (m^3)
V_{in}	cumulative volume entering the network system
V_{out}	cumulative volume discharged in the outlets of each field
WDIA	water delivery per irrigated area

INTRODUCTION

The performance of pressurized irrigation networks is subject to variable operating conditions which are unpredictable. Therefore, it is very important to know the network response to these uncertain determining factors either in the designing, planning or operation stages (Lamaddalena & Khadra 2001). Then, an evaluation of irrigation distribution systems is necessary to improve and modernize networks (Lamaddalena & Pereira 2007a). Neri (1998) established that the global performance of an irrigation system comes from its response to farmers' requirements, considering the limits imposed by policies and the resource's availability. Molden & Gates (1990) described irrigation service in terms of adequacy, reliability and equity. So, when designing or managing an irrigation system, the main constraint is that the required flows should be supplied to water users adequately (Farmani *et al.* 2007). Therefore, adequacy measures how farmers' needs are satisfied. Reliability deals with the number of failures in the distribution system. A good service also entails an equitable distribution of water to ensure that all the farmers receive their full water allocation with the required pressure. Then, equity is needed either when water supply is limited or when water is not a constraining factor and farmers have a high freedom level for planning their activity (Ines *et al.* 2006).

Efficient on-farm irrigation management considers several sources of data such as rainfall, evapotranspiration and crop water requirements or network operating parameters. The lack of reliable information processed in a manageable format often leads to the wrong decisions (Jiracheewee *et al.* 1996). According to Kitchen (2008), the information-to-action decision process in modern agriculture needs to consider *in situ* sensor-based and real-time computer processing for providing transparent information to the operator/manager for decision-making. In order to minimize time and labor for collecting data, agricultural technology is moving towards the handling of remotely collected information with a consequent saving of resources (Mendoza-Jasso *et al.* 2005). So in many pressurized networks, remote control systems and metering devices are implemented. They are able to provide a considerable amount of data about volumes, flows and pressures at every hydrant in real time. Then all this information needs to be usefully stored and processed. In order to simplify the assessment of all available information in an irrigation system, the use of performance indicators (PIs) is highly recommended. A PI is basically a quantitative measure of a relevant aspect of irrigation behavior which helps to evaluate and monitor irrigation systems (Alegre *et al.* 2000). PI values are ratios that relate variables in such a way that a large amount of information can be reduced to a single number (Rodríguez Díaz *et al.* 2008).

Hydraulic models are used to simulate network performance under diverse management alternatives and water demand scenarios (George *et al.* 2004b; Rodríguez Díaz *et al.* 2009). Thus, the integration of these hydraulic models in a decision support system (DSS) allows the evaluation of actions and the introduction of different factors in the simulation process to assess unforeseen events (Lilburne *et al.* 1998; Le Bars & Le Grusse 2008).

Geographic information systems (GIS) provide a basis for combined management and guidance applied to field operations thanks to the capability to process data to produce basic mapped outputs for management purposes (Earl *et al.* 2000). They are very helpful in irrigation network management for detecting critical points or identifying malfunctions. Normally, most of the GIS-based applications are independent of automatic data collection systems and they require the information to be imported manually (Ojeda-Bustamante *et al.* 2007). For this reason, it is necessary to link the data acquisition system with the analysis tool. Hence, another dimension of integration is based on the use of GIS not only as a common framework and reference point but also as the primary display paradigm. This integration effectively transforms the system into a spatial decision support system (SDSS) (Ochola & Kerkides 2004). SDSS is an increasingly widely used tool in decision-making processes in the industry as well as in agriculture. Implementations of SDSS have been evolving rapidly in recent years (Cohen *et al.* 2008). A District Management System (DMS) can be defined as an evolution of SDSS, putting together a visual system (GIS) and hydraulic simulation algorithms to allow the analysis of water demands and distribution management at field level (Fipps & Pope 1998).

There are several examples of applications integrating hydraulic models with a GIS interface (George *et al.* 2004a; Khadra & Lamaddalena 2010) as tools to improve water use performance (Fortes *et al.* 2005; Kim & Evans 2009), irrigation planning systems (Muthanna & Amin 2005) or a DSS to estimate water demands in real time (Rao *et al.* 2004). Lamaddalena & Sagardoy (2000) developed a software called COPAM (Combined Optimization and Performance Analysis Model) to analyze the hydraulic performance of an irrigation system. Lamaddalena & Khadra (2001) combined COPAM with a GIS in order to better identify failure areas of irrigation systems in terms of relative pressure deficit and reliability. Lamaddalena & Pereira (2007b) used the FLUCS (Model Flow Upstream Control System) model combining indicators to study different conditions considering the effects of installed pressure and discharge regulation devices. SIMIS is an FAO conceptual DSS used in irrigation districts for planning, maintenance and administrative tasks (Mateos *et al.* 2002). Recently, other tools have integrated some of the described characteristics. For example, ADOR is a specialized database linked to a GIS which helps to manage information on water delivery parameters, fields and water users; it can also be used for billing operational and maintenance services, thus becoming a software tool for the daily water management of irrigation districts (Lecina *et al.* 2010). It is used to manage detailed information about district water management and to promote better on-farm irrigation practices with a GIS interface (Playán *et al.* 2007). GESTAR is a computational hydraulic software application adapted for the design, planning and management of pressurized irrigation networks with an interactive graphical interface enabling hydraulic and energy sizing, analysis and management in pressurized systems. It can also be used for optimum network control and parameter calibration (Estrada *et al.* 2009). However, none of these applications include real-time network assessment using PIs and the possibility of simulating new conditions such as different operational and climate scenarios or changes in cropping patterns. In the case of HuraGIS, a DSS combined with a GIS and a hydraulic model, some indicators are used. It was developed to simulate agronomic irrigation processes and the hydraulic and water quality behavior in pressurized networks (Jimenez Bello 2008; Jimenez-Bello *et al.* 2010a, b).

The objective of this work is to accomplish another step of integration to assess the distribution networks' performance and the quality of service provided in an irrigation district. PIs are calculated using the information obtained by hydraulic simulations and remote data collection systems. The results can be spatially identified and managed in the incorporated GIS application. As a result, the computer tool named the Irrigation Networks' Manager (INM) has been developed and tested in an irrigation district in southern Spain.

SYSTEM ARCHITECTURE

A combination of a GIS, a hydraulic simulation model (HSM) and a module for PI calculation is used for the development of the INM. A database is used to store the data collected from the remote control and acquisition systems in addition to the irrigation districts' records, and climate and crop information. This database feeds the system, generating simulated and real indicators spatially located in order to make decisions (Figure 1).

The INM can work in two different ways. First, it can collect flow and pressure records from the remote telemetry system calculating the PIs for these real data. Second, the

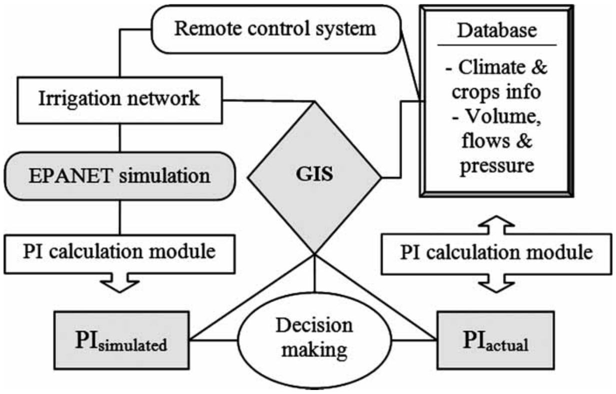


Figure 1 | Flowchart showing system architecture.

system can work in an alternative way, checking if the actual performance is similar to that obtained by hydraulic modeling. For this, the INM gets the actual demands for every outlet and uses this information as an input for the simulation module. Then it calculates the theoretical PIs using simulated flows and pressures which are compared with the real ones. This function is very useful in order to detect water losses or drops in pressure due to operative problems or poor network maintenance as a complete assessment of the overall network performance is carried out.

Software development

The Java programming language has been selected for the development of this computer tool due to its versatile architecture. It is object-oriented and dynamic with an enriched API (Application Programming Interface) which covers system codification needs (Natali *et al.* 2006). The Unified Modeling Language (UML) has been applied for the specification and modeling graphic techniques which enhance connections between different system components (Pinet *et al.* 2007). In the codification stage, Java Standard Development Kit (JDK) 5.0 version has been used due to its efficient work with dynamic data structures. The system database has been developed in PostgreSQL adding the graphical objects' support with a PostGIS module.

Hydraulic simulation model (HSM)

One of the most widespread HSMs is EPANET, which is a public domain software developed by EPA's Water Supply and Water Resources Division that models water distribution piping systems and performs extended-period simulation of the hydraulic and water quality behavior within pressurized pipe networks (Rossman 2000). EPANET has been mostly used to model urban distribution networks (Ostfeld *et al.* 2002) but there are some applications for the management of irrigation networks (González *et al.* 2003). The use of the EPANET model, which is based on a demand-driven analysis approach, has some limitations as they are incapable of simulating pressure-deficient conditions properly (Tanyimboh *et al.* 2001). Under these conditions, the demand-driven analysis will compute heads below the minimum required for outflow to occur physically at some nodes (Ang & Jowitt 2006). Therefore, in some cases, a pressure-driven analysis is necessary to obtain a better estimate of flow through the network and to ascertain the consequences of pipe failures or water loss via leakage (Giustolisi *et al.* 2008a). Problems with network connectivity may appear using EPANET in some situations such as reliability assessment analysis which requires closing system pipes (Giustolisi *et al.* 2008b). These described limitations should be taken into account when using the INM for certain analysis.

EPANET's computational engine has been integrated into the INM using its dynamic link library (DLL) functions available in the EPANET Programmer's Toolkit.

Geographic information system (GIS)

The GIS is used for visualizing data as a framework for analysis and modeling operations (Santé-Riveira *et al.* 2008). The functionality of the map controls within the GIS component was implemented in this case with Map Objects Java Edition (ESRI 2004). It provides a robust, Java-based API to perform a wide variety of geographic-based display, query and data retrieval activities directly embedded in the application (it is not necessary to have any GIS software installed on the computer).

Performance indicators (PIs)

There is a huge number of PIs developed to analyze several aspects of irrigation processes (Burt & Styles 1998; Malano & Burton 2001; Alexander & Potter 2004) so a selection has been made focusing on two main issues: performance and quality of irrigation service in the network. In the first case, adequacy, productivity and supply indicators are used while in the second some quality of service indicators (QSI) regarding network characteristics and performance (pressures and flows) are implemented. Gorantiwar & Smout (2005) reported a complete review of indicators used for irrigation water management; some of them were adapted by Pérez Urrestarazu (2007). Table 1 shows the selected PIs, their scope of calculation (field, checkpoint or network) and their typology as these PIs can be calculated for a period or for a certain instant (Pérez Urrestarazu *et al.* 2009). The last two PIs are network descriptors which point up the main characteristics of the network. Descriptors do not usually change in time unless a huge modernization process takes place in the irrigation district. The group of selected indicators was tested previously to assess their aptitude to study irrigation districts' performance (Rodríguez Díaz *et al.* 2005, 2008; Pérez Urrestarazu *et al.* 2009).

In order to calculate these indicators it is necessary to previously define the required variables which are easily obtained parameters used to form the indicators due to simple operations between them (Rodríguez Díaz *et al.* 2005). The information about these variables will come from either real data (irrigation district's records, remote control system) or simulated data (EPANET calculation module).

Selected PIs are defined as follows:

- Relative water supply (RWS). This indicator shows the relationship between the water that enters the system and the required water, that is, the volume of water applied and the theoretical crop water requirements measured as crop evapotranspiration (ET_c) (Levine 1982). The main function of RWS is to gain insight as to how crop requirements are satisfied with the water applied by farmers in addition to natural contributions (Molden *et al.* 1998):

$$\mathrm{RWS}_{\mathrm{Period}} = \frac{\sum_{\mathrm{Period}} \mathrm{Rainfall} + \sum_{\mathrm{Period}} \mathrm{Irrigation}}{\sum_{\mathrm{Period}} \mathrm{ET_c}}. \quad (1)$$

  when RWS is around 1, crop water requirements are fully met (Rao 1993). It is dimensionless. Crop water requirements are estimated according to the FAO 56 methodology (Allen *et al.* 1998)
- Output per unit irrigated area (O_a) and output per unit irrigation supply (O_s). Both O_a and O_s are catalogued as

Table 1 | PIs selected for the Irrigation Networks' Manager

PI	Scope	PI typology
Relative water supply (i)	Field	Periodic
Output per area unit (O_a)	Field	Periodic
Output per volume unit (O_s)	Field	Periodic
Water delivery per irrigated area (WDIA)	Field	Periodic
Flow adequacy (FA)	Field	Periodic
Pressure equity (PE)	Network	Periodic/instantaneous
Outlet operation ratio (OR)	Field	Periodic
Real/assigned pressure ratio ($P_{r/a}$)	Checkpoint	Instantaneous
Real/simulated pressure ratio ($P_{r/s}$)	Checkpoint	Instantaneous
Real/assigned flow ratio ($F_{r/a}$)	Checkpoint	Instantaneous
Real/simulated flow ratio ($F_{r/s}$)	Checkpoint	Instantaneous
Pressure reliability (PR)	Checkpoint/network	Periodic
Supply reliability (SR)	Network	Periodic
Distribution efficiency (DE)	Network	Periodic
Area supplied per outlet (AS)	Network	Descriptor
Network coverage (NC)	Network	Descriptor

productive efficiency indicators (Malano *et al.* 2004), essentially used for comparison of scheme outputs against key inputs (land and water):

$$O_a = \frac{\mathrm{VAP}}{A_f} \quad (2)$$

where VAP is the value of agricultural production (€) and A_f is the area of the field supplied (ha). It is measured in €/ha.

O_s is a measure of the so-called water productivity. It is defined as the amount of output produced per unit of water involved in the production (Igbadun *et al.* 2006). Crop production may be expressed in terms of total dry-matter yield (kg) or, when dealing with different cropping patterns, yield may be transformed into monetary units (Playán & Mateos 2006; Ali & Talukder 2008):

$$O_s = \frac{\mathrm{VAP}}{V_{ws}} \quad (3)$$

where VAP is value of agricultural production (€) and V_{ws} is the volume of water supplied (m^3). It is measured in €/m^3.

- Water delivery per irrigated area (WDIA) (Yildirim *et al.* 2007):

$$\mathrm{WDIA} = \frac{V_{ws}}{A_f} \quad (4)$$

where V_{ws} is the volume of water supplied (m^3) and A_f is the area the field supplied (ha). It is measured in m^3/ha.

- Flow adequacy (FA):

$$\mathrm{FA} = \frac{Q_a t_i \mathrm{Ef}}{\max\{\sum_{\mathrm{period}} (\mathrm{ET}_c - R_{ef})\} \cdot 10 A_f} \quad (5)$$

where Q_a is the allocated flow to the field studied (m^3/h), t_i is the irrigation time or duration (h), Ef is the irrigation efficiency, ET_c is the crop evapotranspiration (mm), R_{ef} is the effective rainfall (mm) and A_f is the area of the field (ha). The desired value is 1. Higher values mean that the outlet is oversized and, if lower, the maximum flow supplied will not be enough for crop requirements.

- Pressure equity (PE). This QSI studies how pressure is distributed in the network using Interquartile ratio (Abernethy 1986; Bhutta & Van der Velde 1992; Bos *et al.* 1994):

$$\mathrm{PE} = \frac{\bar{P}_{pq}}{\bar{P}_{bq}} \quad (6)$$

where $\bar{P}_{pq}$ is the average pressure in the poorest quartile and $\bar{P}_{bq}$ is the average pressure in the best quartile, taking into account all the network's checkpoints.

- Outlet operation ratio (OR) (Pérez Urrestarazu 2007; Pérez Urrestarazu *et al.* 2009):

$$\mathrm{OR} = \frac{Nd_o}{Nd} \quad (7)$$

where Nd_o is the number of days in which the outlet has worked and Nd is the number of days in the period that water has been available to farmers.

- Real/assigned pressure ratio ($P_{r/a}$) and real/simulated pressure ratio ($P_{r/s}$) (Pérez Urrestarazu 2007; Pérez Urrestarazu *et al.* 2009):

$$P_{r/a} = \frac{P}{P_a}; \quad P_{r/s} = \frac{P}{P_s} \quad (8)$$

where P is the real pressure measured in the checkpoint, P_a is the design pressure and P_s is the simulated pressure in that point.

- Real/assigned flow ratio ($F_{r/a}$) and real/simulated flow ratio ($F_{r/s}$):

$$F_{r/a} = \frac{F}{F_a}; \quad F_{r/s} = \frac{F}{F_s} \quad (9)$$

where F is the real flow measured in the outlet, F_a is the allocated flow and F_s is the simulated flow. It has also been defined as Delivery Performance Ratio (DPR) (Mondal & Saleh 2003).

- Reliability. A system is reliable if it works properly, following the settled parameters and giving the desired service. Therefore, it can be defined as the probability of no occurrence of failures (Renault & Vehmeyer 1999). It can be referred to pressure at checkpoints

(PR_c), pressure in the whole network (PR_n) and water supply (SR):

$$PR_c = \frac{Nd - Nd_p}{Nd} \quad (10)$$

where Nd is the number of days in the period with the system working and Nd_p is the number of days with a pressure below required at the checkpoint:

$$PR_n = \frac{nO_n - nO_p}{nO_n} \quad (11)$$

where nO_n is the number of outlets of the network and nO_p is the number of outlets with a daily average pressure below required:

$$SR = \frac{D_s - \sum D_i}{D_s} \quad (12)$$

where D_s is the total duration of the service and D_i is the duration of interruptions in supply (hours or days).

- Distribution efficiency (DE) (Pérez Urrestarazu 2007; Pérez Urrestarazu *et al.* 2009):

$$DE = \frac{\sum V_{out}}{\sum V_{in}} \quad (13)$$

where V_{out} is the cumulative volume discharged in the outlets of each field (m^3) and V_{in} is the cumulative volume entering the network system (m^3).

- Area supplied per outlet (AS) (Pérez Urrestarazu 2007; Pérez Urrestarazu *et al.* 2009):

$$AS = \frac{\sum_{i=0}^{n\,\text{fields}} (A_{f_i}/nO_i)}{nFS} \quad (14)$$

where A_f is the area of each field supplied (ha), nO is the number of outlets in each field; nFS is the number of fields supplied and i is the number of the field considered. It is measured in ha/outlet.

- Network coverage (NC) (Pérez Urrestarazu 2007; Pérez Urrestarazu *et al.* 2009):

$$NC = \frac{\sum L}{\sum A_f} \quad (15)$$

where L is the length of each pipe composing the network (m) and A_f is the area of each field supplied by the network (ha). It is measured in m/ha.

Database architecture

The database includes all the necessary information to run the model and calculate the indicators. Figure 2 shows a flowchart with all the relationships among the different database elements, each of them having a key identification code and several values recorded. Furthermore, it enables the user to record values of the calculated indicators in a log file which indicates for each PI: value, date and identification code of the element related.

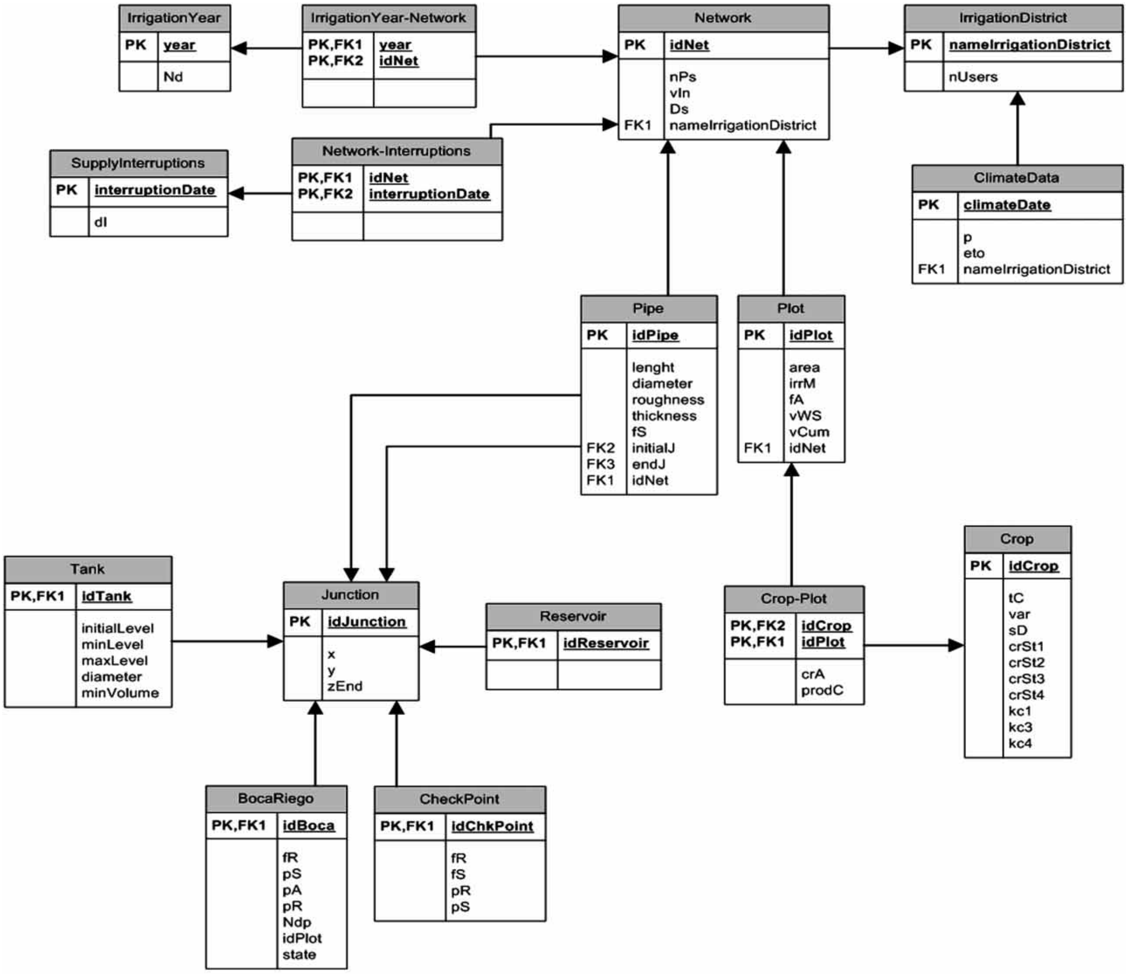
In order to obtain the data in the proper format, a template has been created in Excel format which is included in the program folder in the set-up process.

SYSTEM DESCRIPTION

The tool presented combines a hydraulic model, a GIS and a PI calculation module in a friendly user interface: the INM. The application can work on its own (the user is requested to introduce the information manually or use an MS Excel file) or link to a general database from the remote control system which provides the application with real-time data. The INM will be freely available for any user and, as it comes with its own installation package, it will not require any other program installed in the computer.

The INM is able to work with different irrigation districts simultaneously and for each one it stores and generates information on various networks and fields. The user can introduce new data or view the existing information within the network or even in a specific field just by selecting the option.

All the irrigation district descriptors and variables for PI calculations in different irrigation years are stored in the database so the user can easily find the information required. The information stored for each field with basic data about the field (ID, area, irrigation system, current demand, volumes), specific information about the outlets (ID, location and elevation, demand and pressures) and crop data can be viewed and modified by the user. Before



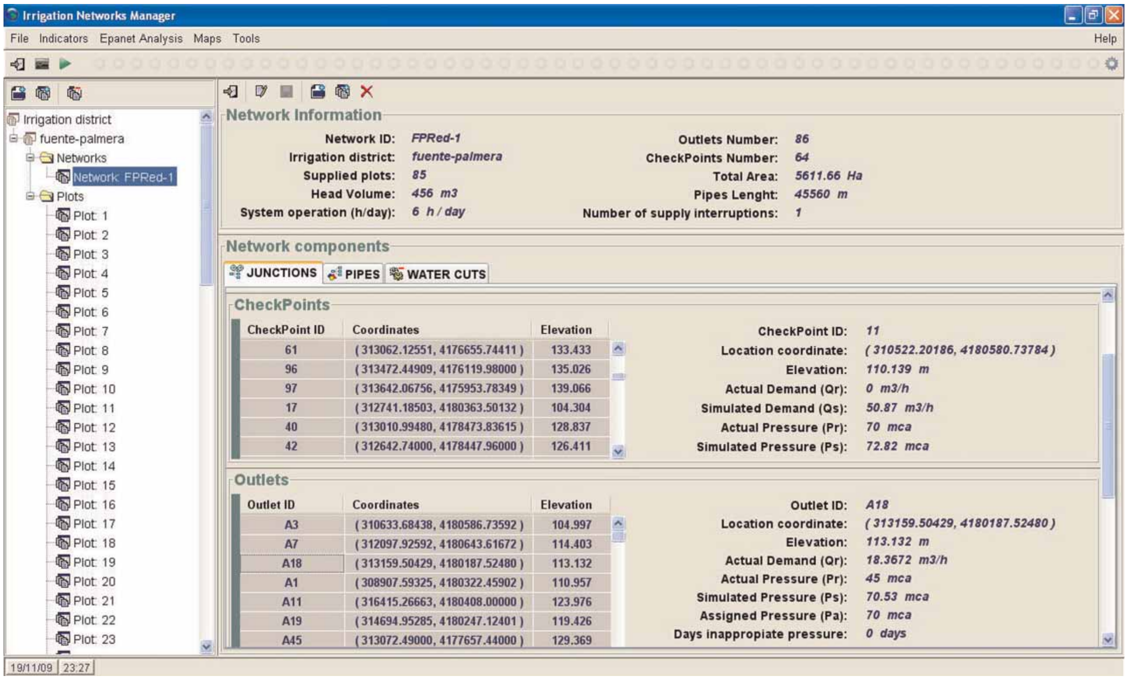
Nd: number of days with the system working; dI: duration of interruptions in supply; nFS: number of plots supplied; vIn: cumulative volume entering the network system; dS: duration of supply; nUsers: number of users; p: rainfall; eto: reference evapotranspiration; fR: real flow; fS: simulated flow; fA: allocated flow; pR: real pressure; pS: simulated pressure; pA: allocated pressure; irrM: irrigation method; vWS: volume of water supplied; vCum: cumulative volume; crA: crop area; prodC: crop production; tC: type of crop; var: variety; sD: seeding date; crSt: crop stages; kC: crop coefficient; zEnd: elevation; x,y: coordinates; Ndp: number of days with a pressure below required; state: open/close

Figure 2 | Database architecture.

doing the analysis, the network must be completely characterized, including all the elements, topology and information required as shown in Figure 3.

Once all the data are provided, PI can be automatically calculated with different options and levels. Indicators can be obtained for one specific network of an irrigation district in the selected irrigation season. Diverse indicators are available for the complete network or for certain fields, outlets and checkpoints designed by the user (Figure 4). Results of PI calculation are reported on the screen and can be exported as a report or Excel file.

If the user wants to know the network response to different situations or scenarios, a simulation module is provided to run several analyses based on the EPANET simulation engine. As a result, simulated values for different variables, such as flows and pressures, can be obtained and used for PI calculation instead of the actual values provided by the user or the remote control system. With all this information,



Network Information

Network ID: FPRed-1
Irrigation district: fuente-palmera
Supplied plots: 85
Head Volume: 456 m3
System operation (h/day): 6 h / day
Outlets Number: 86
CheckPoints Number: 64
Total Area: 5611.66 Ha
Pipes Lenght: 45560 m
Number of supply interruptions: 1

CheckPoints

CheckPoint ID	Coordinates	Elevation
61	(313062.12551, 4176655.74411)	133.433
96	(313472.44909, 4176119.98000)	135.026
97	(313642.06756, 4175953.78349)	139.066
17	(312741.18503, 4180363.50132)	104.304
40	(313010.99480, 4178473.83615)	128.837
42	(312642.74000, 4178447.96000)	126.411

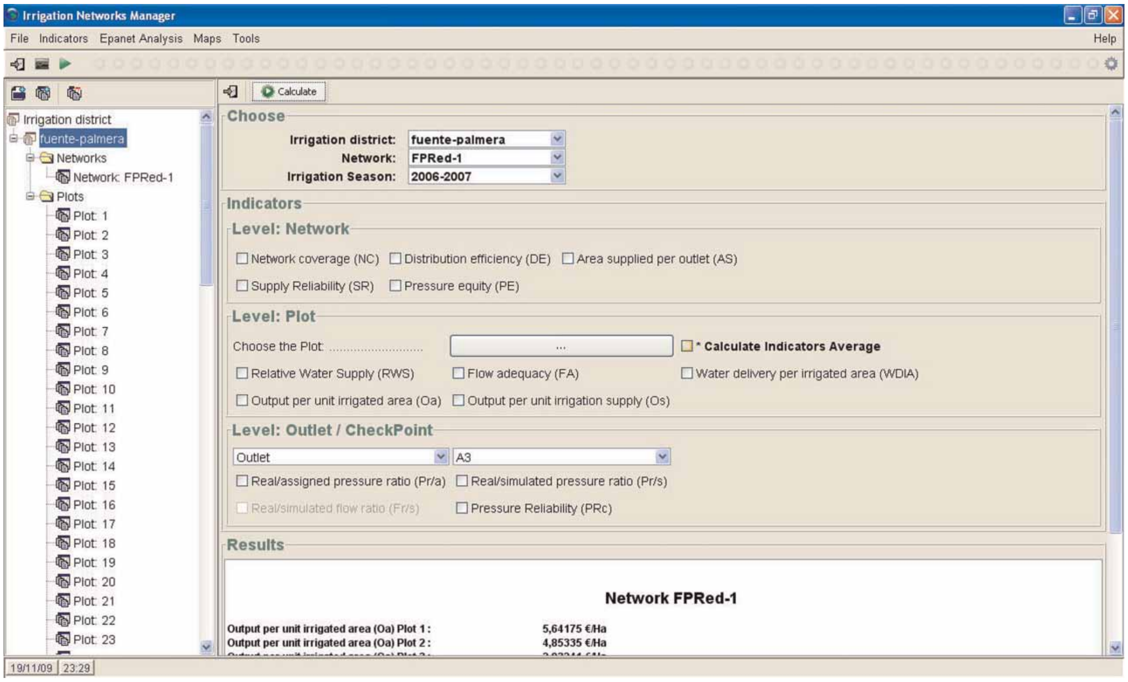
CheckPoint ID: 11
Location coordinate: (310522.20186, 4180580.73784)
Elevation: 110.139 m
Actual Demand (Qr): 0 m3/h
Simulated Demand (Qs): 50.87 m3/h
Actual Pressure (Pr): 70 mca
Simulated Pressure (Ps): 72.82 mca

Outlets

Outlet ID	Coordinates	Elevation
A3	(310633.68438, 4180586.73592)	104.997
A7	(312097.92592, 4180643.61672)	114.403
A18	(313159.50429, 4180187.52480)	113.132
A1	(308907.59325, 4180322.45902)	110.957
A11	(316415.26663, 4180408.00000)	123.976
A19	(314694.95285, 4180247.12401)	119.426
A45	(313072.49000, 4177657.44000)	129.369

Outlet ID: A18
Location coordinate: (313159.50429, 4180187.52480)
Elevation: 113.132 m
Actual Demand (Qr): 18.3672 m3/h
Actual Pressure (Pr): 45 mca
Simulated Pressure (Ps): 70.53 mca
Assigned Pressure (Pa): 70 mca
Days inappropiate pressure: 0 days

Figure 3 | Network information required.



Choose

Irrigation district: fuente-palmera
Network: FPRed-1
Irrigation Season: 2006-2007

Indicators

Level: Network

☐ Network coverage (NC) ☐ Distribution efficiency (DE) ☐ Area supplied per outlet (AS)

☐ Supply Reliability (SR) ☐ Pressure equity (PE)

Level: Plot

Choose the Plot: .... ☐ * Calculate Indicators Average

☐ Relative Water Supply (RWS) ☐ Flow adequacy (FA) ☐ Water delivery per irrigated area (WDIA)

☐ Output per unit irrigated area (Oa) ☐ Output per unit irrigation supply (Os)

Level: Outlet / CheckPoint

Outlet A3

☐ Real/assigned pressure ratio (Pr/a) ☐ Real/simulated pressure ratio (Pr/s)

☐ Real/simulated flow ratio (Fr/s) ☐ Pressure Reliability (PRc)

Results

Network FPRed-1

Output per unit irrigated area (Oa) Plot 1 :	5,64175 €/Ha
Output per unit irrigated area (Oa) Plot 2 :	4,85335 €/Ha

Figure 4 | PI calculation module.

the user will be able to compare the real situation against the theoretical one or study the difference in network performance when actual conditions are modified. As an example, the user could know the network response to variations in water requirements because of changes in the cropping pattern, irrigation system or even due to climate change (Pérez

Urrestarazu *et al.* 2010). Therefore, providing the program with the new values of water demands in the outlets, the user will obtain the network parameters for the new condition in order to calculate the indicators. An irrigation district manager will also be able to study how the network would work under modifications in network characteristics or topology such as the addition of new outlets, replacement of pipes or the inclusion of a new water reservoir or tank. Indicators obtained with the simulation of these situations could be compared to actual ones to gain valuable conclusions prior to any real modification.

All the information stored or computed by the application can be summarized in a report or exported as an Excel file for analysis. Network data can be exported using an 'inp' file, which is the format utilized by the EPANET application as exchange file.

The GIS module enables the user to view the results on a map where the network and fields are displayed showing all the information available either from PI calculation or from the simulation. Basic GIS operations are available, such as showing results with different color codes (Figure 5).

CASE STUDY

An application of the INM in the Palos de la Frontera irrigation district is presented as an example case study. This irrigation district is located in Huelva (southern Spain) and it has 3,343 ha with 826 fields devoted predominantly to strawberry production. The water is supplied by a pressurized network designed to irrigate on demand and divided into three sectors in order to irrigate each field separately. In recent years, the distribution system was upgraded, improving the network and installing a remote control system which provides information on parameters such as volume, flow or pressure in real time. The allocated flow is 1.2 l/s/ha, with a minimum pressure in the outlets of 3 atm. Each sector has a pumping station with five vertical pumps, which allows a maximum flow of 1,584, 1,056 and 1,372 l/s, and 8.5, 4.5 and 5.5 atm of pressure for sectors I, II and III, respectively. Sector III's network was used for this case study. This sector has 1,143 ha with 125 fields arranged in 54 irrigation units.

Climatic data are obtained from an automatic agro-weather station (Moguer Station: 37°08′52″ N, 06°47′28″ W;

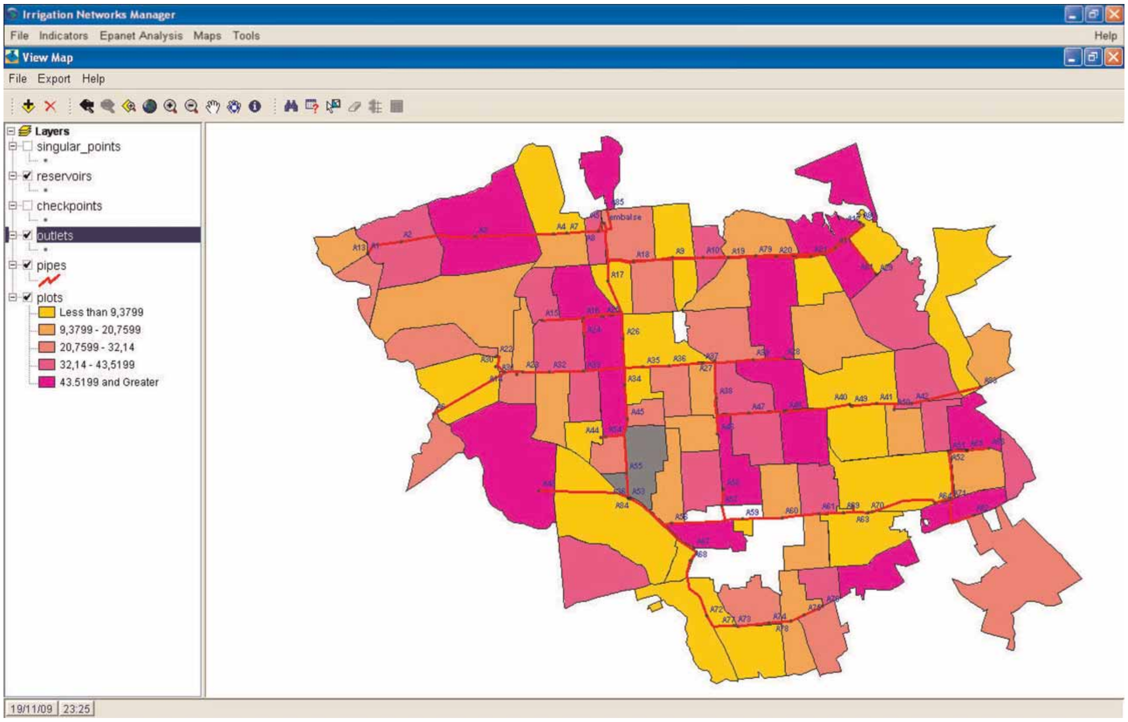


Figure 5 | GIS outputs.

altitude 87 m) providing daily information on rainfall (490 mm annual average), temperature, wind, relative humidity and reference evapotranspiration (1,145 mm annual average). In order to calculate the indicators, variables relating to flows, volumes and pressures were collected from outlets and checkpoints using the remote metering devices available in the irrigation district. The remote control system transmits data to the SCADA (Supervisory Control and Data Acquisition) which is linked to a database that stores these values every 15 min. The information needed for the INM was recovered from this database and arranged following the program template.

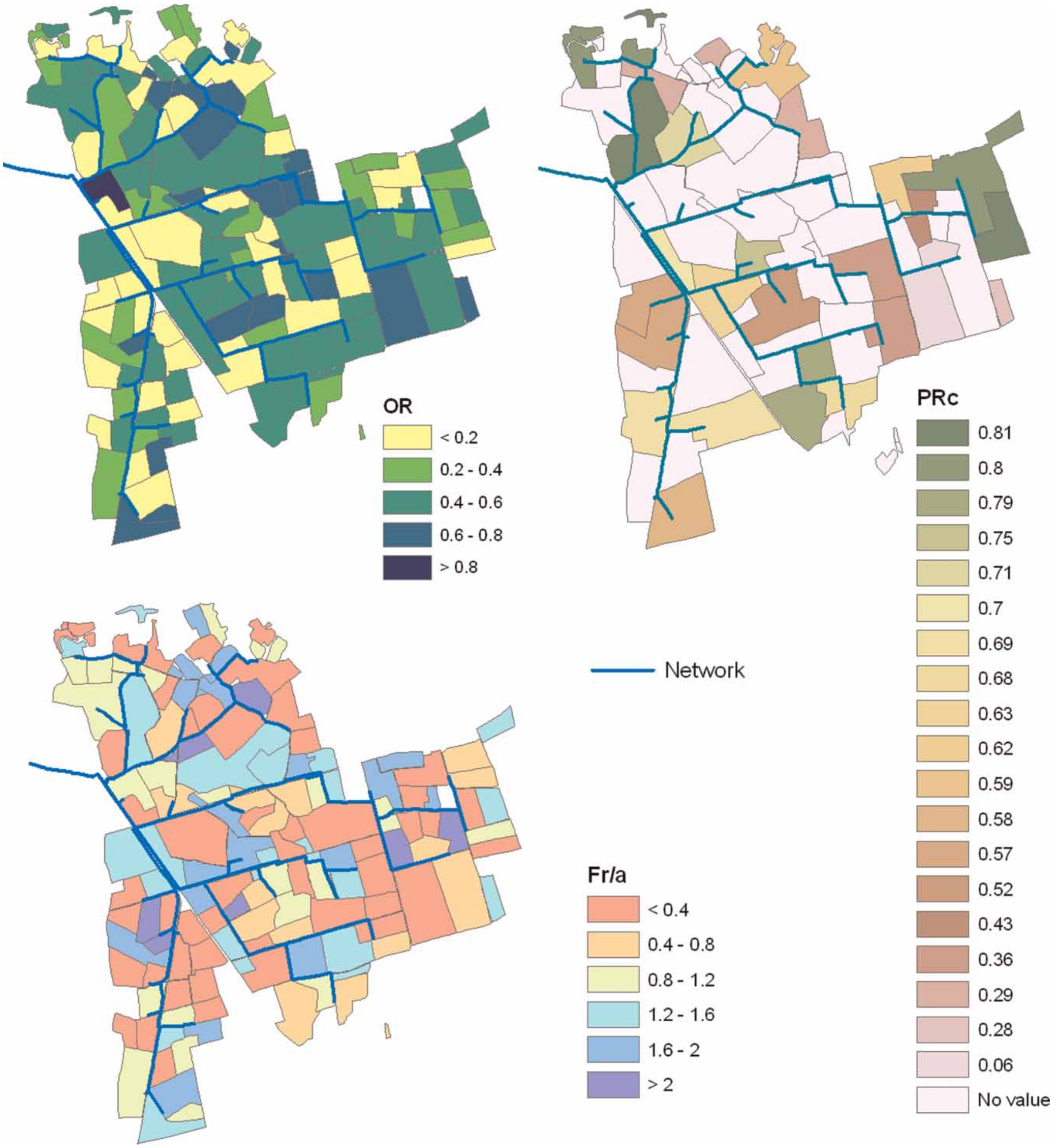


Figure 6 | OR, PR$_c$ and $F_{r/a}$ values represented in the GIS.

Palos de la Frontera's network (sector III) was modeled in the INM and the indicators were calculated using the data recovered during a complete irrigation year (2006). In general, the results showed that the service provided in this sector has good quality in terms of flow adequacy, distribution efficiency and pressure and supply reliability (Pérez Urrestarazu *et al*. 2009). Due to the large amount of results obtained, only an example of some indicators is presented, and in some cases average values are used.

Figure 6 shows OR, PR_c and $F_{r/a}$ values represented in the GIS. The number of outlets with a high operating rate ($OR > 0.8$) is small, representing only 1.4% of the total. This means that, for these conditions, the network design flow is too high. As the OR values are very low for many outlets, usually the network is operating below capacity, so a correct zoning of the network may be advised. The fields where the pressure was frequently under the design pressure show low values for PR_c. Therefore, this information could help to identify problems with the pressure in the outlets or critical points in the network. $F_{r/a} = 1$ implies that the outlet is working with the assigned flow, so higher values mean an excess while low ones show outlets working below the allocated flow. Therefore, some fields in this area could reduce their assigned flow as it is lower than estimated.

DE had a value of 0.896 over the period studied (standard deviation: 0.07) which suggests that water losses in the network are around 10%. PR_n was determined to be 0.77, so in this network 23% of the checkpoints could have average pressures below those required for optimum operation. High values for SR have been observed (0.993), which indicates that there are few supply interruptions. In these terms, the supply service is considered to be very good in this part of the irrigation district. Pressure reliability and ratios helped to identify the points with frequent problems so correction measures can be implemented to improve performance.

Having records of PI values over time may be interesting for district managers in order to know their temporal behavior and identify a poor network performance. As an example, Figure 7 shows the evolution of PE values during the irrigation year. Comparing the value of this indicator with the average (0.55) gives an idea of the network performance in terms of pressure in a certain moment.

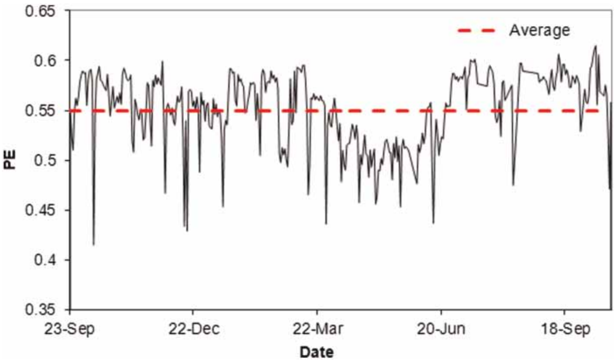


Figure 7 | Temporal distribution of PE values during the irrigation year.

CONCLUSIONS

A valuable tool has been designed to help technicians, managers and assistants to assess the performance of pressurized irrigation distribution networks through an easy and intuitive interface. The application includes a hydraulic model so different scenarios can be evaluated running simulations with new conditions. The GIS module allows users to locate all the available information and critical or problematic points or areas can be determined.

The PIs calculated with the tool presented give important information regarding the network response to different conditions, the use that farmers make of it, the malfunction problems and the failures in supply. They are also useful to study the effects of improvements and the quality of service provided to farmers.

Much information is required and real-time data acquisition is advisable for early detection of problems. For this reason, a better response is obtained when linking the application to a remote control system. This could represent one of the program's main constraints as each remote control system has its own communication protocols and database format so it should be adapted to the one required by the application following the template provided with the program. Also, some problems dealing with the remote control system might occur such as data failures or communication errors. Therefore, a proper maintenance of these systems is required as this tool relies on the information provided by them.

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