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TITOLO TESI

AN INTEGRATED DECISION SUPPORT SYSTEM FOR THE PLANNING, ANALYSIS, MANAGEMENT AND REHABILITATION OF PRESSURISED IRRIGATION DISTRIBUTION SYSTEMS

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Abstract

Water scarcity is a mounting problem in arid and semi-arid regions such as the Mediterranean. Therefore, smarter and more effective water management is required, especially in irrigated agriculture. Irrigation infrastructure such as pressurized irrigation distribution systems (PIDSs) play an important role for the intensification of agricultural production in the Mediterranean region. However, the operation and management of these systems can be complex as they involve several intertwined processes, which need to be considered simultaneously. For this reason, numerous decision support systems (DSSs) have been developed and are available to deal with these processes, but as independent components.

To this end, a comprehensive DSS called DESIDS has been developed and tested in the framework of this research. This DSS has been developed bearing in mind the need of irrigation district managers for an integrated tool that can assist them in taking strategic decisions for managing and developing reliable, adequate and sustainable water distribution plans, which provide the best services to farmers. Hence, four modules were integrated in DESIDS: i) the irrigation demand and scheduling module; ii) the hydraulic analysis module; iii) the operation and management modules; and iv) the design and rehabilitation module.

DESIDS was tested on different case studies located in the Apulia region (Southern Italy), where it proved to be a valuable tool for irrigation district managers as it provides a wide range of decision options for proper operation and management of PIDSs. All this is obtained through a DSS that offers: i) high level of interactivity and ease of use; ii) complete control of the irrigation managers; iii) adaptability and flexibility to the problems related to the operation of PIDSs; and iv) effectiveness in assisting irrigation managers with the decision making process.

The developed DSS can be used as a platform for future integrations and expansions to include other processes needed for better decision-making support.

I dedicate this thesis to

My parents, my sisters and brothers

for their constant support and unconditional love.

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Abdelouahid Fouial

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Abbreviations &Notation

ABBREVIATIONS	
AR	Assessment Report
CV	Check Valve
CWR	Crop Water Requirement
DDA	Demand-Driven Analysis
DESIDS	Decision Support for Irrigation Distribution Systems
DSS	Decision Support System
FCV	Flow Control Valve
GA	Genetic Algorithm
GCMs	Global Circulation Models
GGA	Global Gradient Algorithm
IPCC	Intergovernmental Panel on Climate Change
MOEAs	Multi-Objective Evolutionary Algorithms
NSGA II	Non-dominated Sorting Genetic Algorithm II
PDA	Pressure-Driven Analysis
PI	Performance Indicator
PIDN	Pressurized Irrigation Distribution Network
PIDS	Pressurized Irrigation Distribution System
RCPs	Representative Concentration Pathways
WDS	Water Distribution System

NOTATION		
$\overline{P_{bq}}$	Average pressure head in the best quarter	m
$\overline{P_{pq}}$	Average pressure head in the poorest quarter	m
$\mathbf{A}$	Topological incidence Matrix	-
A	Area irrigated by a hydrant	ha
ADF	Available discharge fraction for a hydrant	-
AVF_{net}	Available Volume fraction for a network	-
CR	Capillary rise from the groundwater table	mm
DP	Deep percolation	mm
$D_{r,}$	Root zone depletion	mm
e_a	Actual vapor pressure	kPa
E_{irr}	Irrigation efficiency	%
e_s	Saturation vapor pressure	kPa

ET_c	Crop evapotranspiration	mm
$ET_{c,adj}$	Adjusted evapotranspiration	mm
ET_o	Reference evapotranspiration	mm
G	Soil heat flux density	MJ m^{-2} day^{-1}
GIR	Gross irrigation requirement	mm
H	Pressure head at a hydrant	m
$\mathbf{H}$	Column vector of the computed nodal total heads	-
$\mathbf{H_0}$	Column vector of the known nodal total heads	
H_{min}	Minimum required pressure head at a hydrants	m
i	Subscript for the day	-
I	Net irrigation depth on a specific day	mm
I_{max}	Maximum possible irrigation depth	mm
j	Subscript indicating hydrants	-
k	Subscript indicating pipes	-
K_c	Crop coefficient	-
K_s	Water stress coefficient	-
l	Subscript indicating loops	-
n	Exponent of the flow in the head loss equation	-
n_0	Number of nodes with known pressure head (reservoirs)	
N_{conf}	Number of open hydrants configurations	-
nd	Subscript indicating nodes	-
N_{hyd}	Total number of open hydrants	-
NIR	Net irrigation requirement	mm
n_n	Number nodes with unknown pressure heads	-
N_o	Total number of times where hydrant j is open	-
n_p	Number of pipes carrying unknown flows	-
N_p	Number of irrigation periods	-
N_s	Number of times the pressure at a hydrant satisfied	-
$OFCR$	Objective function of minimization of total cost of rehabilitation	-
$OFPD$	Objective function of pressure deficit minimization	-
P	Rainfall	mm
PE	Pressure Equity	-
P_{eff}	Effective rainfall	mm
P_{pq}	Pressure Equity	-
q	Nominal discharge of a hydrant	Ls^{-1}
$\mathbf{Q}$	Column vector of the computed pipe flows	-
$\mathbf{q}$	Column vector of the nodal demands	-

q_{avl}	Available discharge at a hydrant	Ls^{-1}
q_{req}	Required discharge at a hydrant	Ls^{-1}
Q_{up}	Upstream discharge at the head of the network	ls^{-1}
R	Resistance factor for a pipe	-
R_a	Extraterrestrial radiation	mm day^{-1}
RAW	Readily available water	mm
Re	Reliability	-
R_n	Net radiation at the crop surface	MJ m^{-2} day^{-1}
RO	Runoff from the soil surface	mm
RPD	Relative pressure deficit	-
T	Mean air temperature	°C
TAW	Total available water	mm
t_h	Operating time of hydrants	h
t_{ir}	Irrigation time	h
T_{max}	Minimum air temperature	°C
T_{min}	Maximum air temperature	°C
u_2	Wind speed at 2 m height	m s^{-1}
V_{act}	Total volume of water actually supplied by a network	m^3
V_{req}	Total volume required to be supplied by a network	m^3
X, Y	*coordinates of nodes*	-
γ	Psychrometric constant	kPa $°C^{-1}$
Δ	Slope vapor pressure curve	kPa$°C^{-1}$
N_k	Total number of pipes in a network	-
L	Length of a pipe	m
D	Pipe diameter	mm
C	Cost associated with commercially available pipes	€m^{-1}

CHAPTER I

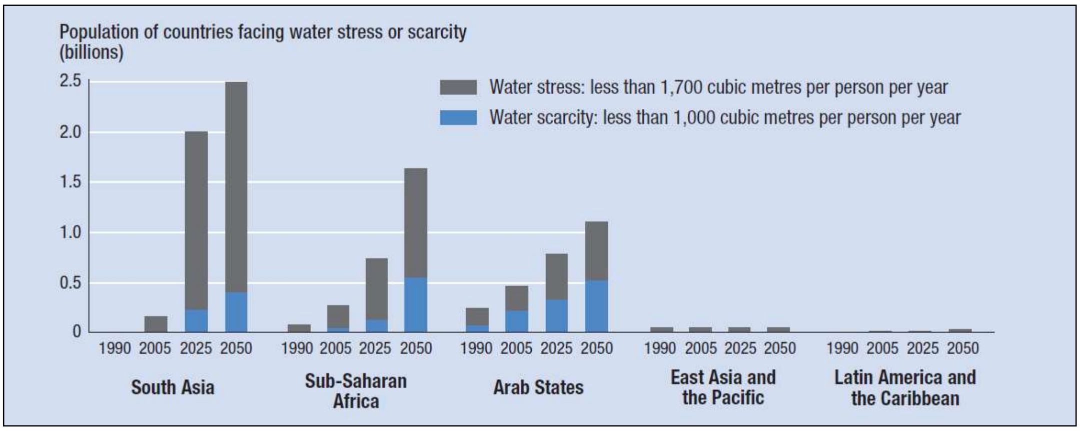
INTRODUCTION

I.1 Background and Motivation

Water scarcity is a mounting challenge that is affecting food security of large areas of the world. FAO (2012) defined water scarcity as a gap between available supply and expressed demand of freshwater in a specified domain, under prevailing institutional arrangements (including both resource 'pricing' and retail charging arrangements) and infrastructural conditions.

Physical water scarcity occurs when there are inadequate resources to satisfy demand. It is also important to consider the economic water scarcity, which is caused by a lack of investment in water to satisfy the demand. Most countries have enough water to meet domestic, agricultural, industrial and environmental requirements. In this case, the problem is in the management. Even though water scarcity is regarded as not having enough water to meet domestic needs, it is agriculture that will face the real challenge as it takes roughly 70 times more water to produce food than people use for domestic purposes (UNDP, 2006).

Food production plays a critical role in sustainable development and provides employment for 40% of the global population (UNEP, 2012). Furthermore, 70% of the world's freshwater withdrawals are already committed to irrigated agriculture and that more water will be needed in order to meet increasing demands for food and energy (biofuels) (WWAP, 2012). This will eventually put a lot of pressure on the available finite water resources. By 2025, more than 3 billion people could be living in water-stressed countries, and 14 countries will slip from water stress to water scarcity as illustrated in Fig. I-1 (UNDP, 2006). In addition, water scarcity is expected to affect more than 1.8 billion people, hurting agricultural workers and poor farmers the most (UNDP, 2014)



Source: UNDP (2006)

Fig. I-1. Projection of the intensity of water stress and scarcity

To tackle this problem, smarter and more effective water management is required as it will be a major challenge to achieve the necessary boost in food production while maintaining an acceptable increase in water use. In other words, there will be needs to invest in modernization of infrastructure, to restructure institutions and to upgrade the technical capacities of water managers and farmers. Water use efficiency, producing more 'crop per drop', will be a major challenge (UNEP, 2012). This will eventually increase water productivity. Molden (2007) stated that, under optimistic assumptions about water productivity gains, three-quarters of the additional food demand can be met by improving water productivity on existing irrigated lands.

The term 'efficiency' is generally defined as the ratio of output to input. This term is often used in the case of irrigation systems and it is commonly applied to each irrigation sub-system: storage, conveyance, off- and on-farm distribution, and on-farm application sub-systems (Pereira et al., 2012). The concept of 'water supply efficiency' or 'irrigation efficiency', defines the difference between water withdrawn and the physical losses resulting from leakage from pipes and open channels as well as on-farm wastage through inappropriate water applications for the crops. This applies to urban distribution networks and irrigation schemes where large amounts of water are lost through leakage and percolation. FAO (2012) estimates that, among the 23 countries of the Mediterranean, an estimated 25% of water is lost in urban networks and 20% from irrigation canals, while global estimates of irrigation efficiency are around 40%. In addition, Hamdy et al. (2003) indicated that, the average conveyance efficiency under traditional open channel systems is around 60% due to conveyance losses which may be subdivided into: seepage, evaporation, leaks in poorly maintained structures and poor water management in the distribution network. Therefore, the focus on water savings by reducing these losses is an extremely important issue in water demand management.

In the agricultural sector, the use of advanced technologies and the modernization of irrigation systems are, without doubt, one of the most promising strategies to meet the abovementioned water challenges. Renault (1999) stated that improved performance in irrigation water management, in order to increase water productivity, can usually be achieved through three types of interventions:

1. Rehabilitation, which consists of re-engineering a deficient infrastructure to return it to the original design. Although rehabilitation usually applies to the physical infrastructure, it can also concern institutional arrangements.

2. Process improvement, which consists of intervening in the process without changing the rules of the water management. For instance, the introduction of modern techniques is a process improvement.

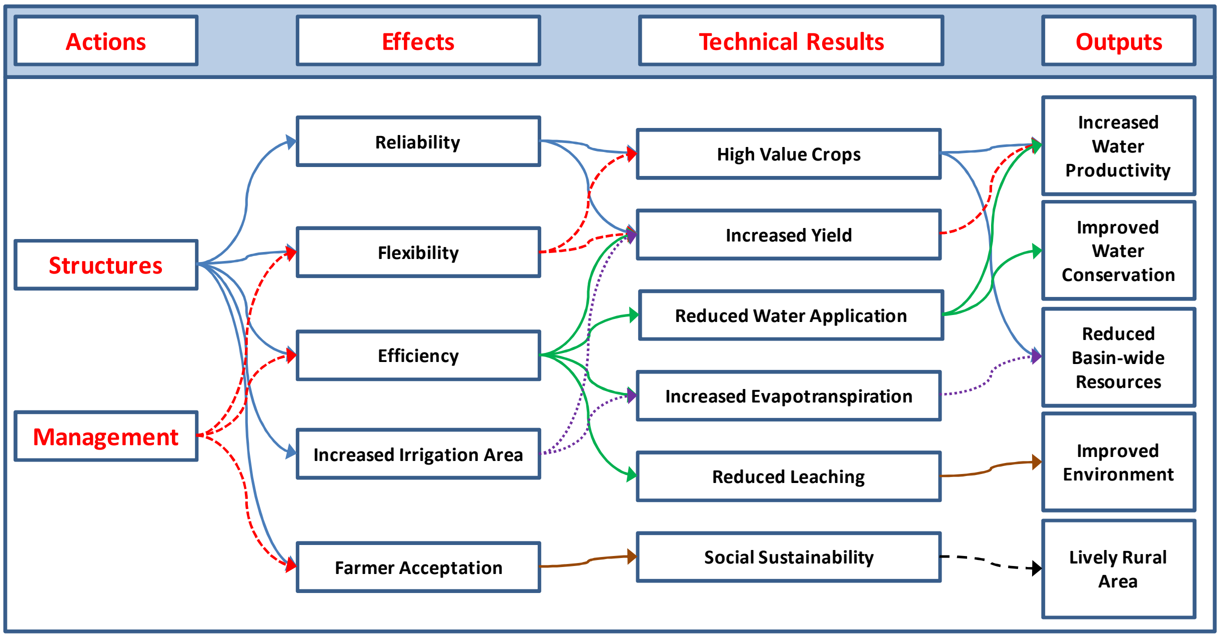
3. Modernization, which is a more complex intervention implying fundamental changes in the rules governing water resource management. It may include interventions in the physical infrastructure as well as in its management.

Modernization and rehabilitation of water delivery and irrigation distribution infrastructures can promote adoption of more efficient technology and management practices on-farm. A number of studies show that on-farm implementation of appropriate pressurized irrigation methods (sprinkler and trickle irrigation) and management practices can lead to significant water savings, creating potential environmental, economic and social benefits. However, the introduction of pressurized water saving techniques at farm level will not take place without upgrading of the main and distribution systems (Plusquellec, 2009). On the other hand, improvements in conveyance and distribution efficiency could be very costly, e.g., converting open channel to closed conduits (Hsiao et al., 2007).

Some countries, such as Italy and Spain, made large investments in the modernization of irrigation conveyance systems to increase water use efficiency in irrigation and generate water savings at farm and basin level. Modernization of some irrigation districts has consisted in the substitution of open channels systems by pressurized networks. Even though there is an indication from this experience that, the amount of water diverted for irrigation to farms has been considerably reduced, there was a significant increase in water costs mainly due to the higher energy requirements. Consequently, farmers switched to more profitable crops with higher water demands (Fernández García et al., 2014; López-Gunn et al., 2013; Rodríguez-Díaz et al., 2011).

Therefore, to avoid unexpected consequences from the implementation of new, rehabilitated or modernized irrigation conveyance (distribution) systems, more reliable information are needed to obtain detailed assessment on the operation process of these systems. The purpose is to identify the best balance between the results and the required investment for adequate operation to attain the water savings goals. Irrigation systems are complex land-water-social systems defined by a set of intertwined parameters in the design, management and operation processes. These parameters include water policy, the variability and volume of water resources and the spatial and temporal variability in demand due to variability in soil, rainfall and crop pattern.

New designs, rehabilitation or modernization of irrigation distribution systems should not rely solely on the use of new technology, as in practice, technology can only work satisfactorily if the users accept it and know how to manage it. On the other hand, if the irrigation district management is poor, it will not be enough to improve its water structures. The purpose of conveyance and distribution systems should be providing sufficient water in a timely manner so that it can be used efficiently for crop production. However, the concept of efficiency is not enough to evaluate the performance of these systems when is intended to assess the reliability and flexibility of deliveries required for improved demand management (Pereira et al., 2002). Fig. I-2 indicates alternative paths through the improvement of irrigation structures and irrigation management (Playán and Mateos, 2006). Flexibility and efficiency can be attained following both paths, and lead to increased water productivity through high value crops and increased yield. Nevertheless, system reliability can usually be tackled only by actions to improve the irrigation structures. Therefore, the success of irrigation distribution systems' improvements requires the consideration of both, structural performance diagnosis as well as good management intervention.



Source: adapted from Playán and Mateos (2006)

Fig. I-2 Diagram of the actions, effects, technical results and outputs related to irrigation modernization and optimization

The operation and management of pressurized irrigation distribution systems (PIDSs) can be complex. An irrigation district manager has to face some of the above-intertwined processes, which include factors that need to be considered simultaneously. Therefore, it is imperative to have an integrated decision support system (DSS) for assisting in taking strategic decisions to increase the performance of PIDSs and thus, providing the best services to farmers which will eventually have positive effects on water use efficiency and crop productivity. A comprehensive DSS should be able to enhance the decision making process by providing accurate information about the present state of a PIDS and assisting the decision maker in selecting appropriate options for improving the performance of that system in the case of failure.

There is a wide range of DSSs and computer models available in the literature and for commercial uses, which can be applied for PIDS. However, there is no DSS that encompasses all the processes needed by an irrigation district manager to deal with all the issues encountered in PIDSs. Therefore, there is a need to provide an integrated solution, a DSS that is based on a real 'need' services that help irrigation district managers with the complex intertwined components, such as planning, performance analysis, management, and rehabilitation of these systems. Rey and Hemakumara (1994) characterized a DSS as “a set of tools and procedures which, if used by the management of a particular system, would enhance the quality of the decision-making processes in this system".

I.2 Aims and objectives

The main aim from this research is to develop an integrated DSS to assist irrigation district managers in taking decisions and make critical day-to-day and long-term planning for PIDSs management. Great care has been given to develop an innovative support tool that is relevant, accurate, user-friendly, and tailored to the needs of decision makers for the planning, analysis, management, and rehabilitation of PIDS. To achieve this main objective, four discrete modules were developed and incorporated in the DSS to create a one-stop tool for decision makers. This has led to the formulation of the following specific objectives:

1. Development of a tool that generates operating hydrants' configurations to simulate more realistic daily operation of PIDS, to give irrigation managers the ability to provide potential management solutions in case of the hydraulic failure of these systems.
2. Development of the core of the DSS, which is a tool that can provide accurate hydraulic analysis of PIDS. This is important, as the actual and future decisions related to the management of these systems require the knowledge of their operational state.
3. Development of a tool for the optimization of hydrants' operation to provide better services to farmers.
4. Development of an innovative optimization tool for the physical rehabilitation of PIDS.

I.3 Outline of the thesis

This thesis is divided into seven chapters including the general introduction (Chapter I).

In Chapter II, a description of the integrated DSS developed in the framework of this research is given. It includes a review of the availability of DSSs for PIDS to provide a more innovative and complete tool for irrigation district managers and decision makers. This chapter also provide a general description of the four modules incorporated in the developed DSS.

Chapter III describes the importance of using more realistic analysis of PIDS. This is achieved through the development of a tool that uses the irrigation demand and scheduling module to generate accurate operating hydrants configurations. The latter are used for the assessment of the hydraulic performance of irrigation systems, hence, allow district managers to evaluate the impact of their decisions not just on the operation of the systems but also on crops yield at farm level.

Chapter IV presents an application of the operation and management module in a real large-scale on-demand pressurized irrigation distribution network (PIDN). The module uses genetic algorithm to assign an irrigation period to each hydrant in the considered network, taking into account the minimization of pressure deficit. This is proven to be useful for irrigation district managers in insuring a satisfactory pressure at all hydrants by switching from on-demand delivery schedule to rotation schedule.

Chapter V refers to the design and rehabilitation module. In this chapter, an innovative algorithm was developed for the consideration of localized loops strategy in the physical rehabilitation of PIDSs. The application of this module in the rehabilitation of a real network is described. The module uses non-dominated sorting genetic algorithm (NSGA II) in the multi-objective optimization process considering the minimization of both, the pressure deficit and the cost of rehabilitation. It was proven that this comprehensive module is a valuable tool to assist planners and decision makers in the determination of the most cost-effective strategy for the rehabilitation of PIDNs.

In Chapter VI, the capability of the developed DSS were implemented to deal with an important issue, namely climate change. The effect of climate change on an existing PIDN was simulated considering two future scenarios for 2050s and 2080s time periods. Accordingly, an adaptation strategy was investigated using localised loops to increase the hydraulic capacity of the network without affecting farmers' operation flexibility that characterises on-demand delivery schedule. This relatively cost effective strategy showed an improvement in the hydraulic performance of the system under current and future increases in water demand.

The key outcomes and novel aspects introduced in this research are highlighted in Chapter VII.

I.4 References

FAO, 2012. Coping with water scarcity: An action framework for agriculture and food security. FAO Water Reports, no. 38, Rome, Italy.

Fernández García, I., Rodríguez Díaz, J.A., Camacho Poyato, E., Montesinos, P., Berbel, J., 2014. Effects of modernization and medium term perspectives on water and energy use in irrigation districts. Agricultural Systems 131, 56-63. doi:10.1016/j.agsy.2014.08.002

Hamdy, A., Ragab, R., Scarascia-Mugnozza, E., 2003. Coping with water scarcity: water saving and increasing water productivity. Irrig. and Drain. 52, 3-20. doi:10.1002/ird.73

Hsiao, T., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irrig Sci 25, 209-231. doi:10.1007/s00271-007-0063-2

López-Gunn, E., Mayor, B., Dumont, A., 2013. Implications of the modernization of irrigation systems, in: De Stefano, L., Llamas, R. (Eds.), Water, Agriculture and the Environment in Spain: can we square the circle? CRC Press (Taylor & Francis Group), Leiden, The Netherlands, pp. 241-255.

Molden, D., 2007. Water for Food, Water for Life: A comprehensive assessment of water management in agriculture, London, UK: Earthscan and Colombo, Sri Lanka: International Water Management Institute.

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manage. 108, 39-51. doi:10.1016/j.agwat.2011.08.022

Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manage. 57, 175-206. doi:10.1016/S0378-3774(02)00075-6

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manage. 80, 100-116. doi:10.1016/j.agwat.2005.07.007

Plusquellec, H., 2009. Modernization of large-scale irrigation systems: is it an achievable objective or a lost cause. Irrig. and Drain. 58, S104-S120. doi:10.1002/ird.488

Renault, D., 1999. Modernization of irrigation systems: a continuing process, in: FAO (Ed.), Modernization of irrigation system operations. Proceedings of the fifth international ITIS (Information Techniques for Irrigation Systems) network meeting, Aurangabad, Maharashtra, India. 28-30 October 1998, pp. 7-12.

Rey, J., Hemakumara, H.M., 1994. Decision support system (DSS) for water distribution management: theory and practice. International Irrigation Management Institute (IIMI) vii, 44p. (IIMI Working Paper 031) Colombo, Sri Lanka.

Rodríguez-Díaz, J.A., Pérez-Urrestarazu, L., Camacho-Poyato, E., Montesinos, P., 2011. The paradox of irrigation scheme modernization: more efficient water use linked to higher energy demand. Spanish Journal of Agricultural Research 9, 1000-1008. doi:10.5424/sjar/20110904-492-10

UNDP, 2006. Beyond scarcity: Power, poverty and the global water crisis. Human Development Report 2006. United Nations Development Programme, NY, USA.

UNDP, 2014. Sustaining human progress: Reducing vulnerabilities and building resilience. Human Development Report 2014. United Nations Development Programme, NY, USA.

UNEP, 2012. The UN-Water status report on the application of integrated approaches to water resources management. United Nations Environment Programme, Nairobi, Kenya.

WWAP, 2012. The United Nations world water development report 4: Managing water under uncertainty and risk. World Water Assessment Programme. UNESCO, Paris.

CHAPTER II

DESIDS: DECISION SUPPORT FOR IRRIGATION DISTRIBUTION SYSTEMS

II.1 Introduction

The decision-making processes associated with collective PIDSs is very complex, and require thorough consideration and analysis. The decision support process for collective distribution systems includes (De Nys et al., 2008): (i) the determination of the existing problems to be solved and the targeted objectives; (ii) analysis of the current operation processes (mainly the links between the manager's and the farmers' decisions); (iii) definition of management plans; (iv) and assessment of possible operation and management strategies and their expected impact on farmers. Nowadays, irrigation district managers are in need of several tools to assess the performance and the management of PIDSs, such as hydraulic models or DSSs which are available but as independent elements (Urrestarazu et al., 2012).

Even though there are many models developed for irrigation and water distribution systems (WDSs), only few are adopted in practice. Kizito et al. (2009) identified some of the reasons why users do not use DSSs, which include: (i) not considering the user in the development of DSSs; (ii) the "black-box" nature of some DSSs; (iii) the cost; (iv) the DSS is not related to "realistic" problems; and (v) the high level of complexity of DDSs. Extensive studies are reported in the literature concerning the development of computer models and DSSs to be used at farm level and at district level. The two levels are linked, thus an adequate DSS has to consider a balanced approach giving importance to both.

At farm level, irrigation scheduling models are practically useful for the simulation of alternative irrigation schedules relative to different levels of farmers' management practices. Many models and software are available to support farmers' when it comes to the calculation of crop water requirements (CWRs) and determination of irrigation scheduling such as CROPWAT (Smith, 1992), GISAREG ((Fortes et al., 2005), WISCHE (Almiñana et al., 2010) and IRRINET (Mannini et al., 2013).

At district level, the integration of different models is required as the operation and management of collective distribution systems become more complex. For WDSs, most of the available DSSs deal with the operation, management, and rehabilitation of drinking WDSs, focusing on the control of pipes leakage and optimization (Arsene et al., 2012; Dias et al., 2014; Giustolisi and Berardi, 2009; Savić et al., 2011). In the agricultural sector, Mateos et al. (2002) presented SIMIS, Scheme Irrigation Management Information System, a DSS for managing irrigation schemes. SIMIS encompasses two management modules: i) the water management module, which includes four sub-modules, crop water requirements, irrigation plan, water delivery scheduling, and water consumption; and ii) the financial management module, which includes accounting, water fees, and control of maintenance activities sub-modules. In addition, it comprises a performance assessment sub-module that allows the calculation of several indicators related to the water distribution, agricultural intensity, maintenance, and financial matters. The water delivery in SIMIS mainly addresses open canal systems and is applicable to only branched irrigation distribution systems. In addition, it can handle three main water delivery modes: fixed rotation, semi-demand, and proportional supply. SIMIS has been shown to be a useful tool for the management of irrigation schemes. However, the analysis of more flexible delivery modalities is tedious within SIMIS, and it requires calculations outside of SIMIS (Lozano and Mateos, 2008).

Concerning PIDS, Lamaddalena and Sagardoy (2000) presented COPAM, the Combined Optimization and Performance Analysis Model (COPAM), a software package for the design and analysis of large-scale distribution networks. It includes three modules: i) the generation of demand discharges using Clément probabilistic method (Clément, 1966); ii) the optimization of pipe sizes using Labye's iterative discontinuous method (Labye, 1981); iii) and the analysis of hydraulic performance by randomly generating large number of open-hydrants configurations. COPAM is also limited to only the design and analysis of branched networks.

GESTAR (Estrada et al., 2009) is a computational hydraulic software tool specially adapted for the design, planning, and management of both, collective and on-farm pressurized irrigation networks. This tool integrates two main modules: i) the optimization of branched networks with predefined layouts, using a combination of continuous Lagrange method and discontinuous Labye method (Aliod and González, 2008); and ii) the module for hydraulic and energy analysis. This module includes several features such as scenario generation tools with deterministic and random demand states, quasi-steady time evolutions (extended period simulation), computation of accumulated or stochastic flow rates, pumping station and system curve computation, estimation of probability density function of the discharge flow rates, and deterministic or stochastic computation of the energy consumed at pumping station, instantaneously or in a given period. The design optimization in GESTAR is limited to only branched network.

Urrestarazu et al. (2012) developed an integrated computational tool called INM (Irrigation Networks' Manager) to assess the distribution networks' performance and the quality of service provided in an irrigation district. The tool combines GIS, a hydraulic model, EPANET (Rossman, 2000), and performance indicators (PIs) to create a database that deals with most information required in an irritation district. Different PIs are calculated using information obtained from hydraulic simulations (simulated measures) and remote data collection systems (real measures). The obtained results, which can be spatially identified and managed, give information about networks performance and their response to different conditions to improve performance of irrigation districts.

There are other examples of models and expensive software, which have been developed and can be used for PIDSs. However, there is no DSS that encompasses all the processes needed by an irrigation district manager to deal with all the issues encountered in PIDSs. Therefore, there is a need to provide an integrated solution, a DSS that is based on a real 'need' services that help irrigation district managers with the complex intertwined components of PIDS, such as planning, performance analysis, management and rehabilitation. An effective DSS should incorporate, simultaneously, all these components and must be flexible to adjust to new requirements and changes needed by the user. A DSS should also offer an effective platform for managers to understand the impact of their future decisions on the overall performance of the PIDS and on the quality of services provided to farmers.

The main objective of this work is to develop an integrated DSS tool that will allow irrigation district managers to evaluate options for managing and developing reliable, adequate, and sustainable water distribution plans that provide the best services to farmers. This tool will permit the analysis of the hydraulic performance of existing PIDSs, the evaluation of different scenarios for managing these systems, optimization of system operations, and the optimization of rehabilitation plans if needed.

II.2 DSS description

The developed DSS, called DESIDS (Decision Support for Irrigation Distribution Systems), is a stand-alone software, written in Microsoft® Visual Basic® programming language and supported by a user-friendly graphical user interface (GUI) and built-in GIS capabilities (Fig. II-1). Prodigious care has been taken in creating a flexible, relatively easy to handle software, which could be used in different contexts of PIDS from planning to management and rehabilitation. DESIDS is set to address the different processes needed for managing collective irrigation systems (De Nys et al., 2008): operational (daily irrigation scheduling and distribution), tactical (changing systems' operation without modifying the infrastructures) and strategic (changing structural capacities through new investments, e.g. structural rehabilitation). Therefore, it is set to help irrigation district managers address the different issues identified specifically in their districts.

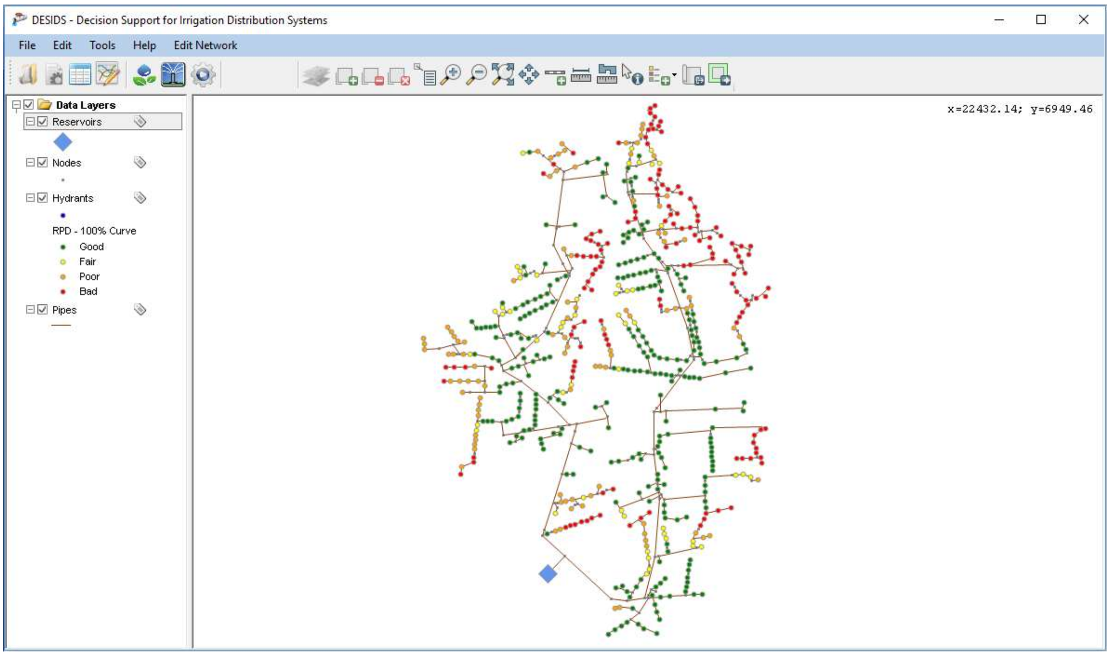


Fig. II-1. Main interface of DESIDS

DESIDS encompasses four separate, yet easily integrated elements or modules: i) an irrigation demand and scheduling module that calculates CWR, irrigation demand, irrigation scheduling for an entire irrigation district, and generates operating hydrants configurations; ii) a hydraulic analysis module that uses different PIs to evaluate the performance of a PIDS. The analysis is carried out by either randomly generating a large number of hydrant opening configurations or by using realistic configurations from the previous module; iii) an operation and management module that provide optimal operation strategies to achieve the best services (demand and pressure) to farmers; and iv) a rehabilitation module that implements multi-objective optimization for the rehabilitation of existing networks as well as the design of new ones.

The outputs of each of the above modules are presented in tabular and graphical forms to facilitate the interpretation of the results. Some of the outputs are designed to be used as inputs for one of the available modules to enable the integration and the flow of information in the DSS as illustrated in Fig. II-2. Detailed descriptions of the four modules are presented in the following sections.

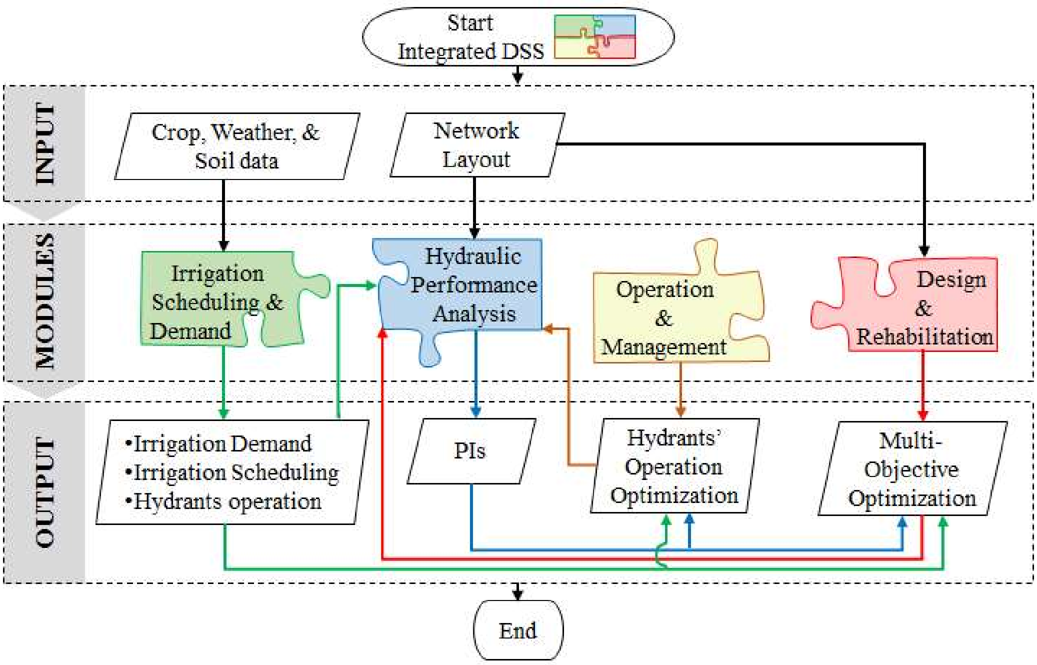


Fig. II-2. DESIDS integrated modules

II.3 Irrigation demand and scheduling module

To evaluate the performance of PIDSs and to take the appropriate decisions concerning the operation and management of these systems, it is necessary to know the allocation of water at farm level. To this end, the irrigation demand and scheduling module is used to simulate CWR and irrigation scheduling for each field in an irrigation district. The incorporation of this module in DESIDS is imperative as it allows irrigation system managers to more efficiently match available discharges and pressures supplied by the system to on-farm water use. Thus, take the necessary decisions to provide adequate PIDSs performance to meet the crop water demand. Irrigation demand and irrigation scheduling are determined following the approach of CROPWAT using climatic, crop and soil parameters. The required data can be entered through the GUI and stored in a database to be retrieved when needed. All the input data and the results are displayed in tabular and graphical form to facilitate their interpretation (Fig. II-3). The estimation of irrigation requirements is one of the principal parameters for the planning, design, and operation of PIDSs. In this module, monthly available data are used to estimating the crop water and irrigation requirements, especially during the peak period, for a proposed cropping pattern for the planning and design of a PIDS. While the daily data if very important in formulating the policy for optimal allocation of water as well as in decision making in the day-to-day operation and management of the systems.

II.3.1 Irrigation Requirements

To estimate irrigation requirements, daily (or monthly) reference evapotranspiration (ET_0) has to be provided or calculated using either FAO-56 Penman–Monteith (Eq. II-1) or Hargreaves (Eq. II-2) methods, depending on the availability of data (Allen et al., 1998):

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad \textit{Eq. II-1}$$

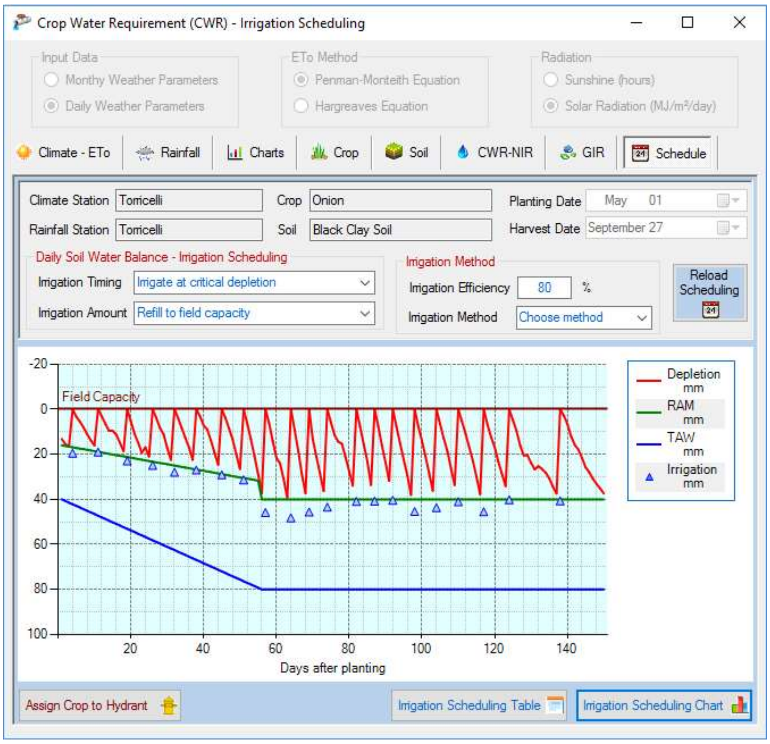


Fig. II-3. Irrigation demand and scheduling module

where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

$$ET_0 = 0.0023\,(T + 17.8)(T_{max} - T_{min})^{0.5} R_a \qquad \textit{Eq. II-2}$$

where T_{max} and T_{min} are, respectively, the maximum and minimum temperatures (°C), R_a is the extraterrestrial radiation (mm day^{-1}).

It is worth mentioning that, the values of crop evapotranspiration (ET_c) and CWR are identical herein, whereby ET_c refers to the amount of water lost through evapotranspiration and CWR refers to the amount of water that is needed to compensate for that loss. ET_c is determined by multiplying ET_0 by the crop coefficient (K_c) provided for each growing stage. In this module, the planting dates for all crops are pre-defined by the user to mimic the real situation in the field.

The crop evapotranspiration under non-standard conditions, $ET_{c,adj}$, is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. $ET_{c,adj}$ is calculated using a water stress coefficient (K_s).

The net irrigation requirement (*NIR*) is calculated as the difference between $ET_{c,adj}$ and the effective rainfall. The latter can be estimated based on the provided rainfall data using four different options: i) fixed percentage of the actual rainfall; ii) FAO formula for dependable rainfall; iii) empirical formula; and iv) USDA Soil Conservation Service formula. It is also important to consider the losses of water, expressed in terms of efficiencies (E_{irr}), incurred during irrigation application to the field. The gross irrigation requirement (*GIR*) is then calculated as:

$$GIR = NIR/E_{irr} \qquad \textit{Eq. II-3}$$

II.3.2 Irrigation scheduling

Once the crops irrigation requirements have been calculated, the next step is the determination of irrigation scheduling. Concerning the latter, Pereira et al. (2003) recommended the use of soil water balance simulation when to be applied in the irrigation practice. For irrigation scheduling purposes, daily time steps are required because the irrigation managers are most often interested in estimating the irrigation depth and date(s) of application needed to maintain soil water content at a certain level. Three parameters have to be considered: the calculated daily CWR, the soil (particularly its total available moisture or water-holding capacity) and the effective root zone depth.

In this module, net irrigation depths are estimated using daily soil water balance expressed in terms of depletion at the end of the day (Allen et al., 1998):

$$I_i = D_{r,i-1} - D_{r,i} - (P - RO)_i - CR_i + ETc_i + DP_i \qquad \textit{Eq. II-4}$$

where I_i is the net irrigation depth on day i, $D_{r,i}$ is the root zone depletion at the end of day i, $D_{r,i-1}$ is water content in the root zone at the end of the previous day, i-1, P_i is the actual rainfall on day i, RO_i is the runoff from the soil surface on day i, CR_i is the capillary rise from the groundwater table on day i, ETc_i is the crop evapotranspiration on day i, and DP_i is the water loss out of the root zone by deep percolation on day i, all expressed in mm.

II.3.3 Generation of open hydrants configurations

To create a more realistic operation of hydrants in a PIDS, this module is set to generate hydrants' configurations (hydrants operating simultaneously) for the entire irrigation season or a pre-defined period such as the peak period, using 15, 30 or 60 minutes time steps. After assigning each field in the irrigation district to a hydrant. The irrigation time can either be fixed by the user or generated randomly and the maximum irrigation time per day can also be limited if the PIDS is operated under rotation delivery schedule.

When it is time to irrigate, a hydrant j is opened and remains as such for the time of irrigation ($t_{ir,j}$), until the desired irrigation depth is delivered. On the other hand, when $t_{ir,j}$ is greater than the operating time of the hydrant j, $t_{h,j}$ (hours), irrigation scheduling for the entire season is adjusted to deliver the maximum possible irrigation depth, $I_{max,j}$ (mm), and to fully satisfy irrigation requirements:

$$I_{max,j} = \frac{0.36 t_{h,j} q_j}{A_j} \qquad \textit{Eq. II-5}$$

where 0.36 is a units adaptation coefficient, q_j is the nominal discharge of hydrant j (ls^{-1}) and A_i is the area irrigated by hydrant j (ha)

All fields and the hydrants used to irrigate them are added to a table representing the irrigation scheme. In this module, the determination of the seasonal peak period is achieved by applying the moving average method to the daily volumes of irrigation water, for periods pre-defined by the user. The final step is the generation of hydrants' opening configuration for the entire irrigation season or the period defined by the user. These configurations can be saved in a file to be used by the hydraulic analysis module.

II.4 Hydraulic analysis module

This module is the core of DESIDS, as it is the tool to evaluate the hydraulic performance of PIDSs and assess the impacts of their operations. This module combines the stochastic analysis capabilities for on-demand systems of COPAM (Lamaddalena and Sagardoy, 2000) and the analysis of complex systems using EPANET (Rossman, 2000) hydraulic solver to calculate unknown discharges and pressures for each operating hydrant in the considered PIDS.

There are two types of hydraulic analysis in WDSs: i) the demand-driven analysis (DDA), where the demands are assumed constant at hydrants regardless of the available pressure, thus it is not suitable for operating conditions with insufficient pressure (Tanyimboh and Templeman, 2010); and ii) the pressure-driven analysis (PDA), which considers the variation of demands depending on the pressure status. Several researchers have highlighted the use of PDA for its ability to deliver realistic results under different pressure conditions (D'Ercole et al., 2016; Giustolisi et al., 2009; Ozger and Mays, 2003).

II.4.1 Demand-Driven Analysis

The hydraulic analysis module assesses the performance of PIDSs using EPANET hydraulic solver, which is based on the conventional DDA. This solver is used by most of the developed models found in the literature to check the hydraulic feasibility of their generated solutions (De Corte and Sörensen, 2013). The solver provides the hydraulic analysis module with the ability to perform "extended period simulations", which is used here for the simulation of hydrants operation for long periods of time (peak period or the entire irrigation season), by means of a succession of steady states.

Following the DDA formulation given in Todini and Pilati (1988), the Global Gradient Algorithm (GGA) is used to solve the mass and energy conservation laws. The general equation describing every element of a network is expressed as:

$$\begin{bmatrix} \mathbf{A}_{pp} & \mathbf{A}_{pn} \\ \mathbf{A}_{np} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{Q} \\ \mathbf{H} \end{bmatrix} = \begin{bmatrix} -\mathbf{A}_{p0}\mathbf{H}_0 \\ \mathbf{q} \end{bmatrix} \qquad \textit{Eq. II-6}$$

were

- **Q** = $[Q_1, Q_2,\ldots, Q_{np}]^T = [n_p, 1]$ is a column vector of the computed pipe flows and n_p is the number of pipes carrying unknown flows;
- **H** = $[H_1, H_2,\ldots, H_{nn}]^T = [n_n, 1]$ is a column vector of the computed nodal total heads and n_n is the number nodes with unknown pressure heads;
- $\mathbf{H_0}$ = $[H_{01}, H_{02}, \ldots, H_{0n0}]^T = [n_0, 1]$ is a column vector of the known nodal total heads and n_0 is the number of nodes with known pressure head (reservoirs);
- **q** $=[q_1, q_2, \ldots, q_{nn}]^T = [n_n, 1]$ is a column vector of the nodal demands

In Eq. II-6, $\mathbf{A}_{pp}$ represents a $[n_p, n_p]$ diagonal matrix whose elements are defined as=

$$\mathbf{A}_{pp}\,(k,k) = R_k|Q_k|^{n-1} \qquad k \in 1, n_p \qquad \textit{Eq. II-7}$$

while $\mathbf{A}_{pn} = \mathbf{A}_{np}^T$ and $\mathbf{A}_{p0}$ are topological incidence submatrices, of size $[n_p, n_n]$ and $[n_p, n_0]$, respectively, derived from the general topological matrix $\bar{\mathbf{A}}_{pn} = [\mathbf{A}_{pn}|\mathbf{A}_{p0}]$ of size $[n_p, n_n + n_0]$; R_k is resistance factor for pipe k depending on whether the Darcy-Weisbach, Hazen-Williams or Manning equation is used; and n is an exponent of the flow in the head loss equation ($n = 2$ for Darcy-Weisbach).

II.4.2 Pressure-Driven Analysis

In PIDSs, it is vital to deliver the minimum pressure at hydrants level required for the adequate functioning of on-farm irrigation systems and to supply the necessary water demand to meet irrigation requirements for the crops. In this context, the ability to perform PDA was added to the developed module to evaluate the actual discharges delivered by hydrants when the pressure at these hydrants is less than that needed to fully satisfy demand, hence, assess the effects of demand deficiencies at hydrant level on crops' yield.

Several methodologies have been proposed for the application of PDA in WDSs:

1. Using the emitter element within EPANET for pressure driven modelling. However, the emitter has no upper limit for the discharge when the pressure is higher than the

minimum required pressure and it produces wrong results when the pressure is negative (negative discharges);

2. Embedding PDA in the governing network equations (Giustolisi et al., 2008; Muranho et al., 2014; Siew and Tanyimboh, 2012; Sivakumar and Prasad, 2014; Tanyimboh and Templeman, 2010);
3. Using DDA and iterating with successive adjustments made to specific parameters until a sufficient hydraulic consistency is obtained (Ozger and Mays, 2003); and
4. Using DDA with non-iterative methods by modifying the topological structure of the network, i.e., adding devices to the existing network such as valves, reservoirs, and emitters (Abdy Sayyed et al., 2015; Gorev and Kodzhespirova, 2013; Pacchin et al., 2016).

Nowadays, PDA is commonly employed in available WDSs models, which provide correct hydraulic analysis under both normal and pressure-deficient conditions. However, the majority of these models are fitted for drinking WDSs, e.g., for leakage modelling. The applications of this type of models in irrigation systems are seldom and only very few models are reported in the literature such as FLUC (Lamaddalena and Pereira, 2007) and GESTAR (Estrada et al., 2009).

For this study, the use of PDA in PIDSs is particularly important to assess the reliability of these systems when referring to their ability to provide the required discharges needed to meet on-farm water demands. To achieve this goal, the non-iterative method suggested by Abdy Sayyed et al. (2015) was applied in this module. This method was selected because it provides the possibility to perform PDA by directly using the EPANET toolkit with a single simulation. It was also compared to other similar method and applied on three real-life cases where it proved to provide accurate and reliable results, reproducing the functioning of a network in the pressure-driven mode (Pacchin et al., 2016)

The method consists of adding artificial string of check valve (CV), flow control valve (FCV), and emitter, in series, at each hydrant to model pressure deficient PIDS as illustrated in Fig. II-4.

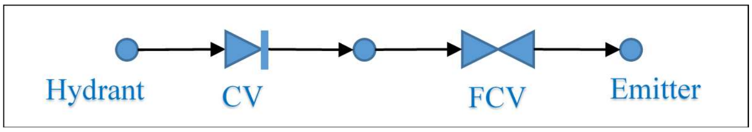


Fig. II-4. Setting of the added devices for each open hydrant in the PDA

When the PDA option is selected for assessing the performance of a PIDS, the hydraulic analysis module automatically adds the abovementioned devices to all open hydrants following the procedure describe in Abdy Sayyed et al. (2015):

1. Add two nodes near to each open hydrant in the network. Add a CV pipe with negligible resistance between the hydrant and the first added node to restrict the negative flows, i.e., the length of pipe is given a very small value of 0.001. Add an FCV between first and second added nodes.
2. Make the base demand at all open hydrants as zero.
3. Set the elevation of both added nodes same as that of the corresponding hydrant.
4. Set the valve settings for each FCV to the demand at the corresponding hydrant. This will restrict the hydrant discharge to the desired maximum.
5. The second added node is provided with emitter coefficient for the corresponding hydrant to simulate partial discharge condition. The module provides the option to set the emitter exponent to a single value for all hydrant or set different value for each hydrant.
6. The PDA is then performed where the hydrant is considered as a dead end. Consequently, for each hydrant, the resulting discharge is available at the emitter and the pressure at the hydrant.

II.4.3 Performance indicators

PIs are used to evaluate the hydraulic behaviour of a PIDS by quantifying its hydraulic reliability. In this module, four indicators are used in order to efficiently analyse the performance of the analysed PIDS:

Relative Pressure Deficit, RPD (Lamaddalena and Sagardoy, 2000): the actual pressure head for hydrant j (H_j) is compared with the minimum pressure ($H_{min,j}$), required at the same hydrant for an appropriate on-farm irrigation. Thus, the hydraulic performance for each hydrant j is obtained through the computation of the relative pressure deficit defined hereafter.

$$RPD_j = \frac{H_j - H_{min,j}}{H_{min,j}} \quad \text{Eq. II-8}$$

with the RPD, the range of variation of the pressure head at each hydrant is determined and consequently, the critical zones of the system are identified.

Reliability, Re (Lamaddalena and Sagardoy, 2000): it indicates the ability of a PIDS to provide an adequate level of service, referring to the pressure, to farmers under several operating conditions and within a pre-defined operation time. Hence, this indicator is calculated as the probability that the pressure at any hydrant in the network is at or above the minimum required pressure. Therefore, Re_j is calculated as the probability that the hydrant j is in a satisfactory state ($H_j \geq H_{min,j}$):

$$Re_j = \frac{N_{s,j}}{N_{o,j}} \quad \text{Eq. II-9}$$

where $N_{s,j}$ is the number of times the pressure at hydrant j is satisfied and $N_{o,j}$ is the total number of times where hydrant j is open.

During a DDA simulation of PIDSs, it is not possible to use PIs based on water demands delivered to farmers because the demands remain fixed, i.e., not dependent of pressure (Laucelli et al., 2012). Using PDA, two additional PIs were added to quantify demands deficit at hydrant and network levels. These were added to the module because they have a physical interpretation unlike the reliability based on pressure deficiencies.

Available Discharge Fraction ADF (Ozger and Mays, 2003): the available discharge at hydrant j ($q_{j,avl}$) is compared with the required discharge ($q_{j,req}$), at the same hydrant, set to meet the irrigation requirements at farm level. Hence, this indicator is used to estimate the fraction of the discharge that is actually delivered by hydrant j.

$$ADF_j = \frac{q_{j,avl}}{q_{j,req}} \qquad \textit{Eq. II-10}$$

Available Volume Fraction AVF_{net}: this indicator is used to assess the reliability of the entire irrigation network and is calculated as:

$$AVF_{net} = \frac{V_{act}}{V_{req}} \qquad \textit{Eq. II-11}$$

were V_{act} and V_{req} are the total volume of water actually supplied by the network and the total volume required to be supplied (m^3), respectively.

II.4.4 Assessment of the hydraulic performance

The assessment of the hydraulic behaviour of a PIDS can be accomplished using the hydraulic analysis module given the topology of the network, the geometry of the pipes, the discharges delivered by the hydrants and the required minimum pressure at these hydrants. When importing this information, from MS-Access® database, DESIDS uses the coordinates of each node to create shapefiles for all elements of the network and displays them in the integrated GIS environment (Fig. II-1).

The module analyses PIDSs under several operation scenarios. This is attained by either deterministic or random configurations of hydrants operating (open) simultaneously. The former is generated using the irrigation demand and scheduling module described above, while the latter is generated randomly by the hydraulic analysis module considering predefined upstream discharges (Fig. II-5). Thus, the total number of open hydrants in each configuration has to respect the following constraint:

$$\sum_{j=1}^{N_{hyd}} q_j \leq Q_{up} \qquad \textit{Eq. II-12}$$

where N_{hyd} is the total number of open hydrants, q_j is the nominal discharge of the hydrant j selected randomly, and Q_{up} is the upstream discharge at the head of the network.

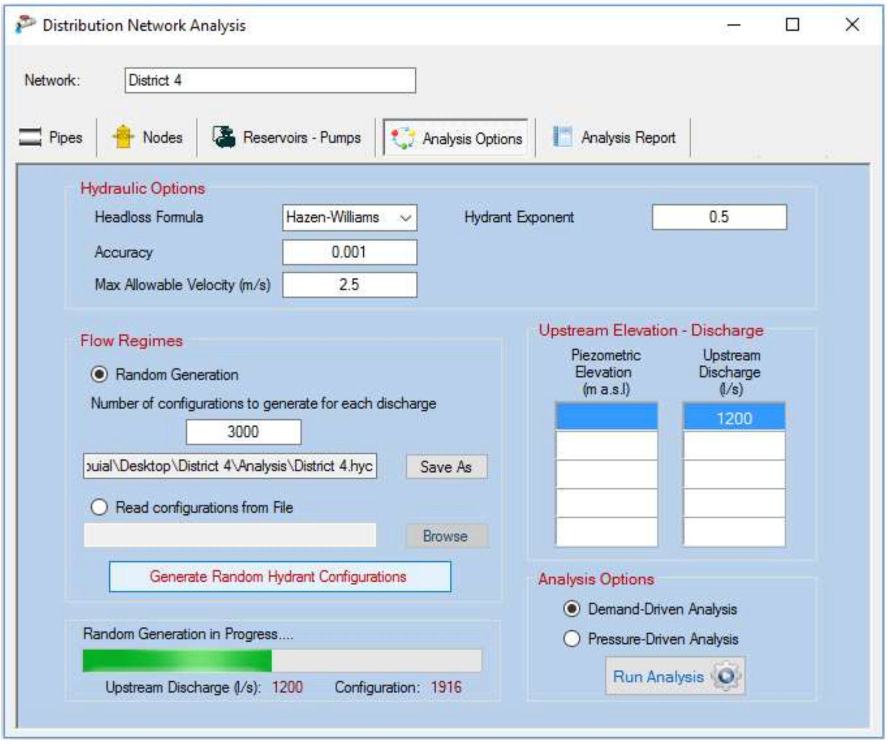


Fig. II-5. Hydraulic analysis module

When the operating hydrants scenarios are available (defined by a certain number of configurations N_{conf}), the user of DESIDS can run either a DDA or PDA according to the intended outcomes. That is if pressures at some hydrant fall below a minimum required level, the flow will be significantly reduced. In this case, PDA can be used to account for both pressure and demand deficiencies in the PIDS.

As abovementioned, the module uses EPANET toolkit for the analysis process. Therefore, to avoid calling the toolkit in each analysed configuration, the module automatically generates the input file for EPANET considering each configuration as a time step in an extended period simulation. The results of the analysis are then sorted and the generated PIs are presented in graphical and tabular forms to facilitate their interpretations. The process of the hydraulic analysis used in the module is presented in Fig. II-6.

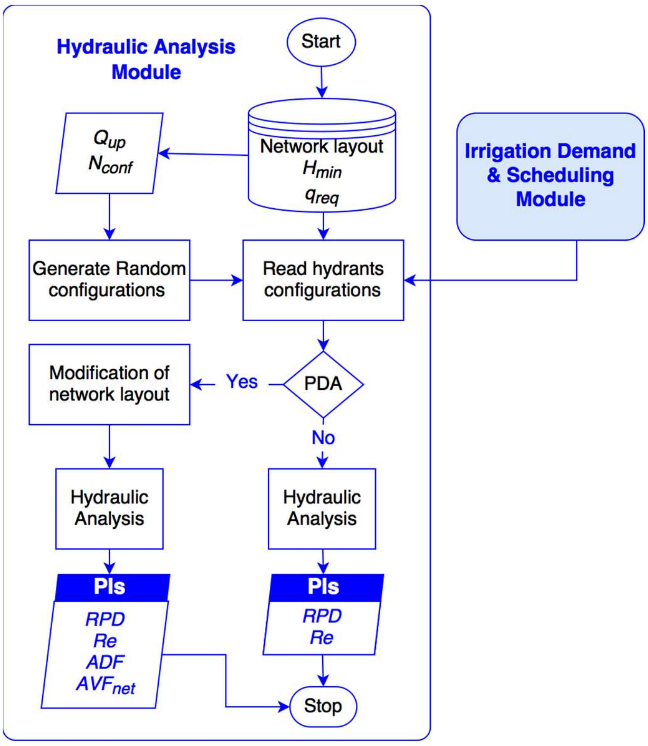


Fig. II-6. Flowchart of the hydraulic analysis module

II.5 Operation and management module

PIDSs are facing mounting burden to provide solutions to the increasing water demand at farm level. Therefore, the operation and management of these systems are crucial factors to achieve an efficient use of both, the available water and the capacity of the systems to deliver the necessary pressures and demands to meet the requirements of on-farm systems and crops.

When designing PIDSs operating on-demand, it is a common practice to calculate the probability of hydrants operation patterns using methods such that proposed by Clément (1966). However, the foremost challenge in managing these systems in actual situations is to identify ahead of time the flows into the networks' pipes, which are random and depend on the behaviour of farmers. In fact, even when the design flows are not exceeded, very low hydraulic performance can occur in these systems during their operation (Lamaddalena and Pereira, 2007).

To this end, the aim from developing the operation and management module is to provide irrigation district managers with a useful tool, which can be effectively used in finding solutions to PIDSs management under a wide range of scenarios. These solutions allow the improvement of the actual operation as well as the sustainability of these systems. Accordingly, this module offers optimal management strategies for PIDSs through the smooth transition to rotation delivery schedule for systems designed for on-demand when they are facing performance problems, especially during the peak irrigation demand periods. The module uses Genetic Algorithm (GA) for the optimization of irrigation periods taking into account, the minimization the pressure deficit at the most unfavourable hydrant as objective function (Fig. II-7).

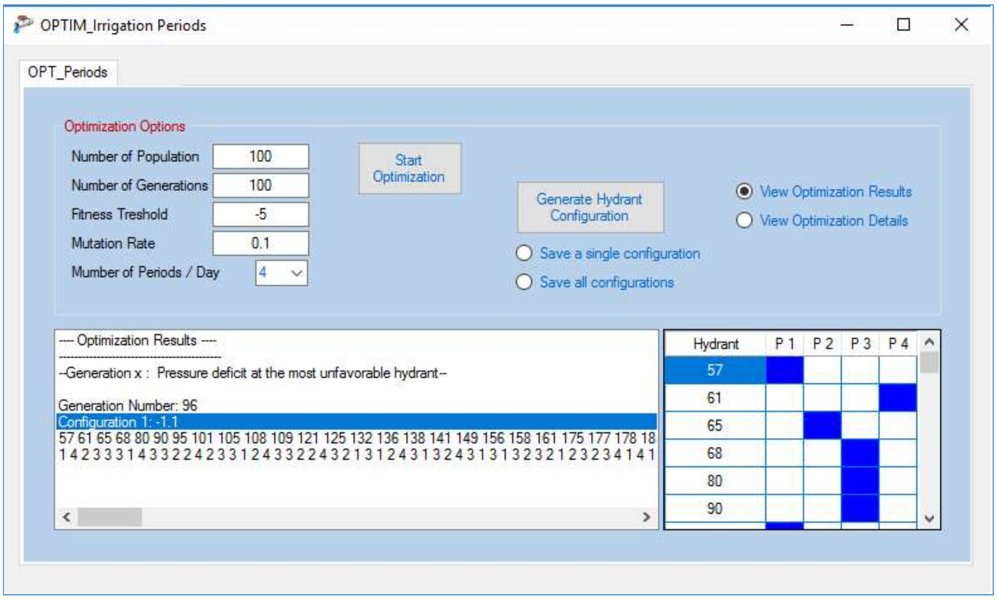


Fig. II-7. Optimization of irrigation periods

II.5.1 Genetic Algorithms

GAs (Goldberg, 1989) are powerful metaheuristic search methods used for solving both constrained and unconstrained optimization problems, based on a natural selection process that mimics natural evolution. They use the same combination of selection, recombination and mutation to evolve a solution to a problem. These methods have been applied to the solution of many optimization problems in WDSs (Farmani et al., 2007; Reca and Martínez, 2006; Savic and Walters, 1997), because of the easy use of their properties and their robustness in finding good solutions to difficult problems.

GAs start with a randomly generated initial population, i.e., a set of solutions represented by chromosomes, which evolves through three main operators: i) the selection, where chromosomes are selected from the population according to their fitness values to be parents; ii) crossover, where some genes from parent chromosomes are selected to create new offspring. This is done by randomly choosing one or more crossover point(s) where a pair of parent chromosomes exchange information; and iii) mutation, which changes randomly the new offspring to retain the diversity of the solution in a population and expand the search in the solution space.

II.5.2 Optimization of irrigation periods

The main objective from this module is to offer irrigation district managers a tool to obtain the optimal operation of PIDSs when the latter are facing performance problems. The optimization process is carried out using GA. The module starts with a population of randomly generated individuals (chromosomes), each representing a possible solution that has to be evaluated by means of the considered objective function, which is the minimization of the pressure deficit at the most unfavourable hydrant in the network. The number of variables (genes) within the individuals is determined by the number of open hydrants randomly generated while the values of these variables depend on the number of irrigation periods. In another word, each open hydrant is randomly assigned to an irrigation period. Therefore, the value of each variable ranges between 1 and the number of open hydrants.

The initial population is then evaluated by performing a hydraulic simulation, using the hydraulic analysis module, for each individual to obtain the pressure head of the open hydrants. The pressure deficit at the most unfavourable hydrant is then assigned to each individual and used as its fitness value. Based on their fitness, individuals with the lowest pressure head deficit (fitter solutions) are selected as parents and used to create new individuals (offspring) for the next generation. This is achieved through the processes of crossover and mutation. The crossover process implies that a pair of parent individuals exchange information in order to produce a pair of offspring individuals that inherit their characteristics. Herein, this process is done using a one-point crossover procedure, which entails that randomly selected pairs of parent individuals exchange information to produce offspring. The crossing point, that cuts both parent individuals at a point along the individuals, is selected by randomly generating an integer number from 1 to the number of variables. The mutation process, on the other hand, alters one or more variable values in an individual from its initial state.

With every new generation, the above processes are repeated and the algorithm stops either when an optimal solution has been reached or when the maximum number of generations has been achieved (Fig. II-8).

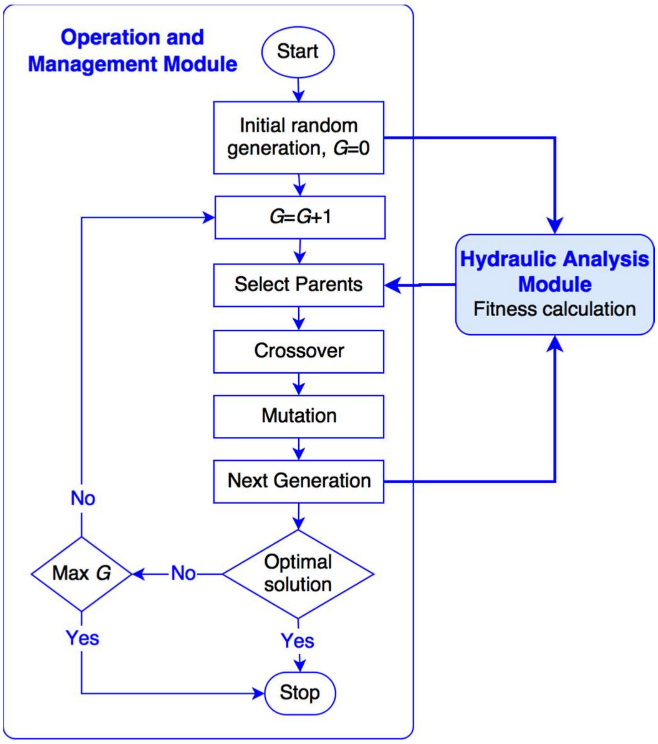


Fig. II-8. General flowchart of the operation and management module

II.6 Design and rehabilitation module

In some cases, improving the operation and management of PIDS alone does not considerably cause an improvement of networks' hydraulic performance unless combined with structural rehabilitation, especially if the systems' performance failures are related to initial design flaws. This rehabilitation must ensure the minimum performance levels required to satisfy farmers while considering the associated cost over an extended period. Therefore, for a DSS to be complete, it is imperative to include a module for structural rehabilitation and design. To this intent, an effective tool for developing rehabilitation plans for existing PIDS or the design of new ones was incorporated in DESIDS. This module uses non-dominated sorting genetic algorithm, NSGA II, for multi-objective optimization considering the minimization of both, pressure deficit at the most unfavourable hydrant and the rehabilitation cost. This algorithm was selected in this module for the optimization process because of its proven ability to efficiently search large decision spaces (Roshani and Filion, 2014).

This module also considers the introduction of localized loops to existing networks' layouts to increase their hydraulic capacity. This method was proposed by Lamaddalena et al. (2015) and Fouial et al. (2016) where it was tested on a real large scale irrigation network and proved its ability to significantly improve the hydraulic performance of the network while providing considerable savings in the cost of rehabilitation. However, finding the position of loops was not automatic and was done by trial and error, thus, extensive and time-consuming data entries and analyses were required. In this module, an innovative algorithm was developed to automatically finding the best looping locations in the network that can improve the overall hydraulic performance.

II.6.1 The non-dominated sorting genetic algorithm II

The NSGA-II (Deb et al., 2002) is one of the most popular Multi-objective evolutionary algorithms (MOEAs) used for the optimization of WDSs (Artina et al., 2012; Roshani and Filion, 2014; Wang et al., 2015). This is due to its efficient non-dominated sorting procedure and strong global elitism that preserves all elites from both the parent and child populations (Tanyimboh and Seyoum, 2016). The objective of the NSGA II algorithm is to improve the adaptive fit of a population of candidate solutions to a Pareto front constrained by a set of objective functions. This algorithm uses an evolutionary process with surrogates for evolutionary operators including selection, genetic crossover, and genetic mutation. The population is sorted into a hierarchy of sub-populations based on the ordering of Pareto dominance. Similarity between members of each sub-group is evaluated on the Pareto front, and the resulting groups and similarity measures are used to promote a diverse front of non-dominated solutions.

II.6.2 The multi-objective optimization of PIDS

The design and optimization module was developed primarily for the rehabilitation of existing PIDSs. If this is the objective of the decision maker using the module, then the layout of the network to be rehabilitated is considered known and all pipes in this case are predetermined based on the positions of existing pipes. The PIDSs rehabilitation is formulated as a bi-objective optimization problem with a selection of pipe diameters as the decision variables. The decision variables (pipes to be sized) and allowable selections for each decision variable (available pipe diameters and permissible range of pipe diameters for each section of the network) are identified. The developed algorithm is set in a way that some constraints are addressed at the beginning of the optimization procedure. First, considering the range of pipe diameters, available diameters for a specific section in the network is constrained to an upper and lower bound. The latter being the existing pipe diameter of the same section. In another word, the algorithm considers only a diameter that is equal or larger than the existing one. In the case where the design of a new network is considered, the initial pipes size can be set to zero which will be the lower bound for all pipes. Second, the algorithm ensures that all the solutions in the search space will respect the constraints that the pipe diameters of the upstream pipes are larger than those of the downstream ones.

The option of considering localized loops was included in the developed model. If this option is selected, the algorithm is set to automatically search for the best looping positions considering pre-defined conditions as illustrated in Fig. II-9. In the case of rehabilitation, the existing PIDS is analysed first, using the hydraulic analysis module as depicted in Fig. II-10. Then the developed algorithm in the design and rehabilitation module starts by generating a random initial population (individuals), respecting the abovementioned pipe constraints. Each individual is then assigned a value for each objective function (cost and pressure deficit). It is worth mentioning that the evaluation of individuals is obtained under extend period simulation mode, i.e. using the same hydrants configurations used in the initial hydraulic analysis of the existing network. The individuals are then sorted into fronts in a way that the solutions of the first front are not dominated by any other solutions in the population. Then, solutions of the second front are only dominated by solutions of the first front, and so on. Next, the solutions within each front are assigned a crowding distance, which gives a measure of how dense the front is in the vicinity of that solution (Deb et al., 2002). Subsequently, an offspring population is created by selecting individuals of the current population and performing the operations of crossover and mutation (respecting pipe constraints) to produce new solutions. When selecting solutions, individuals are compared by their front number giving preference to the lower numbered fronts. If two solutions are from the same front, then the solution with the greater crowding distance is chosen (Olsson et al., 2009). These processes are repeated until maximum number of generations has been reached.

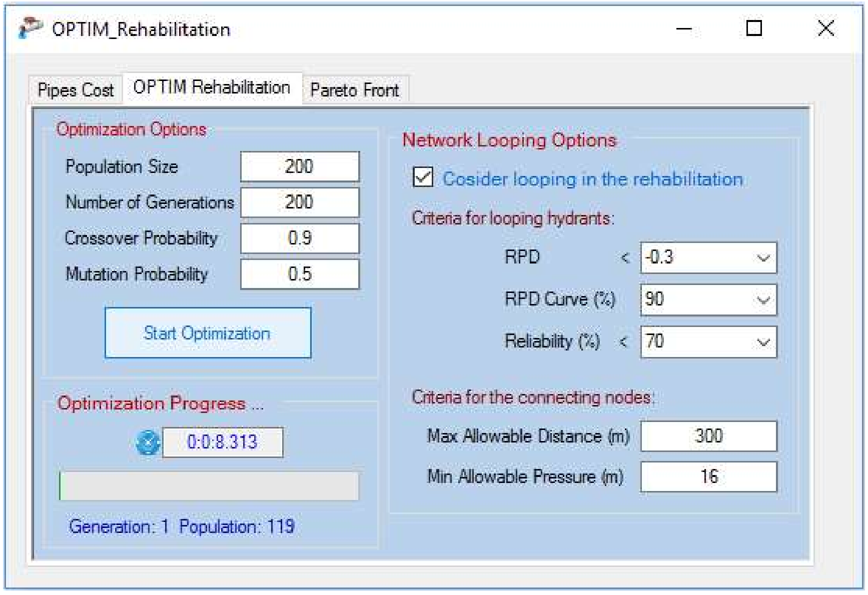


Fig. II-9. The optimization module in DESIDS

II.7 Conclusion

In the framework of this research, an integrated DSS called DESIDS was developed. The DSS, which encompasses four different modules, is an innovative tool to help irrigation district managers and decision makers in addressing the key issues and challenges often found in PIDSs, including planning, analysis, operation, and rehabilitation processes. Four discrete modules were developed in a decoupled fashion to maximize their use in the previously mentioned processes and to support future expansions and integrations in DESIDS. These modules are described in detail with diverse case study applications in the upcoming chapters, to explore different operation and management options available to irrigation managers and decision makers. It is evident that DESIDS is a useful technical tool, which can provide objective information to inform decision making on the actual and future decisions related to PIDSs.

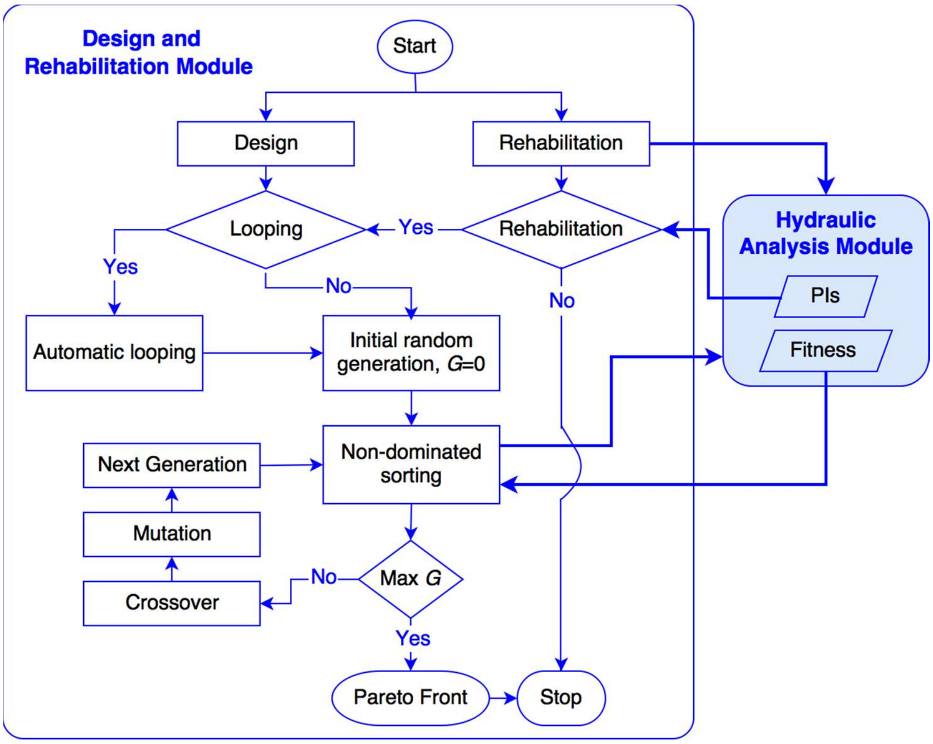


Fig. II-10. General flowchart for the design and rehabilitation module

II.8 References

Abdy Sayyed, M.A.H., Gupta, R., Tanyimboh, T.T., 2015. Noniterative application of EPANET for pressure dependent modelling of water distribution systems. Water Resour. Manage. 29, 3227-3242. doi:10.1007/s11269-015-0992-0

Aliod, R., González, C., 2008. A computer model for pipe flow irrigation problems, in: Garcia-Navarro, P., Playán, E. (Eds.), Numerical modelling of hydrodynamics for water resources. Proceedings of the Conference on Numerical Modelling of Hydrodynamic Systems. Taylor & Francis, London. pp. 293-313., Zaragoza, Spain, 18-21 June 2007., pp. 293-313.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - guidelines for computing crop water requirements. Food and Agriculture Organization of the United Nations, Rome, Italy.

Almiñana, M., Escudero, L.F., Landete, M., Monge, J.F., Rabasa, A., Sánchez-Soriano, J., 2010. WISCHE: A DSS for water irrigation scheduling. Omega 38, 492-500. doi:10.1016/j.omega.2009.12.006

Arsene, C.T.C., Gabrys, B., Al-Dabass, D., 2012. Decision support system for water distribution systems based on neural networks and graphs theory for leakage detection. Expert Systems with Applications 39, 13214-13224. doi:10.1016/j.eswa.2012.05.080

Artina, S., Bragalli, C., Erbacci, G., Marchi, A., Rivi, M., 2012. Contribution of parallel NSGA-II in optimal design of water distribution networks. Journal of Hydroinformatics 14, 310-323. doi:10.2166/hydro.2011.014

Clément, R., 1966. Calcul des débits dans les réseaux d'irrigation fonctionnant à la demande. La Houille Blanche, 553-576

D'Ercole, M., Righetti, M., Ugarelli, R.M., Berardi, L., Bertola, P., 2016. An integrated modeling approach to optimize the management of a water distribution system: Improving the sustainability while dealing with water loss, energy consumption and environmental impacts. Procedia Engineering 162, 433-440. doi:10.1016/j.proeng.2016.11.085

De Corte, A., Sörensen, K., 2013. Optimisation of gravity-fed water distribution network design: A critical review. European Journal of Operational Research 228, 1-10. doi:10.1016/j.ejor.2012.11.046

De Nys, E., Le Gal, P.-Y., Raes, D., Ana, E., 2008. WaDI (water delivery for irrigation): A simulation tool to address strategic interaction of water demand and supply in irrigation schemes. Agric. Water Manage. 95, 224-232. doi:10.1016/j.agwat.2007.10.005

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6, 182-197. doi:10.1109/4235.996017

Dias, N., Ferreira, N., Donnelly, A., 2014. Integration of modelling and monitoring to optimize network control: Two case studies from lisbon. Procedia Engineering 70, 555-562. doi:10.1016/j.proeng.2014.02.061

Estrada, C., González, C., Aliod, R., Paño, J., 2009. Improved pressurized pipe network hydraulic solver for applications in irrigation systems. Journal of Irrigation and Drainage Engineering 135, 421-430. doi:10.1061/(ASCE)IR.1943-4774.0000100

Farmani, R., Abadia, R., Savic, D., 2007. Optimum design and management of pressurized branched irrigation networks. Journal of Irrigation and Drainage Engineering 133, 528-537. doi:doi:10.1061/(ASCE)0733-9437(2007)133:6(528)

Fortes, P.S., Platonov, A.E., Pereira, L.S., 2005. GISAREG—A GIS based irrigation scheduling simulation model to support improved water use. Agric. Water Manage. 77, 159-179. doi:10.1016/j.agwat.2004.09.042

Fouial, A., Khadra, R., Daccache, A., Lamaddalena, N., 2016. Modelling the impact of climate change on pressurised irrigation distribution systems: Use of a new tool for adaptation strategy implementation. Biosystems Engineering 150, 182-190. doi:10.1016/j.biosystemseng.2016.08.010

Giustolisi, O., Berardi, L., 2009. Prioritizing pipe replacement: From multiobjective genetic algorithms to operational decision support. J. Water Resour. Plann. Manage. 135, 484-492. doi:10.1061/(ASCE)0733-9496(2009)135:6(484)

Giustolisi, O., Laucelli, D., Colombo, A.F., 2009. Deterministic versus Stochastic Design of Water Distribution Networks. J. Water Resour. Plann. Manage. 135. doi:10.1061/(ASCE)0733-9496(2009)135:2(117)

Giustolisi, O., Savic, D., Kapelan, Z., 2008. Pressure-driven demand and leakage simulation for water distribution networks. j. Hydraul. Eng. 134. doi:10.1061/(ASCE)0733-9429(2008)134:5(626)

Goldberg, D.E., 1989. Genetic algorithms in search, optimization and machine learning. Addison-Wesley Longman Publishing Co., Inc., USA.

Gorev, N., Kodzhespirova, I., 2013. Noniterative implementation of pressure-dependent demands using the hydraulic analysis engine of EPANET 2. Water Resour. Manage. 27, 3623-3630. doi:10.1007/s11269-013-0369-1

Kizito, F., Mutikanga, H., Ngirane-Katashaya, G., Thunvik, R., 2009. Development of decision support tools for decentralised urban water supply management in Uganda: An Action Research approach. Computers, Environment and Urban Systems 33, 122-137. doi:10.1016/j.compenvurbsys.2009.01.001

Labye, Y., 1981. Iterative discontinuous method for networks with one or more flow regimes, Proceedings of the International Workshop on Systems Analysis of Problems in Irrigation, Drainage and Flood Control, New Delhi, 30 November - 14 December, pp. 31-40.

Lamaddalena, N., Khadra, R., Fouial, A., 2015. Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig. Sci. 33, 453-468. doi:10.1007/s00271-015-0481-5

Lamaddalena, N., Pereira, L.S., 2007. Pressure-driven modeling for performance analysis of irrigation systems operating on demand. Agric. Water Manage. 90, 36-44. doi:10.1016/j.agwat.2007.02.004

Lamaddalena, N., Sagardoy, J.A., 2000. Performance analysis of on-demand pressurized irrigation systems. FAO Irrigation and Drainage Paper 59. Food and Agriculture Organization of the United Nations, Rome, Italy.

Laucelli, D., Berardi, L., Giustolisi, O., 2012. Assessing climate change and asset deterioration impacts on water distribution networks: Demand-driven or pressure-driven network modeling? Environmental Modelling & Software 37, 206-216. doi:10.1016/j.envsoft.2012.04.004

Lozano, D., Mateos, L., 2008. Usefulness and limitations of decision support systems for improving irrigation scheme management. Agric. Water Manage. 95, 409-418. doi:10.1016/j.agwat.2007.11.003

Mannini, P., Genovesi, R., Letterio, T., 2013. IRRINET: Large scale DSS application for on-farm irrigation scheduling. Procedia Environmental Sciences 19, 823-829. doi:10.1016/j.proenv.2013.06.091

Mateos, L., López-Cortijo, I., Sagardoy, J.A., 2002. SIMIS: the FAO decision support system for irrigation scheme management. Agric. Water Manage. 56, 193-206. doi:10.1016/S0378-3774(02)00035-5

Muranho, J., Ferreira, A., Sousa, J., Gomes, A., Marques, A.S., 2014. Pressure-dependent demand and leakage modelling with an EPANET extension – WaterNetGen. Procedia Engineering 89, 632-639. doi:10.1016/j.proeng.2014.11.488

Olsson, R.J., Kapelan, Z., Savic, D.A., 2009. Probabilistic building block identification for the optimal design and rehabilitation of water distribution systems. Journal of Hydroinformatics 11, 89-105. doi:doi:10.2166/hydro.2009.047

Ozger, S.S., Mays, L.W., 2003. A semi-pressure-driven approach to reliability assessment of water distribution networks, Proceedings of 30th IAHR Congress, Thessaloniki, Greece, pp. 345-352.

Pacchin, E., Alvisi, S., Franchini, M., 2016. Analysis of non-iterative methods and proposal of a new one for pressure-driven snapshot simulations with EPANET. water resour. Manage., 1-17. doi:10.1007/s11269-016-1511-7

Pereira, L.S., Teodoro, P.R., Rodrigues, P.N., Teixeira, J.L., 2003. Irrigation Scheduling Simulation: The Model Isareg, in: Rossi, G., Cancelliere, A., Pereira, L.S., Oweis, T., Shatanawi, M., Zairi, A. (Eds.), Tools for Drought Mitigation in Mediterranean Regions. Springer Netherlands, Dordrecht, pp. 161-180.

Reca, J., Martínez, J., 2006. Genetic algorithms for the design of looped irrigation water distribution networks. Water Resour. Res. 42, W05416. doi:10.1029/2005WR004383

Roshani, E., Filion, Y.R., 2014. Water distribution system rehabilitation under climate change mitigation scenarios in Canada. J. Water Resour. Plann. Manage. 141, 04014066. doi:10.1061/(ASCE)WR.1943-5452.0000450

Rossman, L.A., 2000. EPANET 2 users manual. National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, USA.

Savić, D.A., Bicik, J., Morley, M.S., 2011. A DSS generator for multiobjective optimisation of spreadsheet-based models. Environmental Modelling & Software 26, 551-561. doi:10.1016/j.envsoft.2010.11.004

Savic, D.A., Walters, G.A., 1997. Genetic algorithms for least-cost design of water distribution networks. J. Water Resour. Plann. Manage. 123, 67-77. doi:doi:10.1061/(ASCE)0733-9496(1997)123:2(67)

Siew, C., Tanyimboh, T.T., 2012. Pressure-Dependent EPANET Extension. water resour. Manage. 26, 1477-1498. doi:10.1007/s11269-011-9968-x

Sivakumar, P., Prasad, R.K., 2014. Simulation of water distribution network under pressure-deficient condition. water resour. Manage. 28, 3271-3290. doi:10.1007/s11269-014-0677-0

Smith, M., 1992. CROPWAT: A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper 46. Food and Agriculture Organization of the United Nations, Rome, Italy.

Tanyimboh, T.T., Seyoum, A.G., 2016. Multiobjective evolutionary optimization of water distribution systems: Exploiting diversity with infeasible solutions. Journal of environmental management 183, Part 1, 133-141. doi:10.1016/j.jenvman.2016.08.048

Tanyimboh, T.T., Templeman, A.B., 2010. Seamless pressure-deficient water distribution system model. Proceedings of the Institution of Civil Engineers - Water Management 163, 389-396. doi:10.1680/wama.900013

Todini, E., Pilati, S., 1988. A gradient algorithm for the analysis of pipe networks, in: Coulbeck, B., Orr, C.-H. (Eds.), Computer Applications in Water Supply: Systems Analysis and Simulation. Research Studies Press Ltd. , UK, pp. 1-20.

Urrestarazu, L.P., Díaz, J.A.R., Poyato, E.C., Luque, R.L., Jaraba, F.M.B., 2012. Development of an integrated computational tool to improve performance of irrigation districts. Journal of Hydroinformatics 14, 716-730. doi:10.2166/hydro.2012.074

Wang, Q., Creaco, E., Franchini, M., Savić, D., Kapelan, Z., 2015. Comparing low and high-level hybrid algorithms on the two-objective optimal design of water distribution systems. Water Resour. Manage. 29, 1-16. doi:10.1007/s11269-014-0823-8

CHAPTER III

Generating Hydrants' Configurations for Efficient Analysis and Management of Pressurized Irrigation Distribution Systems

III.1 Introduction

On-demand irrigation delivery schedule gives farmers the ability to control the frequency, rate and duration of irrigation. Thus, provides farmers with a high level of flexibility to better match their crop water needs with the amount of water delivered to farms. PIDSs are designed to offer this type of schedule taking into account the minimum required pressure needed to appropriately operate on-farm irrigation systems. However, in most cases, the pipe networks are designed with a constraint to deliver a maximum discharge at the upstream end of the system which does not always guarantee 100% simultaneity of hydrants' use (hydrants operating at the same time).

One of the most challenging uncertainties in the design of on-demand PIDSs is to know, a priori, the number and the position of hydrants in simultaneous operation, thus, the discharges flowing in each section of the network. A widely used probabilistic approach proposed by Clément (Clément, 1966) for the calculation of such discharges, has been contrasted in several studies that considered it appropriate for the design of on-demand irrigation networks (Granados et al., 2015). However, this approach does not permit to take into consideration the variety of flow regimes occurring in an irrigation system.

The occurrence of spatial and temporal variability of hydrants' simultaneity in relation to farmers' decision over time depends on different factors including the cropping pattern, crops grown, meteorological conditions, on-farm irrigation efficiency and farmers' behaviour (Lamaddalena and Sagardoy, 2000). The assumed factors at the design stage may change over time, increasing the demand uncertainties (Lamaddalena et al., 2012). Therefore, exceeding the design simultaneity (higher upstream discharge than the one presumed at the design stage) may occur. This will affect the performance of the distribution network, which may in return affects the performance of the on-farm systems and the yields of the irrigated crops. In fact, even when the simultaneity is not exceeded, hydrants may experience pressure and/or discharge failure depending on their position in the network and hydrants' simultaneity (Khadra and Lamaddalena, 2010; Lamaddalena et al., 2015).

In on-demand networks, the analysis of the performance is often carried out by generating random hydrants' opening to simulate different scenarios. However, the ability to forecast farmers' demand is fundamental to the real-time operational control of an on-demand water distribution system (Pulido-Calvo et al., 2003). For irrigation managers, given the ability to simulate hydrants' opening and the duration of use can greatly help with the prediction of the performance of the network throughout the irrigation season and thus, helps in the decision making for better management.

Many models and software are available to support decision making for water managers and farmers. Some of these models are limited to the calculation of CWRs and determination of irrigation scheduling such as CROPWAT (Smith, 1992), GISAREG ((Fortes et al., 2005) and WISCHE (Almiñana et al., 2010). Others are designed to simulate demand scenarios (hydrants opening) to be used for either the design of new irrigation distribution systems or for the analysis of existing ones.

Moreno et al. (2007) developed the Random Daily Demand Curve (RDDC) method, which generates scenarios for open hydrants during a day and in the peak period to calculate the flow at the main pipe. The probability of a hydrant opening was calculated by considering the irrigation characteristics of each irrigation plot, such as the number of irrigation subunits per plot, irrigation time depending on CWRs, network daily operating time and irrigation interval. This method was improved by Córcoles et al. (2016) to calculate the discharges from all pipes of the network, allowing the determination of the pressure at the pumping station required to guarantee a minimum pressure at the open hydrants.

Khadra and Lamaddalena (2006) developed the WINGENERA model based on the soil water balance for generating daily demand hydrographs for the whole irrigation season in an on-demand irrigation system. The model considers a deterministic component represented by the equation of soil water balance and a stochastic component function of the uncertainties linked to the sowing date of the crops, the initial water reserve and the farmer's management strategy. However, this model does not account for the hydraulic and physical limitations of the irrigation network. The HydroGEN model (Zaccaria et al., 2011) is based on the aforementioned model and simulates the soil water balance for each cropped field (under regulated and deficit irrigation scenarios) supplied by water delivery hydrants and generates the demand hydrographs both at the hydrant level and at the inlet of the distribution networks.

Rodríguez Díaz et al. (2007) also reported a simulation model based on water balance, taking into account farmers' practices, the irrigation systems on the farms, and any existing limitations such as flow rate. This model determines the flows that circulate in each section of a network for each period during the irrigation season, depending on the crop demand (the applied irrigation depth is constant and depends on the irrigation system) and irrigation practices.

The abovementioned models were developed to generate demands to be used in the design stage of irrigation distribution systems. Therefore, rely on many stochastic approaches related to the determination of variables such as planting dates, assigning hydrants to specific plots, used irrigation methods and hydrants opening time…etc. However, for existing networks, these approaches do not give water managers a lot of flexibly in controlling different known variables for determining these demands.

An on-demand network gives farmers the freedom to decide when and how much water to take from this network. However, irrigation managers have to be involved in monitoring the overall operations to ensure good performance of the network. Hence, the management of the network should be done with a coordinated process between the irrigation manager and the farmers. De Nys et al. (2008) proposed a simulation tool for open channels called WaDI (water delivery for irrigation). The model is dedicated to the relations between the manager's water supply and the farmers' demand. It is used for analysing infrastructure and organizational constraints in specific periods, hence, calculates water demand at the farm level on a weekly basis. Nevertheless, this tool simulates ''what-if'' scenarios providing flexibility and capacity to explore a large range of cases and potential solutions.

The objective of this work is to provide water managers with an effective tool that offers support for decision making to maintain satisfactory services to farmers. A prior knowledge of water deliveries to each hydrant, especially during the peak period, is a crucial information for water managers. This tool will hence, help them to understand the behaviour of the distribution network during failure conditions and take the proper decisions to improve the reliability of this network. The tool relies mostly on deterministic processes to be more representative of the actual situation. The only stochastic process can be the simulation of hydrants opening time as to keep the network operating on demand.

III.2 Methodology

III.2.1 Crop water requirements and irrigation scheduling

CWRs and irrigation scheduling are determined using the irrigation demand and scheduling module using climatic, crop and soil parameters. First, the daily ET_0 is calculated using the FAO-56 Penman–Monteith (Eq. II-1). ET_c is then determined by multiplying ET_0 by the crop coefficient K_c. it is worth mentioning that in this module, the planting dates for all crops are pre-defined by the user and not generated randomly to mimic the actual behaviour of the irrigation network. In addition, same crop can have different planting dates for different fields because not all farmers plant the same crop in the same day. CWRs are calculated then as the difference between ET_c and the effective rainfall (P_{eff}), which is estimated as 80% of the actual daily rainfall.

Concerning the determination of irrigation scheduling, net irrigation demands are estimated using daily soil water balance expressed in terms of depletion at the end of each day (Eq. II-4). The initial depletion can be derived from measured soil water content and has to be entered by the user of the module. The latter also takes into consideration that ET_c can be affected by water depletion from the root zone. Therefore, when depletion exceeds the readily available water (RAW), ET_c is reduced and adjusted using a water stress coefficient, k_s (dimensionless transpiration reduction factor). When the depletion is smaller than RAW, $k_s = 1$. Otherwise:

$$k_s = \frac{TAW - D_r}{TAW - RAW} \qquad \textit{Eq. III-1}$$

where TAW is the total available water in mm, which is governed by the type of soil and the rooting depth. The module allows allocating different type of soils for each crop to account for soil heterogeneity in farms.

Gross irrigation demand is then calculated by considering the on-farm irrigation efficiency. This efficiency is assigned, separately, to each specific crop since different crops can be irrigated with different type of irrigation even in the same farm. In addition, the module is set to permit the use of several irrigation management options for each specific crop (irrigate to field capacity, deficit irrigation and salt leaching, irrigate with fix interval, fixed irrigation depth…etc.), as farmers manage irrigation in different ways.

III.2.2 Generation of hydrants opening configurations

The process of generating hydrants' configurations (hydrants operating simultaneously) starts by allocating each crop to a specific hydrant in the distribution network. It should be noted that, hydrants are assigned to each field with a single crop and not to a farm, since farms can encompass more than one crop. Therefore, the module works with the assumption that farmers open hydrants to irrigate each crop separately.

Theoretically speaking, a hydrant can operate 24 hours a day in an on-demand network. However, if more than one field are to be irrigated by the same hydrant, then the hydrant operating time has to be adjusted accordingly, since hydrant are set to irrigate one field at a time. This is a realistic assumption as farmers sharing the same hydrant usually agree to use it at different time of the day if they have to irrigate in the same day. Accordingly, irrigation scheduling for the whole season is adjusted to deliver the maximum possible irrigation depth during the agreed-upon hours of the day.

The irrigation starting time can either be fixed or generated randomly to keep the simulated network operating on-demand. In this process, the day is divided into 5 windows of 4 hours, each window with a user pre-defined probability (proportional to its frequency of occurrence) that fits farmers' behaviour in the irrigation district. In fact, there are hours of the day where farmers prefer to irrigate, according to their commitments, customary, social conditions and availability of pressure at their hydrants (Khadra and Lamaddalena, 2006). Therefore, initially, a field (crop) is assigned to a time window randomly. Then, the irrigation starting time is randomly generated, with a uniform distribution, within this time window (4 hours) for the whole irrigation season. This approach is valid because even if the farmer prefers to start irrigation at a certain time of the day, irrigation will not start at the exact hour throughout the irrigation season.

III.2.3 Hydraulic Analysis

The purpose from generating hydrants configurations using the irrigation demand and schedule module is to provide district managers with deterministic data that can be used to efficiently analyse the PIDS. In this work, the generated data is used to perform both DDA and PDA. The aim is to explore the difference between the outputs of the two analyses and their effects on the decision making process. Three PIs are used for the hydraulic performance analyses namely *RPD* (Eq. II-8), *Re* (Eq. II-9) and *ADF* (Eq. II-10). The latter is only used in the PDA to measure the reliability of hydrants when taking into account the available discharges.

III.2.4 Case study

The abovementioned methodology was applied to an irrigation scheme served by District 1-a irrigation system in Southern Italy. The district receives water through a pumping station located upstream of a branched distribution network, equipped with 74 hydrants having a nominal discharge of 10 ls^{-1}, each supplying water to one or more cropped fields. The pumping station was designed to convey a peak discharge of 300 ls^{-1} and to ensure a constant pressure head of 65 m at the upstream end of the network. The layout of District 1-a system is depicted in Fig. III-1. This system is operated by a restricted-demand delivery schedule, in which all farmers take water at their convenience within the maximum allowed flow rate (nominal discharge) and not exceeding the maximum seasonal allocated shares out of the total water supply available from the dam. The system guarantees a minimum pressure of 20 m at each hydrant to satisfy the operation of on-farm irrigation systems. The scheme under study covers an area of about 212 ha, with the main irrigated crops being tomatoes (35%) and asparagus (30%). The cropping pattern of the scheme is detailed in Table III-1.

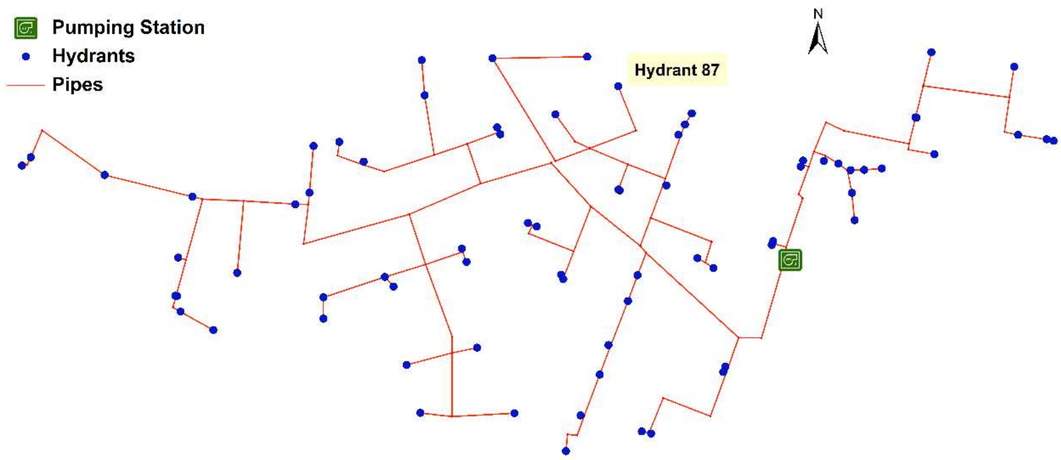


Fig. III-1. Layout of District 1-a system

Table III-1. Crop allocation in District 1-a

Crop	Area (ha)	Percentage
Tomato	74.5	35.2
Asparagus	62.6	29.6
Olive	21.5	10.2
Apple	14.6	6.9
Grapevine	11.5	5.4
Pepper	6.6	3.1
Peach	5.6	2.7
Soybean	5.2	2.4
Artichoke	4.3	2.0
Watermelon	4.1	1.9
Cherry	1.1	0.5
Total	**211.6**	**100.0**

III.3 Results and discussions

For irrigation district managers, the availability of a tool that can provide the ability to simulate hydrants' opening and their duration of use is vital for the prediction of the performance of the network throughout the irrigation season and thus, helps in the decision making for better management. Hence, it was important to develop a tool that links two of the modules incorporated in DESIDS, namely the irrigation demand and scheduling module and the hydraulic analysis module. The tool uses the outputs of the first module to generate configurations of the operating hydrants in a PIDS, to be used in the assessment of the hydraulic performance by means of the second module. This tool was tested on the case study of this work and the results are reported in the following sections.

III.3.1 Estimation of irrigation scheduling

Daily weather data for temperature, humidity, wind speed, and radiation were used for the calculation of ET_0. Subsequently, net irrigation requirements and irrigation scheduling were determined using the available crops and soil data. The irrigation scheduling for each crop is then assigned to a field in the irrigation scheme, served by the hydrants of District 1-a system.

The irrigation scheduling in each field, for the entire irrigation season, is adjusted taking into account the irrigated area of the field, the nominal discharge of the corresponding hydrant, and the maximum allowable irrigation time. The selection of opening times of each hydrant is the only stochastic process in the tool. In this work, the opening time was determined by dividing the day into five windows of four hours, each window with a user pre-defined probability (proportional to its frequency of occurrence) that fits farmers' behaviour in the irrigation district as depicted in Fig. III-2.

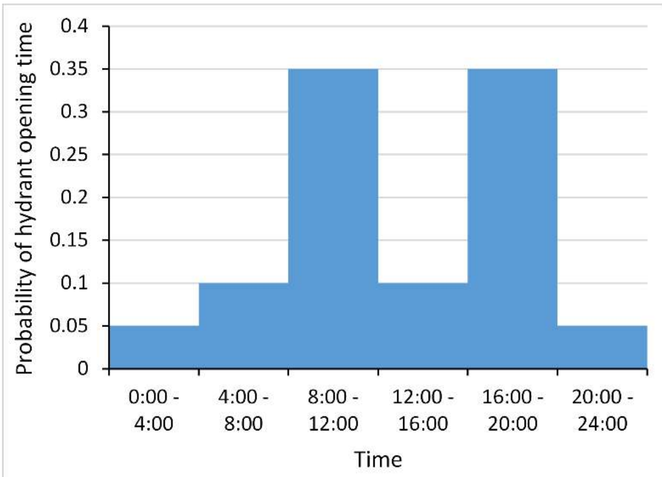


Fig. III-2. Probability of hydrant opening time

III.3.2 Generation of hydrants configurations

After the determination of irrigation scheduling for each field, the hourly operation of each corresponding hydrant is determined for the entire irrigation season. Using this data, the irrigation district manager can generate operating hydrants' configurations for the entire irrigation season or a specific period, particularly the peak demand period. The latter is determined using the moving average method depending on pre-defined number of days. This is achieved by calculating the daily irrigation volumes demanded at the upstream end of the delivery network.

Fig. III-3 shows how the developed tool calculates the daily volumes and sorts the outcome according to the average demand volume for 10 days periods. In this work, the 10 days peak demand period is identified to be between July 2 and July 11 with an average irrigation volume of 18900 m^3.

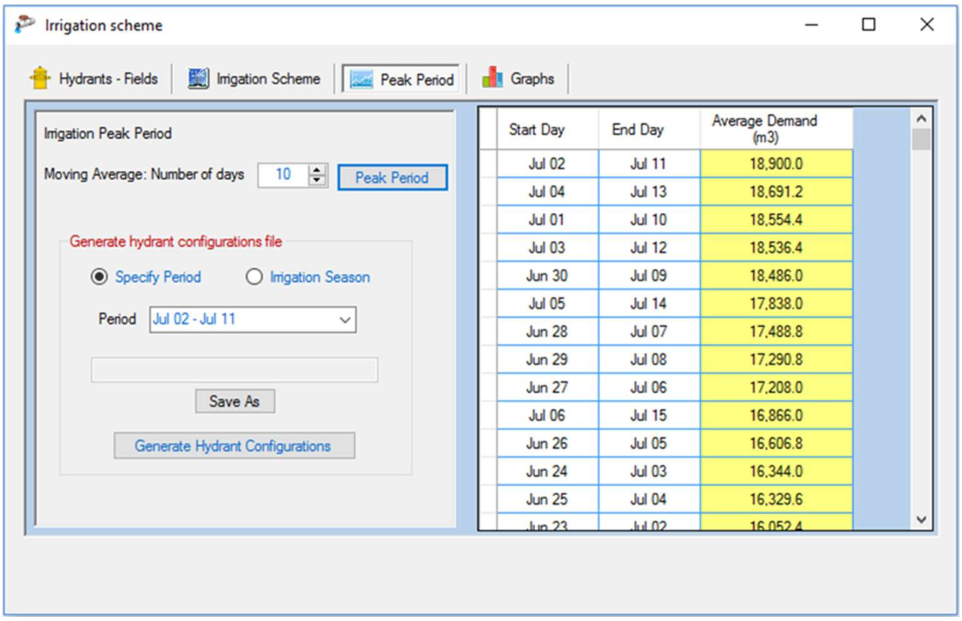


Fig. III-3. Determination of the peak period

It is important to mention that, finding the peak period using the average volumes is significantly affected by the selected length, i.e., number of days, of the peak period to be simulated. For instance, when calculating the volume on a daily basis, the system supplied a volume of 14112 m^3 on July 8, which is included in the 10 days peak period mentioned above. On the other hand, the daily volume recorded on May 20 amounts to 19548 m^3, ranking the fourth highest daily volume for the entire irrigation season. However, when considering a 10 days peak demand, this day is encompassed in the period between May 19 and May 28 with an average volume of 13496 m^3, which is ranked 37^{th} highest 10 days average volume. Hence, to extend the ability of the manager to explore all possible scenarios, the developed tool was set to provide high level of flexibility for a thorough assessment of the functionality of the system throughout the irrigation season.

Fig. III-4 illustrates the hourly water demand volumes as well as the hourly hydrants simultaneity recorded during the 10 days peak period determined above. It is shown that the hourly irrigation volumes supplied by the system in the district are concentrated in the second half of the day and particularly in the late afternoon, compared to relatively low demand in the early morning hours. This is confirmed by the typical farmers' behaviour in the area (Daccache et al., 2010). This information is vital for the district manager to take the appropriate decisions to deal with any unpredicted operation scenario of the system, which may cause insufficient discharge and pressure at hydrant level that may adversely affect the performance of the on-farm irrigation systems.

It should be noted that it is important to consider the hourly operation of all hydrants and not just the daily volumes. Since a high daily water demand does not necessarily entails negative effects on the hydraulic performance of the system. In other words, even if the demand volume recorded during a day is high, this volume may have been supplied evenly throughout the hours of the day. Contrarily, low daily volumes may cause performance problem if the supply is concentrated during few hours a day. For this reason, hourly hydrants simultaneity is calculated by the developed tool and displayed as depicted in Fig. III-4.

This tool provides irritation district managers with the option to track the progress of hydrants simultaneity every 15, 30 or 60 min time steps, throughout the irrigation season. This is extremely important because the simultaneity has great impact on the hydraulic performance of the system. Thus, this option helps managers to take appropriate decisions to avoid high simultaneity, which can be achieved, for instance, by using the operation and management module through the optimization of irrigation periods (Fouial et al., 2017).

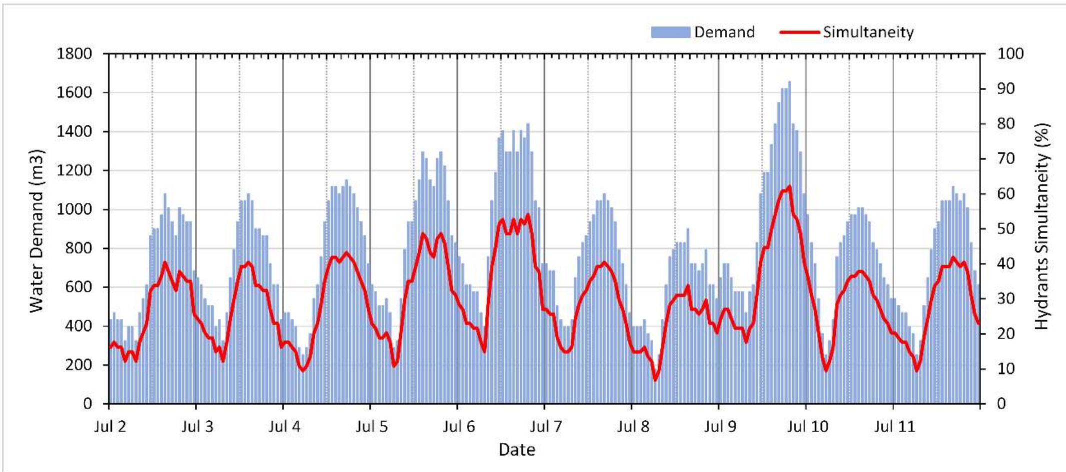


Fig. III-4. Water demand and hydrant simultaneity of the peak period

III.3.3 Hydraulic analysis

The purpose of generating hydrants configurations from irrigation scheduling is to realistically assess the hydraulic performance of PIDSs. The generated configurations, for the specified period, are saved to be used by the hydraulic analysis module in DESIDS. Two types of analyses can be carried out, DDA and PDA. The latter was added to the hydraulic analysis module to overcome the major drawback of the DDA, which is the failure to measure a partially failed network performance. In such cases, the DDA may produce very unrealistic results such as negative pressures. To shed the light on the importance of using PDA in PIDSs, the two analyses are performed for the peak demand day of the irrigation season, i.e. July 9 where the daily volume supplied by the system reached 24840 m^3 and the hydrants simultaneity topped 62%.

Fig. III-5 and Fig. III-6 display, respectively, the maximum *RPD* and reliability of all operating hydrants during the peak demand day. Both indicators show that in some hydrants, the values resulted from DDA demonstrate a greater hydraulic performance failure compared to the results of PDA. Hydrant 87 (highlighted in Fig. III-1) was selected to be studied in detail to compare the two analyses because it has the lowest performance in the network during the selected day. Even though the reliability of this hydrant is 0, i.e. failed to deliver the required pressure during all its operating hours, DDA resulted in a lowest *RPD* with a value of -1.1 compared to -0.5 for PDA. This is due to the fact that, DDA considers the required discharge at the hydrant fully supplied even if the pressure is lower than the minimum required. Therefore, the system is assumed to supply the full anticipated upstream discharge, which consequently leads to the overestimation of failures.

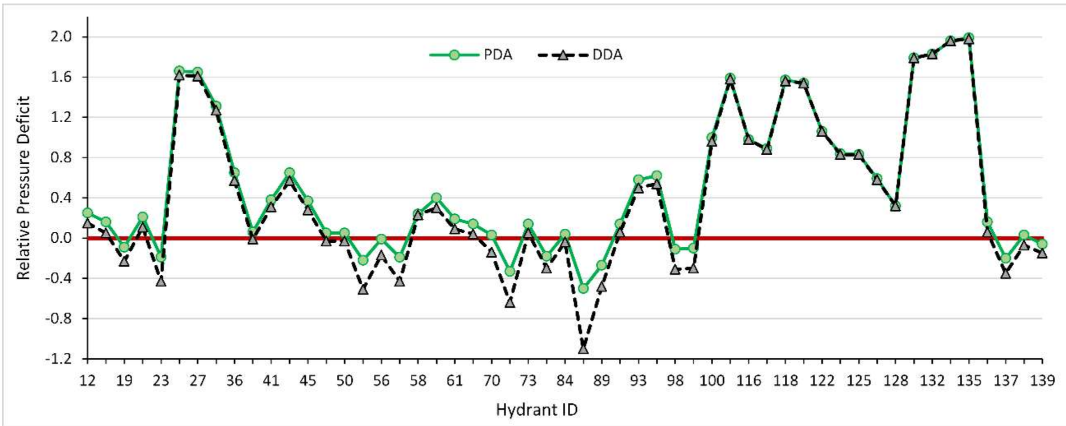


Fig. III-5. RPD indicator for DDA and PDA for the peak demand day

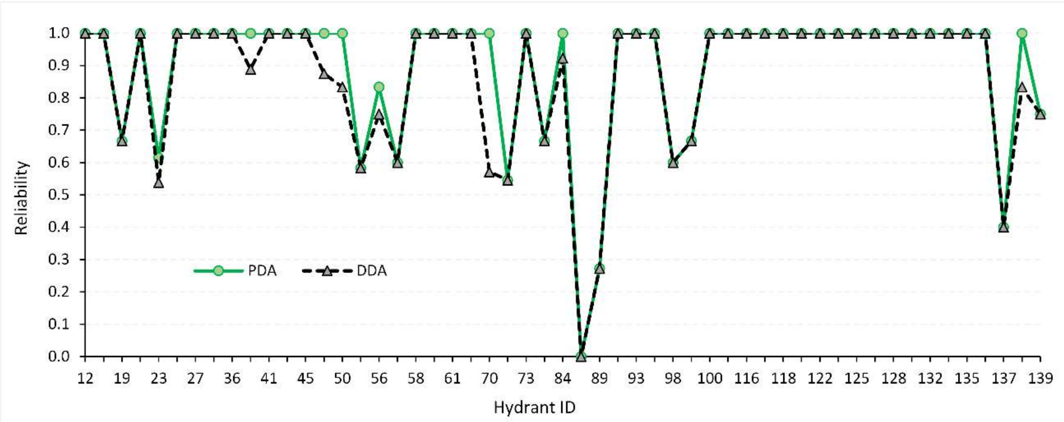


Fig. III-6. Reliability indicator for DDA and PDA for the peak day

On the other hand, PDA provides more realistic modeling of the hydraulic system since discharges are assumed to be driven by pressure. Hence, the actual upstream discharge of the system will be lower than the anticipated upstream discharge in the presence of pressure deficient hydrants. This is illustrated in Fig. III-7, which shows the influence of the available pressure at hydrant 87 on the discharge for both DDA and PDA. It is demonstrated that in the case of DDA, it is assumed that the required discharge at the hydrant is fulfilled while the pressure is lower than the minimum required, i.e. 20 m. in this case the magnitude of the failure in overestimated resulting in negative pressure between 17:00 and 19:00. Conversely, in PDA, the discharge of the hydrant fluctuates depending on the available pressure. This has resulted in much lower pressure deficit compared to DDA. For instance, at 19:00, PDA recorded a pressure deficit of 10 m, which resulted in a discharge of 7 ls^{-1}, i.e. lower than the required 10 ls^{-1}. Whereas DDA recorded a pressure deficit 22 m (negative pressure) while providing the required discharge of 10^{-1}.

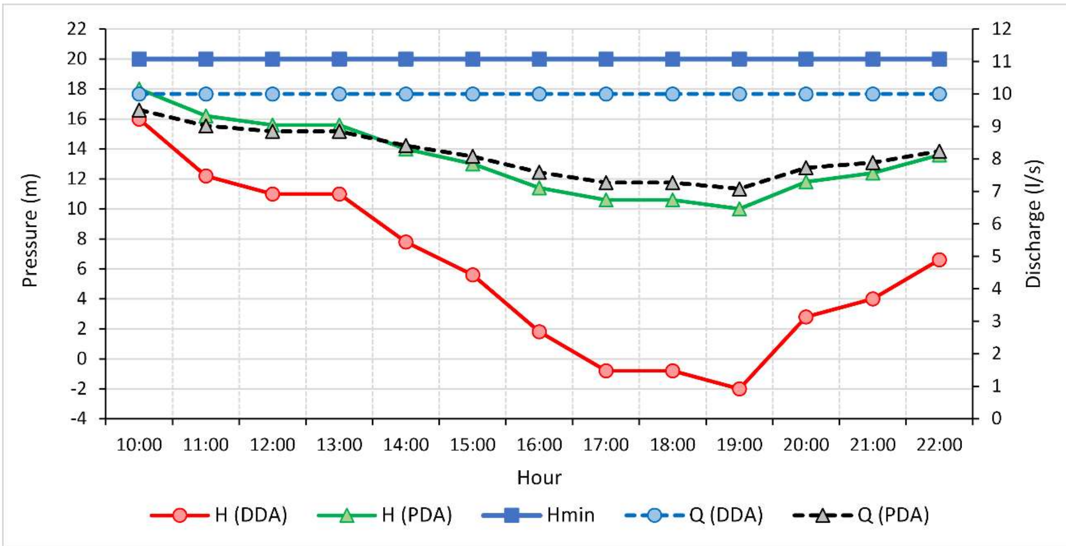


Fig. III-7. Pressure and discharge at hydrant 87 resulted from DDA and PDA

In PIDSs operation, the goal of the irrigation district manager is to guarantee farmers, served by the distribution system, the minimum pressure required for appropriate operation of on-farm systems and the required discharge to meet irrigation demand. The latter is an important issue that is usually ignored when dealing with the hydraulic analysis of PIDSs. The PDA used in the hydraulic analysis module provides an additional indicator, namely *ADF*, used to assess the reliability of the hydrant to deliver the required discharge. Fig. III-8 illustrates the available discharge fraction at hydrant 87 during its operation in the peak demand day. *ADF* is shown to vary between 0.7 and 0.95 for this hydrant between 10:00 and 22:00. During the 13 hours operation, only 81% of the required volume of irrigation water was supplied by this hydrant, i.e. a deficit of 87 m^3. This information is useful to estimate the impact of the reliability of the hydrant to deliver the expected demand throughout the irrigation season and to estimate potential crops yield reduction.

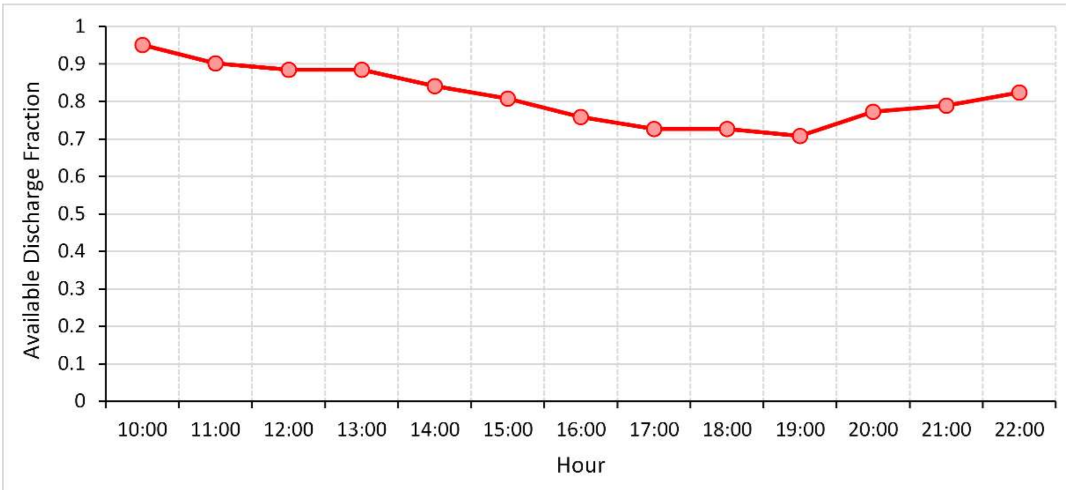


Fig. III-8. ADF resulted from PDA of the peak demand day

III.4 Conclusion

During peak demand periods, the discharge flowing in the system may exceed the design discharge of the system, causing insufficient pressure head at the hydrant level, which can adversely affect the discharges supplied for irrigation. In this work, DESIDS was used to analyse an existing PIDS by generating realistic hydrants configuration. A tool was developed to link two of its incorporated modules, namely the irrigation demand and scheduling module and the hydraulic analysis module. The tool generates operating hydrants configurations, with 15, 30 or 60 minutes time steps, by estimating the irrigation scheduling for each field served by the considered PIDS, using climatic, crop and soil data. Hence, provides irrigation district managers with great flexibility and the ability to assess the operation of PIDSs at any period during the irrigation season. This is achieved by performing either DDA or PDA. This work has shown that using the latter is vital to determine not just pressure deficiencies in the network but also the impact of these deficiencies on the supplied discharges from hydrants. Thus, it estimates the potential negative impact of the overall performance of the PIDS on crops yield. This information is imperative as it gives irrigation district managers the ability to extend the management of the PIDS beyond the distribution structure and understand the real effect of their decisions on crops yield, thus farmers income.

III.5 References

Almiñana, M., Escudero, L.F., Landete, M., Monge, J.F., Rabasa, A., Sánchez-Soriano, J., 2010. WISCHE: A DSS for water irrigation scheduling. Omega 38, 492-500. doi:10.1016/j.omega.2009.12.006

Clément, R., 1966. Calcul des débits dans les réseaux d'irrigation fonctionnant à la demande. La Houille Blanche, 553-576

Córcoles, J.I., Tarjuelo, J.M., Moreno, M.A., 2016. Methodology to improve pumping station management of on-demand irrigation networks. Biosystems Engineering 144, 94-104. doi:10.1016/j.biosystemseng.2016.02.002

Daccache, A., Lamaddalena, N., Fratino, U., 2010. Assessing pressure changes in an on-demand water distribution system on drip irrigation performance—case study in Italy. Journal of Irrigation and Drainage Engineering 136, 261-270. doi:doi:10.1061/(ASCE)IR.1943-4774.0000170

De Nys, E., Le Gal, P.-Y., Raes, D., Ana, E., 2008. WaDI (water delivery for irrigation): A simulation tool to address strategic interaction of water demand and supply in irrigation schemes. Agric. Water Manage. 95, 224-232. doi:10.1016/j.agwat.2007.10.005

Fortes, P.S., Platonov, A.E., Pereira, L.S., 2005. GISAREG—A GIS based irrigation scheduling simulation model to support improved water use. Agric. Water Manage. 77, 159-179. doi:10.1016/j.agwat.2004.09.042

Fouial, A., Fernández García, I., Bragalli, C., Brath, A., Lamaddalena, N., Rodríguez Diaz, J.A., 2017. Optimal operation of pressurised irrigation distribution systems operating by gravity. Agric. Water Manage. 184, 77-85. doi:10.1016/j.agwat.2017.01.010

Granados, A., Martín-Carrasco, F.J., García de Jalón, S., Iglesias, A., 2015. Adaptation of irrigation networks to climate change: Linking robust design and stakeholder contribution. Spanish Journal of Agricultural Research 13. doi:10.5424/sjar/2015134-7549

Khadra, R., Lamaddalena, N., 2006. A Simulation Model to generate the Demand Hydrographs in Large-scale Irrigation Systems. Biosystems Engineering 93, 335-346. doi:10.1016/j.biosystemseng.2005.12.006

Khadra, R., Lamaddalena, N., 2010. Development of a decision support system for irrigation systems analysis. Water Resour Manage 24, 3279-3297. doi:10.1007/s11269-010-9606-z

Lamaddalena, N., Khadra, R., Fouial, A., 2015. Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig Sci 33, 453-468. doi:10.1007/s00271-015-0481-5

Lamaddalena, N., Khadra, R., Tlili, Y., 2012. Reliability-based pipe size computation of on-demand irrigation systems. Water Resour Manage 26, 307-328. doi:10.1007/s11269-011-9919-6

Lamaddalena, N., Sagardoy, J.A., 2000. Performance analysis of on-demand pressurized irrigation systems. FAO Irrigation and Drainage Paper 59. Food and Agriculture Organization of the United Nations, Rome, Italy.

Moreno, M., Planells, P., Ortega, J., Tarjuelo, J., 2007. New methodology to evaluate flow rates in on-demand irrigation networks. J. Irrig. Drain Eng. 133, 298-306. doi:doi:10.1061/(ASCE)0733-9437(2007)133:4(298)

Pulido-Calvo, I., Roldán, J., López-Luque, R., Gutiérrez-Estrada, J.C., 2003. Demand Forecasting for Irrigation Water Distribution Systems. J. Irrig. Drain Eng. 129, 422-431. doi:10.1061/(ASCE)0733-9437(2003)129:6(422)

Rodríguez Díaz, J., Camacho Poyato, E., López Luque, R., 2007. Model to forecast maximum flows in on-demand irrigation distribution networks. Journal of Irrigation and Drainage Engineering 133, 222-231. doi:doi:10.1061/(ASCE)0733-9437(2007)133:3(222)

Smith, M., 1992. CROPWAT: A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper 46. Food and Agriculture Organization of the United Nations, Rome, Italy.

Zaccaria, D., Lamaddalena, N., Neale, C.M.U., Merkley, G.P., Palmisano, N., Passarella, G., 2011. Simulation of peak-demand hydrographs in pressurized irrigation delivery systems using a deterministic–stochastic combined model. Part I: model development. Irrig Sci, 1-16. doi:10.1007/s00271-011-0317-x

CHAPTER IV

OPTIMAL OPERATION OF PRESSURISED IRRIGATION DISTRIBUTION SYSTEMS OPERATING BY GRAVITY*

IV.1 Introduction

In on-demand irrigation networks, farmers are provided with high level of flexibility, because they have the freedom to decide when and how much water to withdraw from an irrigation distribution network to meet their crop water needs (Lamaddalena and Sagardoy, 2000). On the other hand, in irrigation distribution networks operating on-rotation delivery schedule, the operating time is divided into periods or turns. Farmers are then organized in groups where they are enabled a few hours every day to irrigate. These types of networks have a lower investment cost compared to on-demand ones, but they limit the flexibility of irrigation for farmers.

PIDNs are designed so that the pressure at the most unfavourable hydrant is equal or higher than the established minimum pressure required to properly operate the on-farm irrigation systems. However, the actual operating conditions of these systems can be different from those assumed at the design stage. Indeed, the selected on-farm irrigation systems, management decisions and changes in farmers practices and behaviour, may alter the required pressure at each hydrant (Kanakis et al., 2014). In addition, on-farm irrigation scheduling highly affects the simultaneity of hydrants' operation and hence the hydraulic performance of the PIDN (Salvador et al., 2011).

A major challenge in managing irrigation networks operating on-demand is to know beforehand the flows into the networks' pipes, which are random and depend on the number and location of hydrants operating simultaneously (Daccache et al., 2010b). As a result, large spatial and temporal variability of flow regimes occurs, which may produce failures related to the design

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options. In fact, even when the design flows are not exceeded (meet the design simultaneity), very low hydraulic performance can occur in these networks during their operation (Lamaddalena and Pereira, 2007).

To cope with the abovementioned problems, irrigation district managers tend to switch to restricted schedule during the peak period. This action can improve the hydraulic performance of the irrigation system and reduce energy consumption (Jiménez-Bello et al., 2015). Indeed, the replacement of open channel distribution systems with PIDNs has significantly improved conveyance efficiency, but resulted in high energy consumption (Rodríguez Díaz et al., 2011). With the significant increase in energy costs in recent years, many authors have focused their research on energy savings in irrigation distribution systems (Fernández García et al., 2016b; Jiménez-Bello et al., 2011; Khadra et al., 2016; Moreno et al., 2010; Rodríguez Díaz et al., 2009). They concluded that grouping hydrants into sectors (considering their homogeneous energy use and organizing farmers in irrigation turns) is one of the most efficient strategies for decreasing energy consumption, especially during the peak period.

However, the absence of available management tools to select the configurations of open hydrants makes irrigation networks operating on-rotation or restricted schedule more prone to inefficient management (Moreno et al., 2010). To this end, different methods have been developed to optimize the grouping of hydrants into sectors, using energy saving as objective function (Carrillo Cobo et al., 2011; García-Prats et al., 2012). Conversely, there is a lack of attention concerning studies focusing of the optimal management of on-demand systems operating by gravity to improve their hydraulic performance. Lamaddalena et al. (2015) proposed the use of localized loops for the rehabilitation of an existing on-demand network operating by gravity in Italy. The method has shown to improve the performance of the network (Fouial et al., 2016). However, it does not consider the approach of restricted schedule as a solution.

The problem of finding the optimal operating strategy of irrigation distribution networks can be complex. For this reason, heuristic approaches such as GA (Goldberg, 1989) are used when solving this sort of problems. GAs have been successfully used in irrigation distribution networks' design and rehabilitation (Fernández García et al., 2016a; Murphy et al., 1998; Reca and Martínez, 2006), as well as operation and management (Fernández García et al., 2013; González Perea et al., 2016).

The aim of this work is to propose an optimal management tool for proper operation of gravity-fed PIDNs designed for on-demand delivery schedule. A GA has been developed and used to minimize the pressure deficit at the most unfavourable hydrant, during the peak period. The tool has been tested on a real gravity-fed network operating on-demand, located in Southern Italy.

IV.2 Methodology

In this study, the estimation of irrigation requirements was attained using the irrigation demand and scheduling module, while the hydraulic analysis was carried out using the hydraulic analysis module. A third module, the operation and management module has been developed in the framework of this study and incorporated in DESIDS. This module was used for the optimization of irrigation time and periods, using GA, to improve the hydraulic performance of the distribution network. Finally, the behaviour of the hydraulic network, according to the new management, has been evaluated using PIs. The developed tool as well as the results obtained from the optimization process are described in the upcoming sections. Fig. IV-1 shows the general structure of DESIDS including the optimization algorithm.

IV.2.1 Irrigation water requirements

CWRs in the study area are calculated using irrigation demand and scheduling module, based on the potential evapotranspiration of crops and the effective rainfall contribution. Using the cropping pattern of the irrigation district, the weighted average gross water requirements for the peak month are estimated. Then the irrigation time, $t_{irr,j}$ (hour), for hydrant j is calculated by:

$$t_{irr,j} = \frac{I_j A_j}{0.36 q_j} \qquad \textit{Eq. IV-1}$$

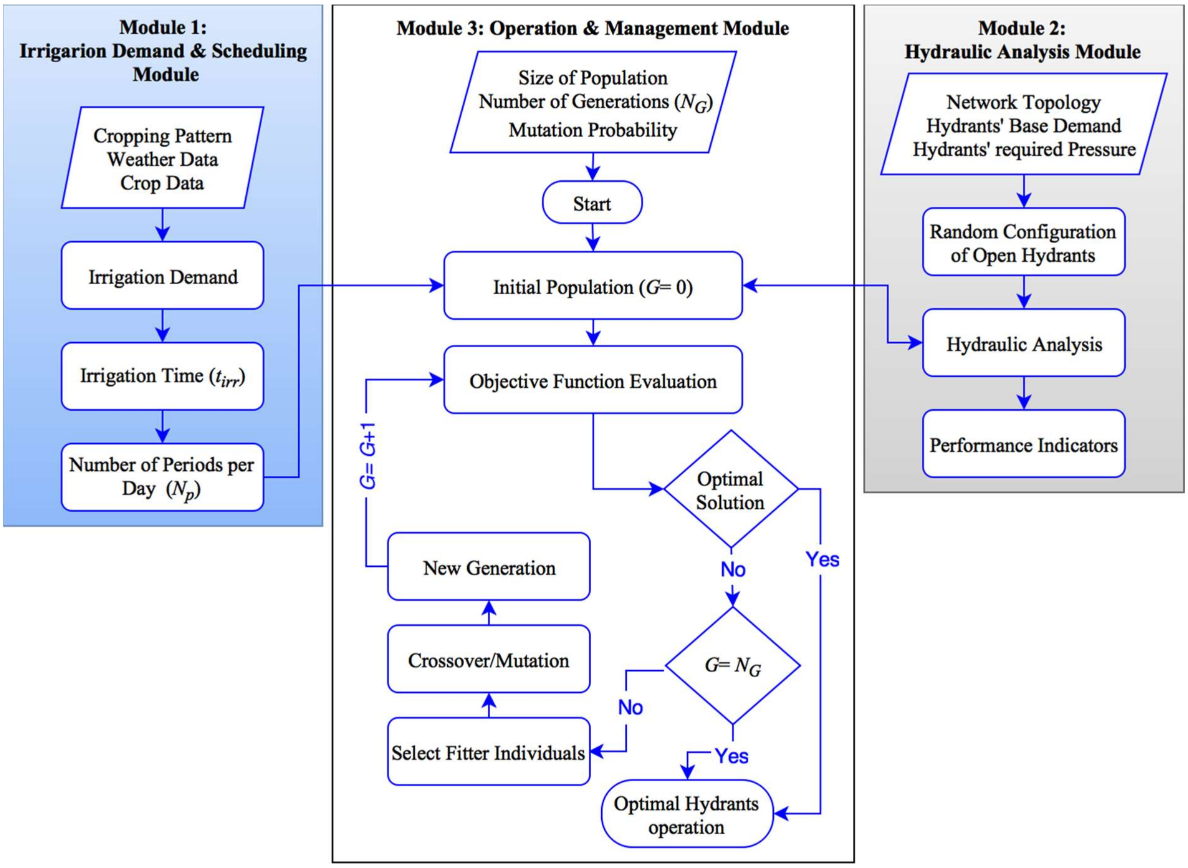

Fig. IV-1. Optimization of irrigation periods using DESIDS

where 0.36 is a units adaptation coefficient, I_j is the irrigation depth (mm/day), q_j is the nominal discharge of hydrant j (ls^{-1}), and A_j is the area irrigated by hydrant j (ha). The number of irrigation periods (turns) considered during the day depends on the calculated irrigation time. Thus, the longer the irrigation time, the lower the number of periods.

IV.2.2 Hydraulic Analysis

The hydraulic analysis of the network is carried out by generating a number of random configurations (hydrants simultaneously opened), in a way that the sum of the discharges of all the opened hydrants is equal to a predefined upstream discharge (Eq. II-12). Hence, the number of randomly open hydrants depends on the nominal discharge of these hydrants and the upstream discharge.

Within each generated configuration, a cloud of points can be plotted, representing the *RPD* at each hydrant. The cloud of points is enclosed between a lower and an upper envelope indicating the range of possible pressures for each hydrant in the network. Intermediate envelopes are also possible to define. For example, the reported 90% envelope shows the *RPD* when excluding the 10% of less favourable cases. These envelopes are useful to identify both, the failing hydrants and the degree of failure. Reliability of each hydrant and the pressure equity are also calculated in the analysis.

IV.2.3 Irrigation periods optimization

The main objective of this work is to offer irrigation district managers a tool to obtain the optimal operation of gravity-fed irrigation distribution networks when the latter are facing performance problems. The optimization process is carried out by a new tool using GA, which is a method for solving optimization problems based on a natural selection process that mimics biological evolution (Goldberg, 1989). As shown in Fig. IV-1, the tool starts with a population of randomly generated individuals (chromosomes), each representing a possible solution that has to be evaluated by means of the considered objective function. In this case, the objective function of the minimization of pressure deficit at the most unfavourable hydrant in the network has been considered. The number of variables (genes) within the individuals is determined by the number of open hydrants randomly generated while the values of these variables depend on the number of irrigation periods, N_p, considered (calculated according to irrigation time). In another word, each open hydrant is randomly assigned to an irrigation period. Therefore, the value of each variable ranges between 1 and N_p.

The initial population is then evaluated by performing a hydraulic simulation, using the hydraulic analysis module, for each individual to obtain the pressure head of the open hydrants. The pressure deficit at the most unfavourable hydrant is then assigned to each individual and used as its fitness value. Based on their fitness, individuals with the lowest pressure head deficit (fitter solutions) are selected as parents and used to create new individuals (offspring) for the next generation. This is achieved through the processes of crossover and mutation. The crossover process implies that a pair of parent individuals exchange information in order to produce a pair of offspring individuals that inherit their characteristics. Herein, this process is done using a one-point crossover procedure, which entails that randomly selected pairs of parent individuals exchange information to produce offspring. The crossing point, that cuts both parent individuals at a point along the individuals, is selected by randomly generating an integer number from 1 to the number of variables. The mutation process, on the other hand, alters one or more variable values in an individual from its initial state.

With every new generation, the above processes are repeated and the algorithm stops either when an optimal solution has been reached or when the maximum number of generations has been achieved. The population size, the number of generations and the mutation probability are input parameters.

IV.2.4 Performance assessment

In this work, PIs are used to evaluate the behaviour of the PIDN under study, for the actual operation situation and the network's operation after the optimization of irrigation periods. In addition to RPD (Eq. II-8) and Re (Eq. II-9), Pressure Equity, PE (Urrestarazu et al., 2009) is used to assess the distribution of pressure head in the network using the interquartile ratio, which relates the average pressure head in the poorest quarter, $\overline{P_{pq}}$, and the average pressure head in the best quarter, $\overline{P_{bq}}$.

$$PE = \frac{\overline{P_{pq}}}{\overline{P_{bq}}} \qquad \text{Eq. IV-2}$$

IV.3 Case Study

The study is conducted on District 4 of the Sinistra Ofanto Irrigation Scheme (Fig. IV-2), located in the Northern Apulia region (Southern Italy). The district is equipped with 658 hydrants, served by an on-demand pressurized irrigation distribution network operated by gravity. All farm hydrants were designed to provide a discharge of 10 ls^{-1} and a service pressure of 20 m. The upstream discharge in the district is limited to the design criteria of the network. Therefore, only a certain number of hydrants can operate at the same time without affecting the hydraulic performance of the network. From the design data, the considered peak continuous flow rate was 0.327 $ls^{-1}ha^{-1}$, when referred to the effectively irrigated area (Lamaddalena, 1997). This value corresponds to a Clément discharge (Clément, 1966) of 1160 ls^{-1}, calculated using COPAM, or a hydrants simultaneity of about 18%. The Clément discharge is based on a probabilistic approach where, within a population of hydrants, the number of hydrants being open simultaneously is considered to follow a binomial distribution.

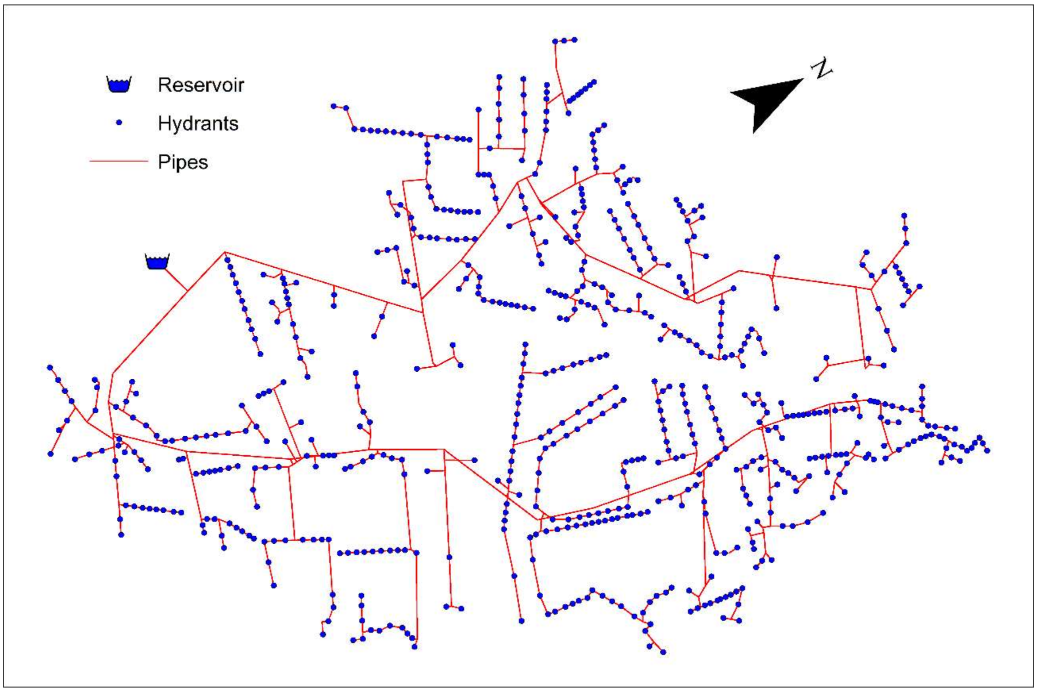

Fig. IV-2. Layout of District 4 irrigation distribution network

Water in the district is delivered through a compensating reservoir with a daily upstream storage capacity of 28,000 m^3 and receives water from a conveyance pipe originating from a dam. The reservoir has maximum and minimum water levels of 143 and 139 m a.s.l., respectively. District 4 network was designed in 1975 for on-demand operation using conventional optimization techniques but, over time, failures related to the design options were observed. These failures are associated either with pressures and discharges at the hydrants, or with water delivery schedules which, often, have to be modified from on-demand into arranged demand, especially during peak periods (Lamaddalena, 1997). Table IV-1 summarizes the cropping pattern of the district, which includes mostly vineyards (63%) and olive orchards (20%).

Table IV-1. Crops allocation in District 4

	Irrigated area (ha)	Proportion from the total irrigated area (%)
Grapevine	1326	63.4
Olive	425	20.3
Fruit trees	71	3.4
Almond	5	0.2
Tomato	118	5.7
Potato	15	0.7
Asparagus	116	5.5
Vegetables	16	0.8
Wheat	0	0
Total	**2093**	**100**

IV.4 Results and discussions

IV.4.1 Water requirements

Water demand was estimated using daily climatic data from the study area and the cropping pattern of District 4 (Table IV-1). The peak water requirements occurred in July with an amount of 5.5 mm/day.

Hydrants in District 4 network are set to irrigate farms with similar areas, with an average of 3.12 ha. Therefore, the maximum time needed for irrigation was estimated to be 4.8 h in the peak period, assuming the total satisfaction of irrigation requirements. To provide more flexibility to farmers, the number of periods per day was set to 4, which gives each farmer 6 hours to irrigate.

IV.4.2 Hydraulic Analysis for the current on-demand operating conditions

Performance analysis of the existing network was carried out by generating 1000 random configurations of simultaneously opened hydrants, each one limited to a maximum upstream discharge of 1200 ls^{-1}, which corresponds to a peak water demand in District 4 (Daccache et al., 2010a). The reservoir piezometric elevation is set at 143 m a.s.l. The nominal discharge of all hydrants in the network is 10 ls^{-1}, hence, the number of open hydrants is 120. Each random hydrant configuration represents the number of hydrants that would irrigate in one single day and is used to simulate the on-demand operation of the network. Although these 120 hydrants may irrigate at any time during the day, a previous work by Daccache et al. (2010a) showed that farmers in the District tend to concentrate the irrigation events during the day and particularly in the late afternoon. This implies a high concentration of hydrants simultaneously open in this part of the day, while at night the demand is very low.

Considering the selected upstream discharge for each generated configuration, a certain number of hydrants in simultaneous operation is randomly selected representing the actual on-demand condition. The discharge in each section of the network is thus computed as the sum of the discharges withdrawn from the downstream. The sum of discharges in all the opened hydrants has to be equal or smaller than the maximum discharge allowed in the water source (the selected upstream discharge). Then for each hydrant within a configuration, *RPD* is computed and represented in a plane (hydrants number, *RPD*) to identify the critical zones in the network. Fig. IV-3 illustrates the upper, lower and 90% *RPD* curves resulting from the hydraulic analysis in the current situation. When considering the lower curve, it is indicated that 47% of hydrants recorded pressures lower than the minimum required. This includes 18% of hydrants with pressure lower than 0 (no pressure at the hydrants), 19% had pressure between 0 and 14 m and 10% between 14 and 20 m. On the other hand, taking into account the 90% curve (excluding the lowest 10% of the results), 17% of hydrants had pressure lower than the required one, including 2% with pressure lower than 0,7% with pressure ranging between 0 and 14 m and 8% between 14 and 20 m.

Fig. IV-4 depicts the reliability indicator *Re* for each hydrant in the current operating condition. Results show that 47% of hydrants had reliability values lower than 1. This includes 46 hydrants (7%) with reliability lower than 0.8, 5 of these hydrants had reliability lower than 0.5 and one hydrant with a reliability value of 0.

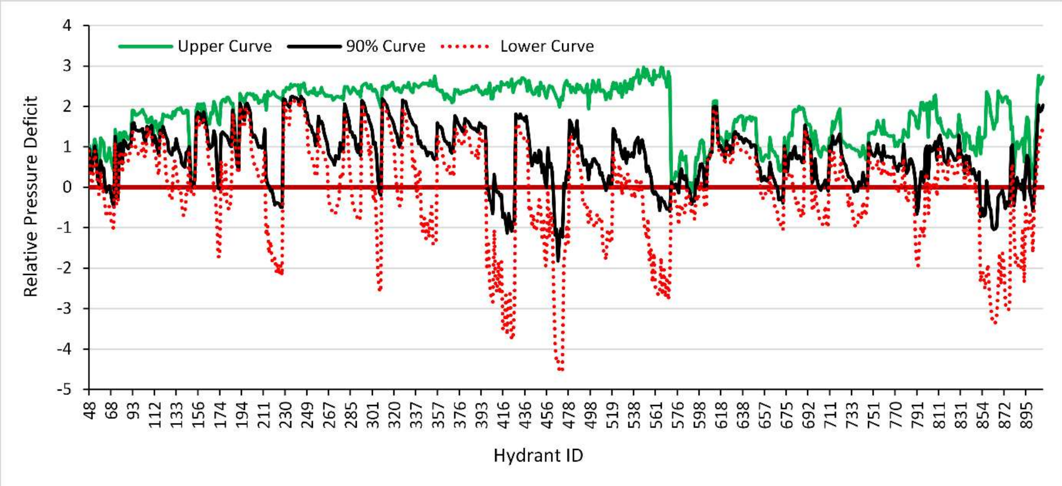

Fig. IV-3. RPD for the current operating conditions with an upstream discharge of 1200 ls^{-1}

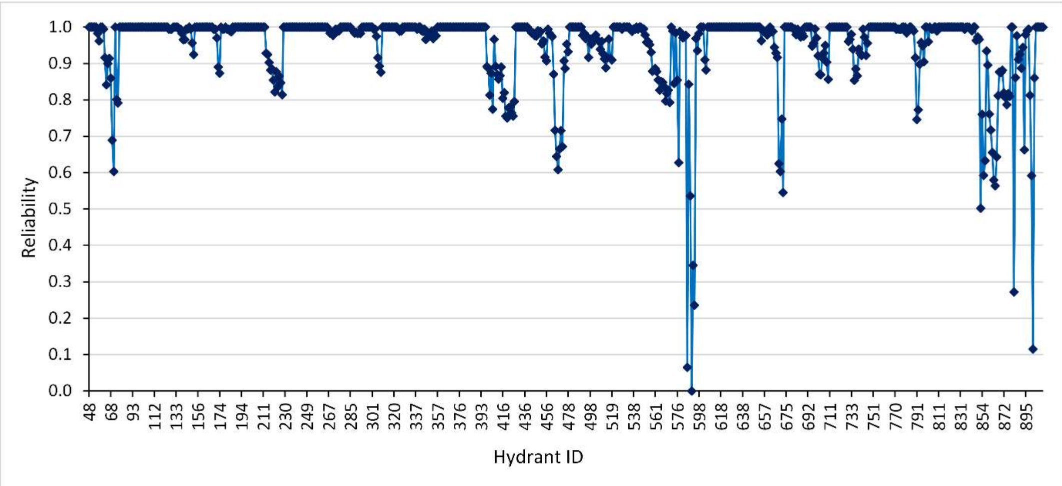

Fig. IV-4. Re for the current operating conditions with an upstream discharge of 1200 ls^{-1}

IV.4.3 Optimal management of the network

The optimization process was accomplished using the module developed in Module 3 (Fig. IV-1). The algorithm parameters were set at 100 individuals and 100 generations, with a mutation probability of 0.1. The number of variables in each individual was the number of open hydrants (120) with values ranging from 1 to 4, representing the 4 irrigation periods per day. Initially, the algorithm randomly assigned an irrigation period to each hydrant. Then, through the process illustrated in Fig. IV-1, an optimal solution, that allocated each hydrant to an irrigation period, was found. The solution provided the minimum deficit at the most unfavourable hydrant in the network. It is worth mentioning that the optimization process does not restrict hydrants from operating during the scheduled day, but rather organize these hydrants in irrigation periods to avoid the peak demand. Therefore, all crops receive their irrigation requirements as scheduled.

Fig. IV-5 shows the outcome of the hydraulic analysis of District 4 after optimization of irrigation periods, using the same 1000 configurations used in the previous section. Results indicate that for the lower curve, the number of hydrants with pressure lower than the minimum required significantly dropped from 310 hydrants (47 %) in the current operating conditions of the network to only 3 hydrants after optimization. The maximum recorded pressure deficit is 1 m, which will not have a noticeable effect on the on-farm irrigation systems. Concerning the 90% curve, only 1 hydrant had pressure deficit (1 m) after optimization. This is a significant performance improvement compared to the current conditions. The improvement is also presented by the reliability indicator. After the irrigation periods optimization, all hydrants recorded reliability values of 1, except one hydrant with a value of 0. However, the maximum deficit at this hydrant was 1 m, which does not affect the proper operation of the on-farm system.

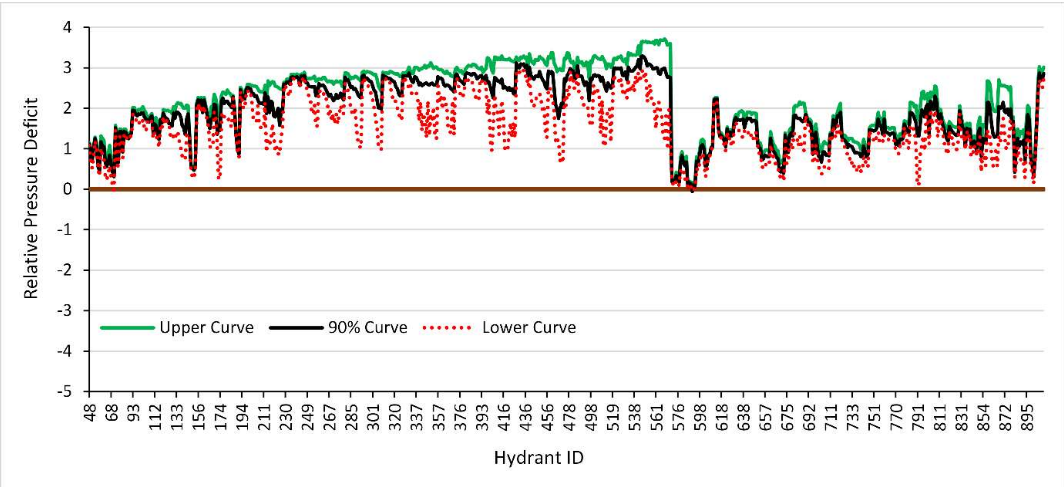

Fig. IV-5. RPD of the optimal solutions with an upstream discharge of 1200 ls^{-1}

The optimal operation strategy obtained from the optimization process showed the ability of the developed module to provide a solution that improves the hydraulic performance of the network. In order to evaluate the effect of this solution on the pressure distribution in the network, *PE* (Eq. IV-2) was determined for each simulated configuration taking into account all open hydrants. *PE* values before and after the optimization of irrigation periods are plotted in

Fig. IV-6. These values ranged between 0.20 and 0.66 with an average of 0.49 when the network was operating on-demand (current operating condition), and between 0.47 and 0.62 with an average of 0.54 after the optimization process.

In the current situation, *PE* varied considerably from one configuration to another due to the location of open hydrants (Fig. IV-6). Indeed, the concentration of open hydrants in the same area of the network affected its overall performance which led to an unequitable distribution of pressure among hydrants. This is indicated in the case of configuration 235, with the lowest value (*PE* =0.20), where 11% of hydrants had pressure lower than 0 (no pressure at hydrants), 6% had pressure between 0 and 14 m and 7% between 14 and 20 m. This problem was solved by the module with an optimal operating condition that provided a *PE* equal to 0.54.

On the other hand, in configuration 130, with the highest *PE* value, the indicator in the current operation condition (0.66) was higher than that obtained after the optimization (0.59). This is due to the fact that in the latter situation, the average pressure in the best quarter was much higher (excess pressure) than the one obtained with the current situation. To conclude, the optimization of irrigation periods has resulted in an increase of pressure equity in 79% of the simulated configurations compared to the current on-demand condition.

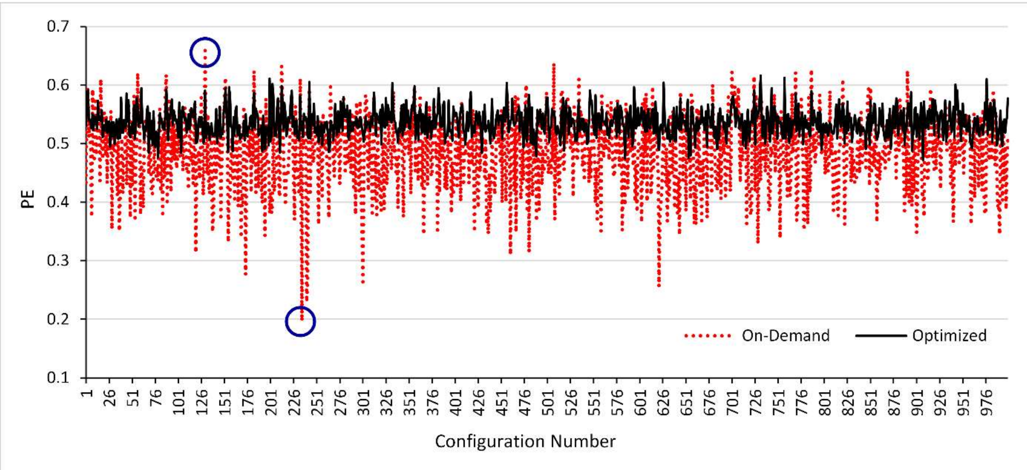

Fig. IV-6. PE for each simulated configuration of open hydrants

IV.4.4 Optimal management with higher upstream discharges

The ability of the optimization process to improve the hydraulic performance of the network with higher water demands has been tested in this section. The current upstream discharge is 1200 ls^{-1}, which represents 18 % of hydrant simultaneity. Simulations were carried out for 25% and 30% of hydrants simultaneity representing, respectively, 1650 and 2000 ls^{-1}. The hydraulic analysis was done by randomly generating a set of hydrants operating simultaneously for each of the new upstream discharges. Concerning the optimization process, the algorithm parameters were set at 100 individuals and 100 generations, with a mutation probability of 0.1. The number of variables in each individual was 165 and 200 for the upstream discharges of 1650 and 2000 ls^{-1}, respectively, representing the number of simultaneously open hydrants. The algorithm then searches for the optimal solution that provides the minimum pressure deficit at the most unfavourable hydrant in the network, as illustrated in Fig. IV-7. This figure shows the pressure deficit of each individual in the last generation in the case of 2000 ls^{-1}.

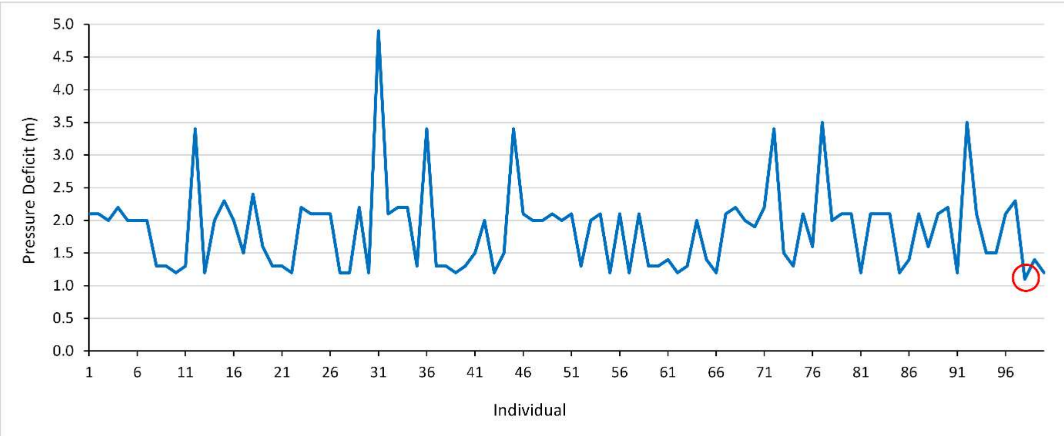

Fig. IV-7. Pressure deficit for each individual in the last generation for the upstream discharge of 2000 ls^{-1}

For the upstream discharge of 1650 ls^{-1} (Fig. IV-8), *RPD* indicator for the on-demand operation showed that 42% of hydrants recorded pressures lower than the required, including 20% with pressure lower than 0 (no pressure available at the hydrant), 13% with pressure between 0 and 14 m and 8% with pressure between 14 and 20 m. Because of the high number of hydrants that recorded very low pressure or no pressure, the *PE* value in this case was 0.01. After the optimization of irrigation periods, all hydrants in the network recorded pressure higher than the minimum required and a *PE* equals to 0.50.

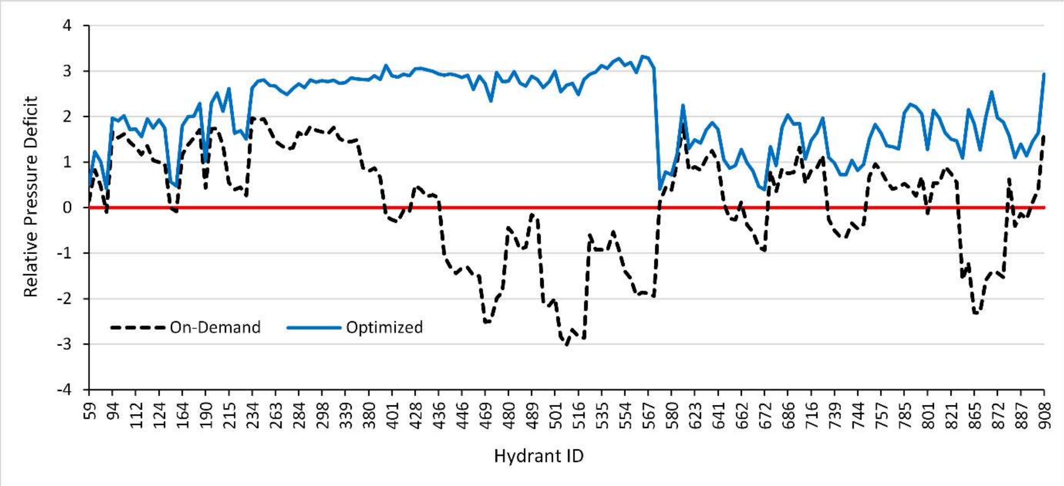

Fig. IV-8. RPD for the current on-demand conditions and the optimal solution with an upstream discharge of 1650 ls-1

Same observations were made when considering the upstream discharge of 2000 ls^{-1} (Fig. IV-9). When the network was operating on-demand, 45% of hydrants had pressure lower than the minimum required. This includes 26% with pressure lower than 0, 8% with pressure between 0 and 14 m and 11% with pressure between 14 and 20 m. Taking into account the optimization of irrigation periods, only one hydrant obtained a pressure deficit of 1 m. The optimal solution (highlighted in Fig. IV-7) also increased the value of *PE* from 0 to 0.49.

The reliability of each hydrant could not be calculated because only one configuration was simulated in the abovementioned cases. However, the reliability of the whole network was considered and calculated as the ratio of satisfied hydrants to the total operating (open) hydrants. Hence, it can be said that the optimization process increased the reliability of the network from 0.58 and 0.56 for the upstream discharges of 1650 and 2000 ls^{-1}, respectively, in the current operating conditions to 1 in both cases.

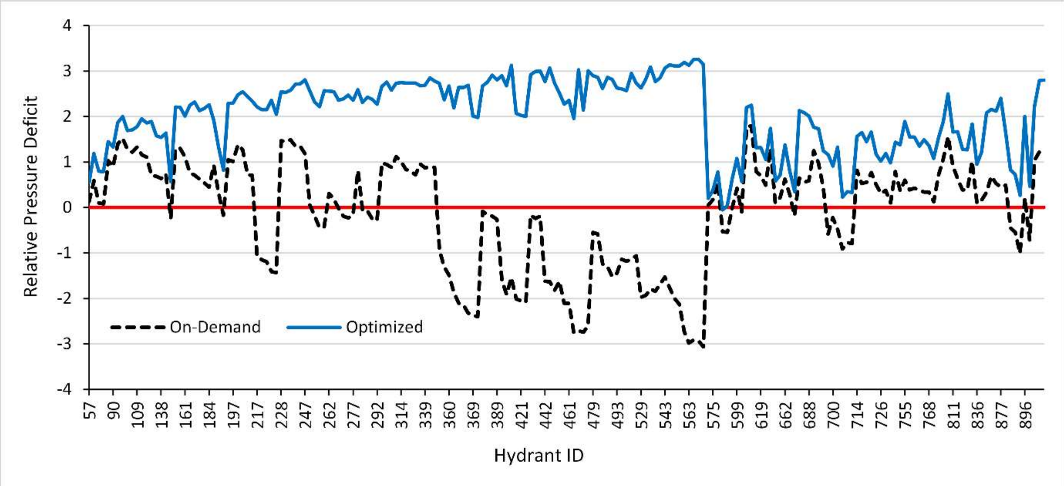

Fig. IV-9. RPD for the current on-demand conditions and the optimal solution with an upstream discharge of 2000 ls^{-1}

The above results show the capability of the optimization process to provide solutions that significantly improve the hydraulic performance of the network even with higher upstream demands.

In this work, an optimization module was developed and tested. It proved to be a useful tool that simulates hydraulic behaviour of a network under on-demand operation and accordingly, proposes the best way to organize farmers in groups to limit pressure deficit at hydrants level. Irrigation district managers can use this tool for more efficient operation of the irrigation network. If managers predict that in the next day, the concentration of the irrigation time (hydrants simultaneity) will have negative effect on the hydraulic performance. They can use the module to organize the operation of these hydrants in a way that provides the best service to farmers. This procedure does not prevent farmers from irrigating in the scheduled day nor reduce the amount of water needed to satisfy their crop water requirements. Its main purpose is to give a solution that avoids the peak demand by optimizing irrigation periods and maximizes the pressure at each hydrant. Fig. IV-10 portrays the distribution of the upstream discharges in District 4 network after the irrigation periods optimization, for the two cases 1650 and 2000 ls^{-1}. Results show that in the first case, the maximum upstream discharge of the considered day decreased from 1650 ls^{-1} to 470 ls^{-1} which was allocated to period 4. Considering the second case, the maximum upstream discharge dropped from 2000 ls^{-1} to 650 ls^{-1} in period 2.

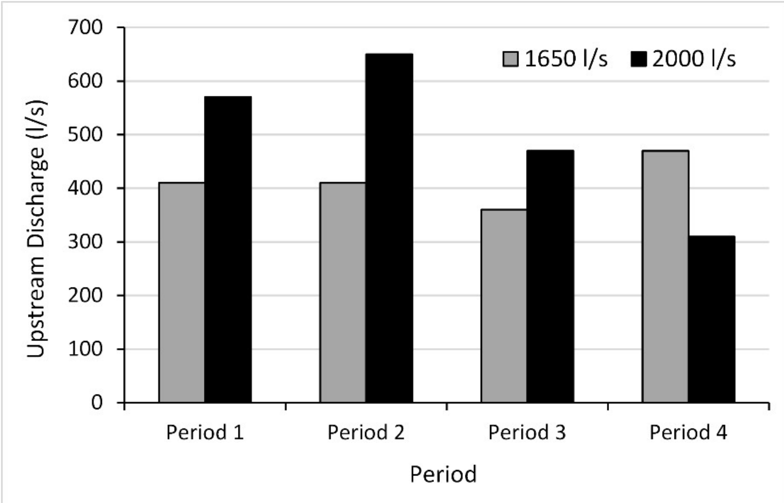

Fig. IV-10. Upstream discharges of District 4 after irrigation periods optimization

IV.5 Conclusion

On-demand irrigation distribution networks operating by gravity may face pressure failures especially during the peak period. Thus, the objective of this study was to provide irrigation district managers with a decision support tool that helps overcoming this problem. For this purpose, a genetic algorithm optimization module was developed and incorporated in the decision support system DESIDS to offer an optimal management solution. The module assigned each operating hydrant to an irrigation period considering as objective function of the optimization problem, the minimization of pressure deficit at the most unfavourable hydrant. The module was tested on a large-scale irrigation distribution network showing management solutions that successfully improve the hydraulic performance of the current failing conditions, ensuring the satisfaction of crop water requirements in all hydrants. These solutions were also able to overcome a significant increase in the upstream discharge. It is worth mentioning that in this study, the allocation of hydrants for each period was done considering only the minimization of the pressure deficit. Therefore, the distribution of the upstream discharge for each period is not constrained to a minimum nor a maximum discharge. However, this can be easily added to the module to favour one period over the other in a way that does not affect the overall performance of the network.

This module gives irrigation district managers a tool that can be used to predict a peak water demand and accordingly provide farmers with different management options. In on-demand irrigation networks, farmers may have to accept a reduction of flexibility to irrigate but in return, they receive better services from the irrigation distribution network.

IV.6 References

Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Montesinos, P., López Luque, R., Camacho Poyato, E., 2011. Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation networks. irrig. Sci. 29, 157-169. doi:10.1007/s00271-010-0228-2

Clément, R., 1966. Calcul des débits dans les réseaux d'irrigation fonctionnant à la demande. La Houille Blanche, 553-576

Daccache, A., Lamaddalena, N., Fratino, U., 2010a. Assessing pressure changes in an on-demand water distribution system on drip irrigation performance—case study in Italy. Journal of Irrigation and Drainage Engineering 136, 261-270. doi:doi:10.1061/(ASCE)IR.1943-4774.0000170

Daccache, A., Lamaddalena, N., Fratino, U., 2010b. On-demand pressurized water distribution system impacts on sprinkler network design and performance. Irrig Sci 28, 331-339. doi:10.1007/s00271-009-0195-7

Fernández García, I., Creaco, E., Rodríguez Díaz, J.A., Montesinos, P., Camacho Poyato, E., Savic, D., 2016a. Rehabilitating pressurized irrigation networks for an increased energy efficiency. Agric. Water Manage. 164, Part 2, 212-222. doi:10.1016/j.agwat.2015.10.032

Fernández García, I., Montesinos, P., Camacho Poyato, E., Rodríguez Díaz, J.A., 2016b. Energy cost optimization in pressurized irrigation networks. Irrig. Sci. 34, 1-13. doi:10.1007/s00271-015-0475-3

Fernández García, I., Rodríguez Díaz, J.A., Camacho Poyato, E., Montesinos, P., 2013. Optimal operation of pressurized irrigation networks with several supply sources. Water Resour. Manage. 27, 2855-2869. doi:10.1007/s11269-013-0319-y

Fouial, A., Khadra, R., Daccache, A., Lamaddalena, N., 2016. Modelling the impact of climate change on pressurised irrigation distribution systems: Use of a new tool for adaptation strategy implementation. Biosystems Engineering 150, 182-190. doi:10.1016/j.biosystemseng.2016.08.010

García-Prats, A., Picó, S.G., Martínez-Alzamora, F., Jiménez-Bello, M.Á., 2012. Random scenarios generation with minimum energy consumption model for sectoring optimization in pressurized irrigation networks using a simulated annealing approach. J. Irrig. Drain Eng. 138, 613-624. doi:10.1061/(ASCE)IR.1943-4774.0000452

Goldberg, D.E., 1989. Genetic algorithms in search, optimization and machine learning. Addison-Wesley Longman Publishing Co., Inc., USA.

González Perea, R., Camacho Poyato, E., Montesinos, P., Rodríguez Díaz, J.A., 2016. Optimization of irrigation scheduling using soil water balance and genetic algorithms. Water Resour. Manage. 30, 2815-2830. doi:10.1007/s11269-016-1325-7

Jiménez-Bello, M.Á., Alzamora, F.M., Castel, J.R., Intrigliolo, D.S., 2011. Validation of a methodology for grouping intakes of pressurized irrigation networks into sectors to minimize energy consumption. Agricultural Water Management 102, 46-53. doi:10.1016/j.agwat.2011.10.005

Jiménez-Bello, M.A., Royuela, A., Manzano, J., Prats, A.G., Martínez-Alzamora, F., 2015. Methodology to improve water and energy use by proper irrigation scheduling in pressurised networks. Agric. Water Manage. 149, 91-101. doi:10.1016/j.agwat.2014.10.026

Kanakis, P.C., Papamichail, D.M., Georgiou, P.E., 2014. Performance analysis of on-demand pressurized irrigation network designed with linear and fuzzy linear programming. Irrig. and Drain. 63, 451-462. doi:10.1002/ird.1853

Khadra, R., Moreno, M.A., Awada, H., Lamaddalena, N., 2016. Energy and hydraulic performance-based management of large-scale pressurized irrigation systems. Water Resour. Manag. 30, 3493-3506. doi:10.1007/s11269-016-1365-z

Lamaddalena, N., 1997. Integrated simulation modeling for design and performance analysis of on-demand pressurized irrigation systems, Instituto Superior de Agronomia. Universidade Técnica de Lisboa, Lisboa.

Lamaddalena, N., Khadra, R., Fouial, A., 2015. Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig Sci 33, 453-468. doi:10.1007/s00271-015-0481-5

Lamaddalena, N., Pereira, L.S., 2007. Pressure-driven modeling for performance analysis of irrigation systems operating on demand. Agricultural Water Management 90, 36-44. doi:10.1016/j.agwat.2007.02.004

Lamaddalena, N., Sagardoy, J.A., 2000. Performance analysis of on-demand pressurized irrigation systems. FAO Irrigation and Drainage Paper 59. Food and Agriculture Organization of the United Nations, Rome, Italy.

Moreno, M.A., Córcoles, J.I., Tarjuelo, J.M., Ortega, J.F., 2010. Energy efficiency of pressurised irrigation networks managed on-demand and under a rotation schedule. Biosystems Engineering 107, 349-363. doi:10.1016/j.biosystemseng.2010.09.009

Murphy, L.J., Dandy, G.C., Simpson, A.R., Gransbury, J.C., 1998. Optimisation of irrigation infrastructure rehabilitation using genetic algorithms, National Conference, Irrigation Association of Australia, Brisbane, Australia.

Reca, J., Martínez, J., 2006. Genetic algorithms for the design of looped irrigation water distribution networks. Water Resour. Res. 42, W05416. doi:10.1029/2005WR004383

Rodríguez Díaz, J.A., Camacho Poyato, E., Blanco Pérez, M., 2011. Evaluation of water and energy use in pressurized irrigation networks in Southern Spain. J. Irrig. Drain Eng. 137, 644-650. doi:doi:10.1061/(ASCE)IR.1943-4774.0000338

Rodríguez Díaz, J.A., López Luque, R., Carrillo Cobo, M.T., Montesinos, P., Camacho Poyato, E., 2009. Exploring energy saving scenarios for on-demand pressurised irrigation networks. Biosystems Engineering 104, 552-561. doi:10.1016/j.biosystemseng.2009.09.001

Salvador, R., Latorre, B., Paniagua, P., Playán, E., 2011. Farmers' scheduling patterns in on-demand pressurized irrigation. Agric. Water Manage. 102, 86-96. doi:10.1016/j.agwat.2011.10.009

Urrestarazu, L., Díaz, J., Poyato, E., Luque, R., 2009. Quality of service in irrigation distribution networks: Case of Palos de la Frontera irrigation district (Spain). J. Irrig. Drain Eng. 135, 755-762. doi:doi:10.1061/(ASCE)IR.1943-4774.0000107

CHAPTER V

MULTI-OBJECTIVE OPTIMIZATION MODEL BASED ON LOCALIZED LOOPS FOR THE REHABILITATION OF PRESSURIZED IRRIGATION DISTRIBUTION NETWORKS

V.1 Introduction

In the last few decades, PIDSs have replaced open channels in an attempt to increase water conveyance efficiency. Nowadays, some of these systems are facing hydraulic performance problems. This is due partly to the ageing of pipe networks, initial design flaws, improper management or/and the increase in water demand. To overcome these problems, rehabilitation of these existing systems may become an inevitable need to preserve an effective operation and provide the best services to farmers. In some cases, improving management alone does not considerably cause an improvement of networks' hydraulic performance unless combined with structural rehabilitation. The latter must ensure the minimum performance levels required to satisfy farmers while considering the associated cost over an extended period.

The design and rehabilitation of WDNs is a complex non-linear combinatorial optimization problem. This problem was initially formulated as a single-objective (least cost) optimization problem with the objective to minimize the total cost of construction and operation (Babayan et al., 2005; Savic and Walters, 1997; Simpson et al., 1994). However, this formulation cannot provide a set of alternative solutions to the problem. The consideration of multi-objective optimization approach offers some advantages over the single-objective optimization as it provides i) a wide range of alternative solutions, ii) more appropriate roles for decision makers, and iii) more realistic definition of the problem (Savic, 2002).

During the last decades, Evolutionary Algorithms and in particular genetic GA (Goldberg, 1989), have been proven to be effective search-and-optimization procedures. Multi-Objective Evolutionary algorithms (MOEAs) are widely used in solving WDSs optimization problems (Farmani et al., 2006; Giustolisi and Berardi, 2009; Saleh and Tanyimboh, 2013; Tanyimboh and Seyoum, 2016; Wu et al., 2013), due to their superior performance over traditional multi-objective optimization algorithms, in terms of effectiveness and robustness (White and He, 2012). These population-based approaches have the ability to search effectively for many non-dominated (trade-off) solutions in a single run. MOEAs explore the Pareto-optimal front in WDSs optimization problems that are too complex to be solved by other methods, such as linear programming and gradient search (Zitzler et al., 2000).

The non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002) is one of the most popular MOEAs used for the optimization of WDSs (Artina et al., 2012; Roshani and Filion, 2014; Wang et al., 2015). This is due to its efficient non-dominated sorting procedure and strong global elitism that preserves all elites from both the parent and child populations (Tanyimboh and Seyoum, 2016). Nicolini (2004) compared the performance of three MOEAs on the design problem formulated with two objective functions, specifically the minimization of both, the total costs and the maximum pressure deficit at nodes. The results indicated that NSGA-II performs better than the other MOEAs.

Most of the extensive literature related to WDSs optimization and rehabilitation focus on urban WDSs and only few emphasise on PIDSs. The two shares various characteristics but also present significant different features (Aliod and González, 2008): i) majority of PIDNs are branched with sparse layout, ii) small number of independent users but with intensive demand, and iii) demand nodes have discontinuous demand patterns. Therefore, it is important to consider these differences in the formulation of PIDNs optimization.

Murphy et al. (1998) used GA to run several optimization options in a real project for the rehabilitation of an aged pressurized pipe system. They concluded that the design achieved by the GA search saved 11% of the estimated cost for the supply and construction of pipelines, compared to the design determined by the conventional design approach based on experience and the trial-and-error application of a hydraulic simulation package. However, in this study, options of possible alternative new pipe routes and duplication of existing pipes consideration were decided a priori to each optimization.

Reca and Martínez (2006) developed a computer model (GENOME) for optimizing the design of looped PIDNs. The model is based on GA, formulated to minimize networks investment cost. An optimization of a real complex irrigation network was carried out to evaluate the potential of GA for the optimal design of large-scale networks. The authors concluded that GAs are a suitable tool for the looped water network optimization.

Farmani et al. (2007) used a modified GA for the optimization of new PIDN by introducing two operators. The first one ensures that none of the solutions in the search space will violate the constraints that the pipe sizes of the upstream pipes should be larger than those of the downstream ones. The second is a deterministic perturbation algorithm that addresses the problem of inefficient mutation known to occur in GA problems with a large number of decision variables. The optimum design was considered for two scenarios, on-demand and rotation delivery scheduling. The modified GA performed better than the linear programming and conventional GA in optimum design of a branched irrigation network. Comparison between on-demand and rotation delivery scheduling showed that more than 50% saving in the total cost could be achieved by adopting rotation delivery scheduling.

The abovementioned studies show the suitability of GA for the design and rehabilitation of branched and looped PIDNs. However, in those studies, the problem was formulated as a single-objective optimization. Fernández García et al. (2016) proposed a methodology for the rehabilitation of PIDSs based on a NSGA-II multi-objective approach that simultaneously optimize installation and long term operational costs. This methodology was based on two steps: i) The application of two alternative optimization algorithms to determine optimal trade-offs between installation costs and pump power absorption, considering the simultaneous operation of all hydrants in the network, which is not realistic, and ii) the post-processing of the optimal solutions from the Pareto front in terms of long term costs under various possible scenarios generated, featuring various values of the useful construction life and of the capital recovery factor. This methodology was tested on a real PIDS and proven to be powerful tools to optimize the energy requirements in pressurized networks. However, the method was formulated only for energy saving and cannot be used for gravity-fed networks. In addition, it does not explore the possibility of adding loops as an option to increase network capacity. Lamaddalena et al. (2015) and Fouial et al. (2016) proposed the approach of localized loops for the rehabilitation of PIDNs. The positions of localized loops were identified based on the overall performance improvement that can be achieved. This method was tested on a branched, gravity-fed large-scale network operating on-demand and showed to be a cost-effective solution. It demonstrated its ability to improve the hydraulic performance of the network even under higher future demand (Fouial et al., 2016). However, finding the position of loops was not automatic and was done by trial and error, thus, extensive and time-consuming data entries and analyses were required.

The objective of this work is to develop a comprehensive optimization module to assist planners and decision makers in the determination of the most cost-effective strategy for the rehabilitation of PIDNs, taking into consideration the option of looping branched networks. Two phases are considered in the present study. In the first phase, the developed algorithm searches for the possibility of introducing localized loops according to pre-defined conditions to connect bad performing hydrants to nearby nodes or hydrants with good hydraulic performance. In the second phase, the NSGA-II multi-objective optimization of PIDNs, considering an extended period of time, is carried out to obtain the least cost rehabilitation that minimizes the pressure deficit at the most unfavourable hydrant in the network. The module was tested on a gravity-fed medium-size PIDN located in Southern Italy.

V.2 Methodology

In the framework of this study, a multi-objective optimization module for the design and rehabilitation of PIDNs was developed. This module can be used for the design of new branched or looped pipe networks, assuming pre-defined networks layout (topology and patterns of connectivity). It can also be used for the rehabilitation of existing networks with the option of adding localized loops to branched networks. The module was integrated in DESIDS to allow the use of the hydraulic analysis module in the optimization process. Moreover, the GUI of DESIDS with its GIS capability and the network database are used to determine the coordinates of each node to be used in the looping process.

This module is tested herein for the rehabilitation of a branched gravity-fed network. The rehabilitation process was carried out following two steps:

V.2.1 Case study

The performance of the design and rehabilitation module developed in the framework of this study was assessed on Sector 13, a medium-size network. This sector is part of District 4 network describe in section IV.3. Sector 13, as depicted in Fig. V-1, covers and irrigable area of 107.6 ha and encompasses 52 nodes of which 40 are hydrants designed for a nominal discharge of 10 ls^{-1}. The land elevation of the intake node is 59 m a.s.l. and the minimum design pressure head at all hydrants is 20 m, considering that almost all the farms are equipped for drip irrigation.

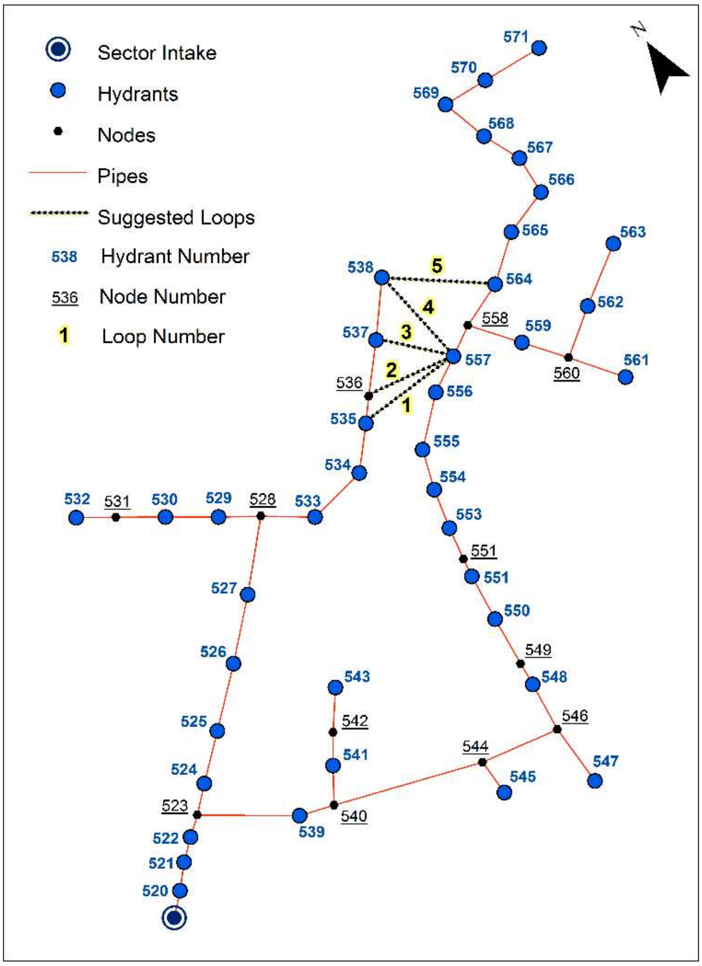

Fig. V-1. Layout of Sector 13 network

V.2.2 Step 1: Initial hydraulic analysis of the existing network

The decision to rehabilitate any PIDN requires prior knowledge of the actual hydraulic performance and operating conditions of that network. As mentioned above, the case study network (Sector 13) is part of a larger network (District 4). Therefore, the discharge and the piezometric elevation at the intake of this sector are unknown parameters and depend on the on-demand operating conditions of the whole network. To estimate these two parameters, it is imperative to simulate a large number of operating configurations of the district. Then the upstream flow and the piezometric elevation of Sector 13 are selected from the obtained distribution of frequency of both parameters.

Afterwards, a hydraulic analysis of the existing case study network is performed using the selected parameters. This analysis starts by generating a number of random configurations (hydrants simultaneously opened), in a way that the sum of the discharges of all the opened hydrants is equal to a predefined upstream discharge (Eq. II-12). Thus, the number of randomly open hydrants depends on the nominal discharge of these hydrants and the upstream discharge.

Within each generated configuration, a cloud of points can be plotted, representing the *RPD* (Eq. II-8) at each hydrant. The cloud of points is enclosed between a lower and an upper envelope (*RPD* curve) indicating the range of possible pressures for each hydrant in the network. Intermediate curves are also possible to define. For example, the 90% curve shows the *RPD* when excluding the 10% of less favourable cases. These curves are useful to identify both, the failing hydrants and the degree of failure. The *Re* (Eq. II-9) of each hydrant is also calculated in the analysis.

V.2.3 Step 2: Optimization of PIDN rehabilitation

In this step, the optimization of PIDN rehabilitation was carried out using NSGA-II, an elitist, MOEA that is characterized by the concepts of non-dominated sorting and crowding distance. Two separate optimizations were performed. The first one uses the actual branched layout of the existing network, while the second one considers the option of adding localized loops to the existing branched network.

V.2.3.1 Determination of looping positions

The option of considering localized loops was included in the developed module. If this option is selected, the algorithm is set to automatically search for the best looping positions considering pre-defined conditions. The latter are related to the initial hydraulic analysis results.

- A hydrant j is considered as potential starting node for a loop l if its resulting *RPD* and reliability values are lower than the pre-defined limits.

- The *RPD* value of hydrant j belongs to the pre-defined *RPD* curve. i.e., the resulted *RPD* from the initial performance analysis are organized into different *RPD* curves as explained in the previous section. The user of the developed module can select an *RPD* value for the considered hydrant from one of these curves, e.g. 90% curve.
- A node *nd* (can be a connecting node or hydrant) is considered as potential ending node for the loop l (starting from hydrant j) if its distance from hydrant j is smaller than the pre-defined maximum allowable distance. The distance is calculated from the X and Y coordinates of hydrant j and node *nd* using:

$$Distance = \sqrt{(X_{nd} - X_j)^2 - (Y_{nd} - Y_j)^2} \qquad \textit{Eq. V-1}$$

- The node *nd* is considered if its pressure head is higher than the minimum allowable limit.

The aforementioned conditions are set to i) position the localized loops only when needed to improve the hydraulic performance and ii) limit the number of suggested loops to increase the efficiency of the algorithm during the optimization. Fig. II-9 shows the looping conditions when looping is considered in the optimization of PIDN rehabilitation.

Each of the selected hydrants in this process is compared to all nodes in the network. If all the above conditions are met, the looping pipes are added to the original layout database, with their respective length, initial and final nodes, and an initial pipe diameter value of 0.

V.2.3.2 Objective functions

The multi-objective optimization of PIDN rehabilitation is used herein to explore the trade-off between the two considered objective functions, formulated mathematically as:

1) An objective function of pressure deficit minimization (*OFPD*) described as:

$$OFPD = H_{j,min} - H_j \qquad \textit{Eq. V-2}$$

were $H_{j,min}$ is the minimum pressure head required at hydrant j (m), and H_j is the actual pressure head at hydrant j (m). Both values are related to the most unfavourable hydrant in the network. Thus, a positive value of the $OFPD$ indicates the highest available pressure deficit in the network while a negative value indicates the lowest pressure surplus. This formulation provides a wider range of solutions, hence, a better comparison between the cost of allowing some deficit in the network (that do not affect farmers) and pressure surplus.

2) An objective function of minimization of total cost of rehabilitation:

$$OFCR = \sum_{k=1}^{N_k} C_k L_k \qquad \textit{Eq. V-3}$$

were k is the pipe index, N_k is the total number of pipes in the network including the suggested loops, C_k is the unit cost associated with commercially available pipe diameter D_k (€m^{-1}), and L_k is the length of pipe k (m). $OFCR$ is formulated to be used for both, the design of a new network as well as the rehabilitation of an existing one. In the latter case, only the cost of the replaced pipes is considered. Thus, the cost, C_k, of the remaining pipes is set to 0.

Also, because the network in this work is gravity-fed, only costs associated to pipe replacement and installation is considered. However, other costs such as energy cost (in case of pumps) can be easily incorporated into $OFCR$.

The constraints of the optimization related to the nodal mass balance and energy conservation equations are automatically respected through the use of the hydraulic analysis module.

V.2.3.3 Optimization process

Because this work focuses on the rehabilitation of PIDNs, the network layout is already pre-defined and pipes are predetermined based on the positions of existing pipes. The PIDN rehabilitation is formulated as a bi-objective optimization problem with a selection of pipe diameters as the decision variables. The decision variables (pipes to be sized) and allowable selections for each decision variable (available pipe diameters and permissible range of pipe diameters for each section of the network) are identified. The developed algorithm is set in a way that some constraints are addressed at the beginning of the optimization procedure. First, considering the range of pipe diameters, available diameters for a specific section in the network is constrained to an upper and lower bound. The latter being the existing pipe diameter of the same section. In another word, the algorithm considers only a diameter that is equal or larger than the existing one. Second, the algorithm ensures that all the solutions in the search space will respect the constraints that the pipe diameters of the upstream pipes are larger than those of the downstream ones.

The NSGA-II is used herein for the optimization process (Fig. V-2) because of its proven ability to efficiently search large decision spaces (Roshani and Filion, 2014). The developed algorithm firstly generate a random initial population (individuals), respecting the pipe abovementioned constraints. Each individual is then assigned a value for each objective function (cost and pressure deficit). It is worth mentioning that the evaluation of individuals is obtained under extend period simulation mode, i.e. using the same randomly generated configurations used in the initial hydraulic analysis of the existing network. The individuals are then sorted into fronts in a way that the solutions of the first front are not dominated by any other solutions in the population. Then, solutions of the second front are only dominated by solutions of the first front, and so on. Next, the solutions within each front are assigned a crowding distance, which gives a measure of how dense the front is in the vicinity of that solution (Deb et al., 2002). Subsequently, an offspring population is created by selecting individuals of the current population and performing the operations of crossover and mutation (respecting pipe constraints) to produce new solutions. When selecting solutions, individuals are compared by their front number giving preference to the lower numbered fronts. If two solutions are from the same front, then the solution with the greater crowding distance is chosen (Olsson et al., 2009). These processes are repeated until maximum number of generations has been reached.

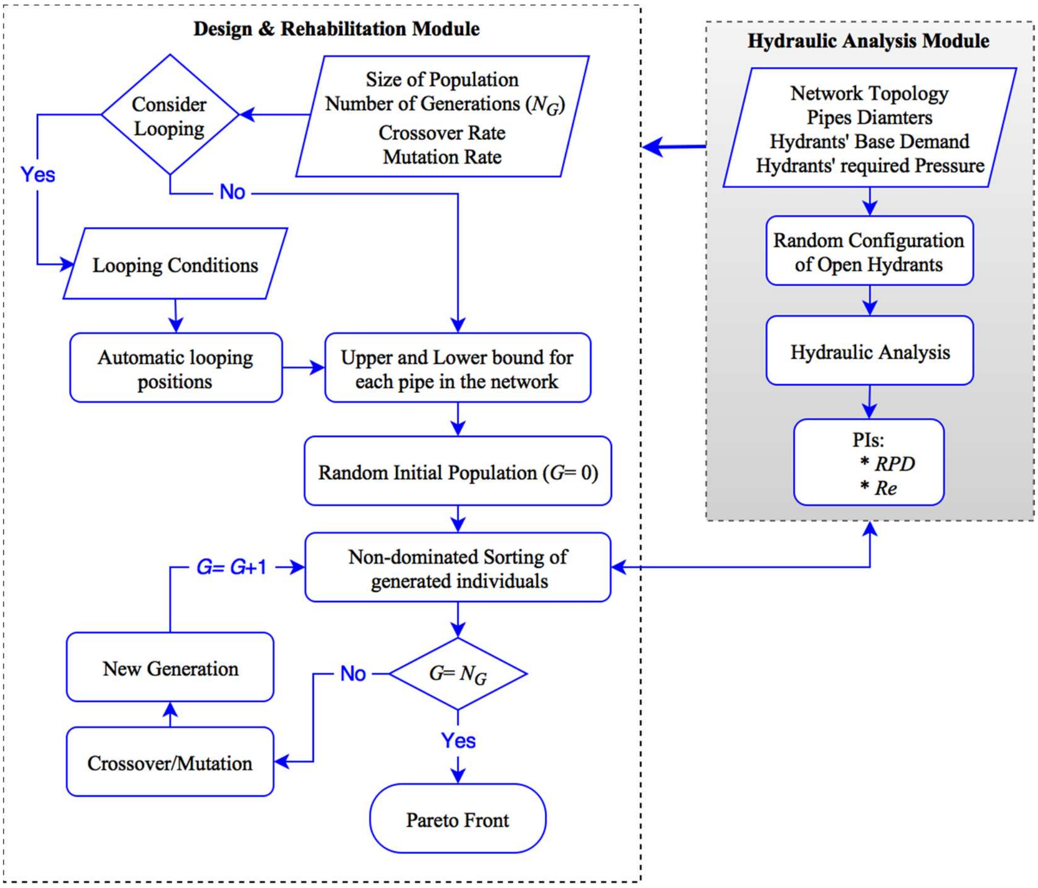

Fig. V-2. Flowchart for the optimization of rehabilitation

V.3 Results and discussions

V.3.1 Determination of the upstream discharge and piezometric elevation

Sector 13 is part of District 4 network. Hence, the discharge and the piezometric elevation at the intake of this sector depend on the operating conditions of the whole network. For this reason, a large number (5000) of randomly generated configurations of open hydrants in the district were analysed to evaluate the range of pressure and flow occurring at the intake node of Sector 13. The nominal discharge of all hydrants in the district is 10 ls^{-1}, and the minimum required pressure head at all hydrants is 20 m. District 4 network was designed for an upstream discharge of about 1200 ls^{-1} (Lamaddalena, 1997). In this study, the predicted future demand of 1500 ls^{-1} (Fouial et al., 2016) is selected for the analysis to provide a ground for rehabilitation need.

For each simulated configuration of District 4, a piezometric elevation (considering the pressure head and the land elevation of the intake node) and a discharge upstream of Sector 13 was obtained. Fig. V-3 displays the frequency and cumulative frequency of the piezometric elevation and the flow at the intake of Sector 13. Results of the analysis of District 4 shows that the piezometric elevation at the intake node of Sector 13 ranged between 69.6 and 124.8 m. In around 83% of all analysed configuration, the piezometric elevation recorded values equal or higher than 95 m, including 64% of values equal or higher than 100 m. Additionally, the flows passing through the intake ranged in magnitude between 10 and 180 ls^{-1}. Flows equal of higher than 90 ls^{-1} were recorded in around 58% of all configuration, this includes 42% with flows equal or higher than 100 ls^{-1}.

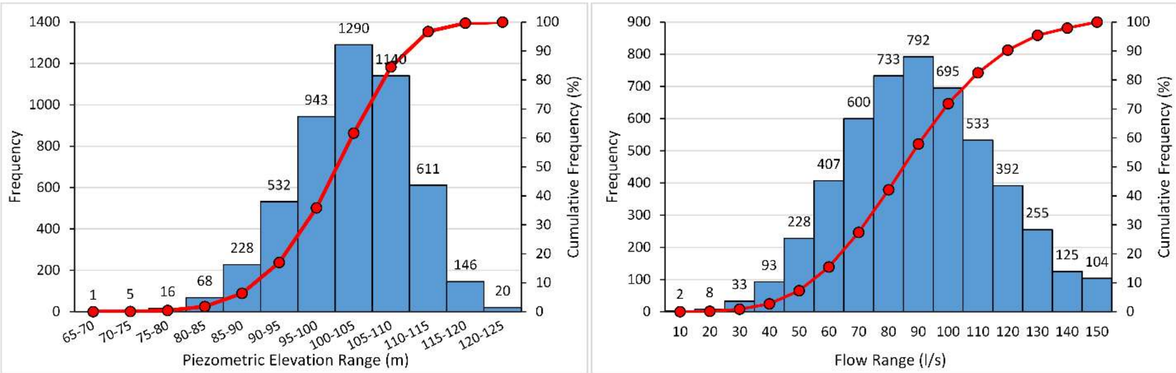

Fig. V-3. Frequency of flow and piezometric elevation at the intake of Sector 13

V.3.2 Initial hydraulic Analysis of the existing network

The initial hydraulic performance analysis of Sector 13 was carried out by generating 100 random operating configurations. An upstream discharge of 100 ls^{-1} (representing hydrants simultaneity of 25%) and a piezometric elevation of 100 m were selected at the intake of the sector. The upper, lower and 90% *RPD* curves resulting from the hydraulic analysis are illustrated in Fig. V-4. Considering the lower curve, 23 out of 40 hydrants in the network (around 58%) recorded pressure deficit. This includes 13 hydrants with 0 pressure and 7 hydrant with a pressure deficit higher than 4 m. For the 90% curve, 16 hydrants had pressure deficit including 4 with 0 pressure and 10 with a pressure deficit higher than 4. Hydrants experiencing major pressure head problems are concentrated in the right side of the sector starting from hydrant 556 (Fig. V-1). This statement is supported by the reliability indicator shown in

Fig. V-5. 14 of the hydrants in this part of the network registered a reliability lower than 0.8, including 5 with a reliability lower than 0.5. These results clearly demonstrates the need of rehabilitation to improve the performance of the mentioned hydrants.

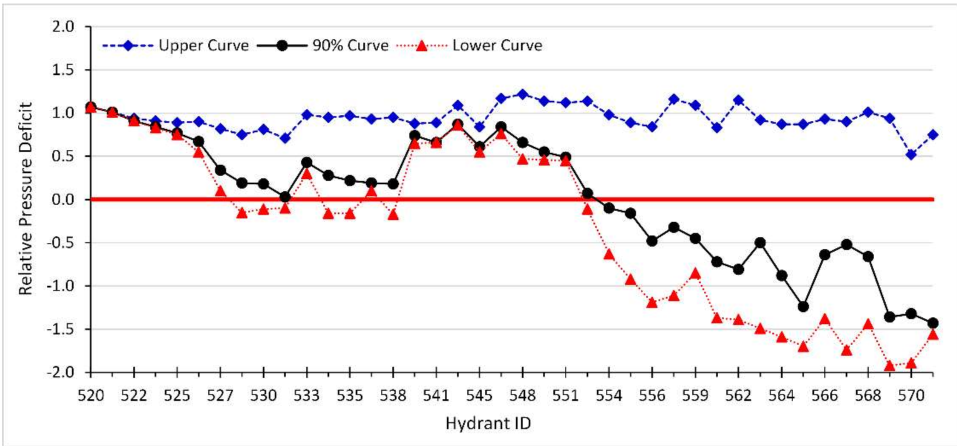

Fig. V-4. RPD for the actual situation of Sector 13 network

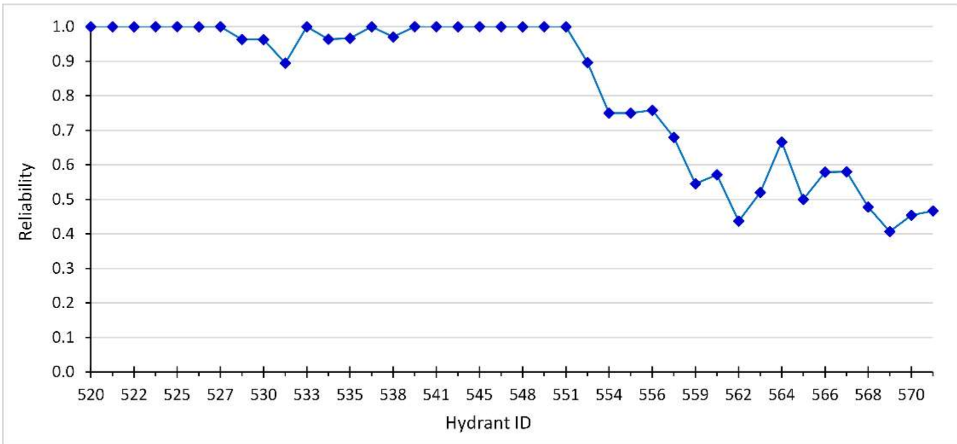

Fig. V-5. Reliability for the actual situation of Sector 13 network

V.3.3 Rehabilitation alternatives

Two different optimizations of sector 13 rehabilitation were carried out using NSGA-II. In the first optimization, the existing network layout is used and pipes are predetermined based on the positions of existing pipes. Therefore, the number of decision variables is the number of the existing pipes, which is 52. Whereas, in the second optimization, the option of adding additional loops is considered. The conditions of this option (Fig. II-9) where set such that all hydrants with an *RPD* lower than the limit of -0.3 (selected from the 90% curve) and a reliability lower than 0.7 are considered as starting nodes for potential loops. Furthermore, all nodes with a distance, from the considered hydrants, shorter than 300 m and a pressure higher than 16 m will be considered as ending nodes for potential loops. Using these conditions, the developed algorithm automatically added 5 potential loops to the existing network (Fig. V-1). In this case, the number of decision variables is 57.

The algorithm was run with a population of 200 individuals and the number of generations was set to 200. The crossover probability was set to 0.9 and the mutation probability was set to 0.5 for the two runs. Each individual is evaluated by an extended period simulation considering the same randomly generated configurations used in the initial hydraulic analysis of the existing network of Sector 13.

The first look at the two Pareto front solutions, depicted in Fig. V-6, clearly indicates that the optimization with the consideration of loops provided much better results than that excluding loops. It is worth mentioning that, in the former optimization, all the Pareto front solutions included at least 1 loop. This highlights the importance of looping in the improvement of the overall performance of the network. Three cases were selected from the two Pareto fronts for detailed analysis (see Fig. V-6). The detailed results for these cases are shown in Annex V-1.

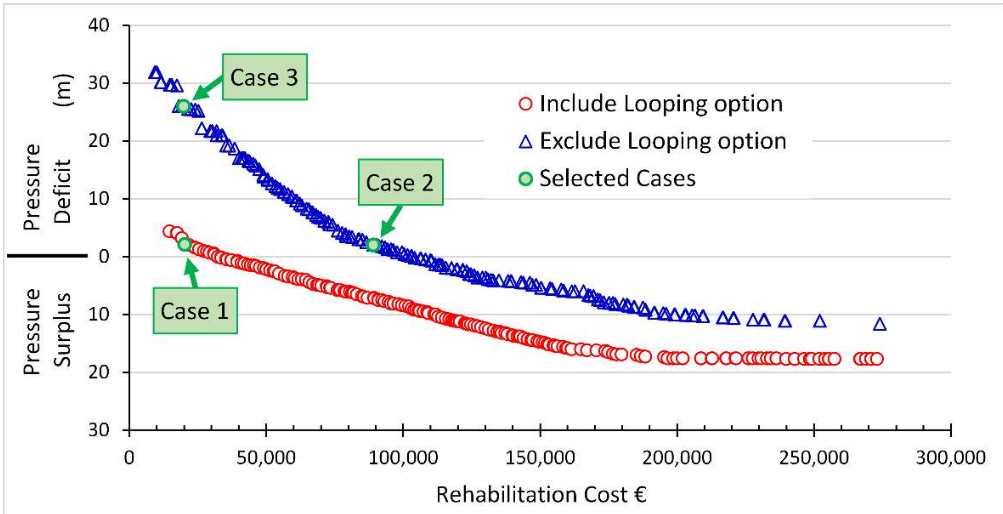

Fig. V-6. Pareto optimal solutions

Case 1: a solution was selected from the Pareto front solutions of the optimization that included looping option. In this solution, a pressure deficit of 2 m was allowed assuming that this will not affect the proper operation of on-farm equipment. The selected rehabilitation solution involved the introduction of 2 new loops (see Fig. V-1):

- Loop 2, connecting hydrant 557 and node 536 with a pipe diameter of 125 mm and a length of 220.8 m.
- Loop 5, connecting hydrants 564 and 538 with a pipe diameter of 160 mm and a length of 267.7 m.

In addition to the loops, only one pipe in the existing network (connecting node 523 to hydrant 524) was replaced with a lager diameter, from 180 mm to 250 mm. the cost of rehabilitation amounts to 20,214 €.

A detailed performance analysis for this solution was carried out using the same random configurations. Results of *RPD* and reliability are illustrated in Fig. V-7 and Fig. V-8, respectively. These results clearly show the significant improvement of the performance of all hydrants. Only 3 hydrants had trivial problems, which will not have any influence on the operations of on-farm equipment.

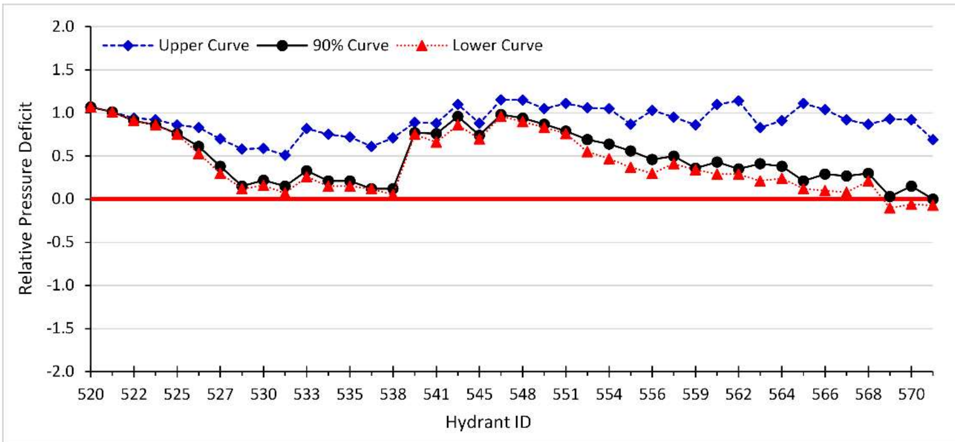

Fig. V-7. RPD for the rehabilitated Sector 13 network (Case 1)

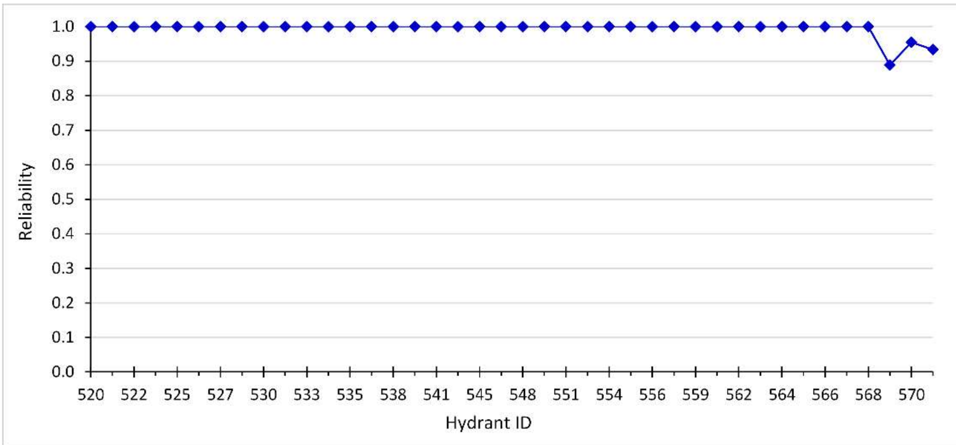

Fig. V-8. Reliability for the rehabilitated Sector 13 network (Case 1)

Case 2: a solution was selected from the Pareto front solutions of the optimization that excluded looping option. The purpose from selecting this solution is to match the pressure deficit in the first case, which is 2 m. This solution involved the replacement of 13 pipes in the existing network with a rehabilitation cost of 89,154 €, representing a cost increase of 341 % compared to case 1. A detailed hydraulic performance was also done to compare the results with the first case as well as the existing network. Results (Fig. V-9 and Fig. V-10) show that this solution also provided a substantial hydraulic performance improvement from the original network. However, the drawback here is the very high cost compared to the previous case.

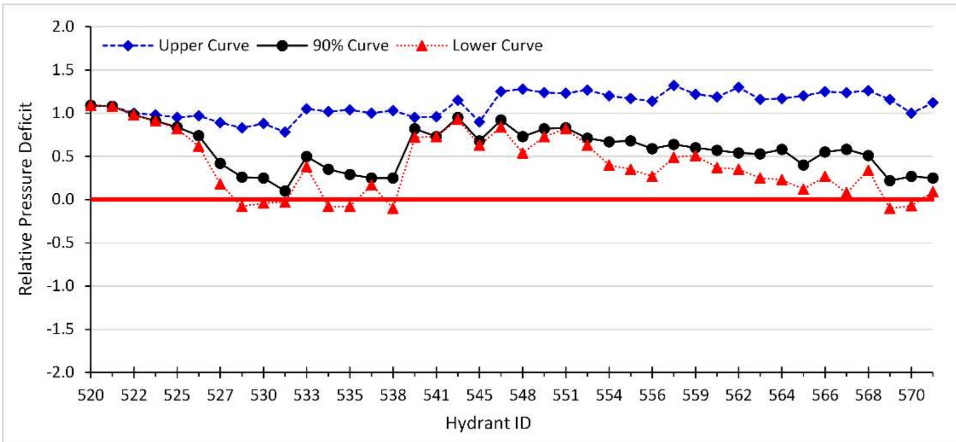

Fig. V-9. RPD for the rehabilitated Sector 13 network (Case 2)

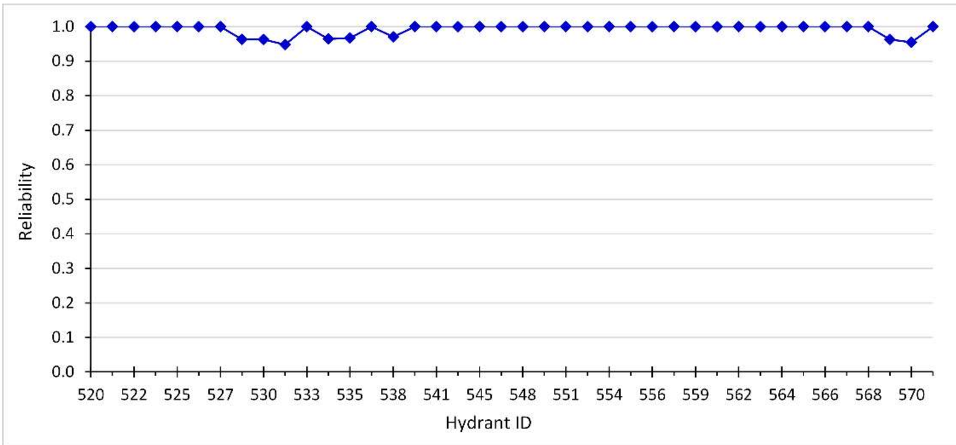

Fig. V-10. Reliability for the rehabilitated Sector 13 network (Case 2)

Case 3: It was important to consider a second case from the optimization without looping. The purpose here is to get a solution from the Pareto front with the closest rehabilitation cost to the first case, assuming that the rehabilitation budget is limited to that cost. The selected solution included the replacement of 6 pipes in the existing network with a cost of 19,792 €. As for the two previous cases, a detailed hydraulic analysis was also performed for this case. Results demonstrate that by limiting the rehabilitation budget to around 20,000 € and excluding the looping option, no significant improvement is achieved. *RPD* in this solution is illustrated in Fig. V-11, showing that the right part of the network (starting from hydrant 556) still have considerable performance problem but with lesser magnitude than the existing network. For example, the number of hydrants having 0 pressure decreased from 14 to 5 for the lower curve and from 4 to 0 for the 90% curve. On the other hand, the number of hydrants recording a reliability lower than 0.8 decreased from 14 to 12 as depicted in Fig. V-12.

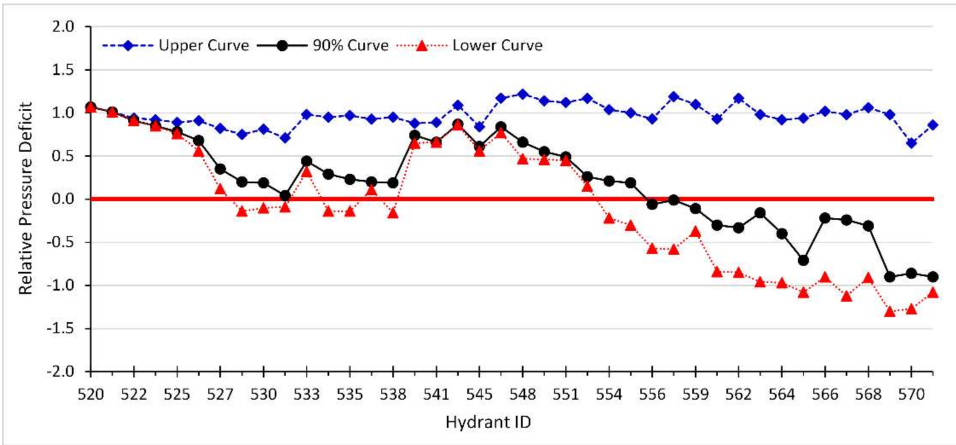

Fig. V-11. RPD for the rehabilitated Sector 13 network (Case 3)

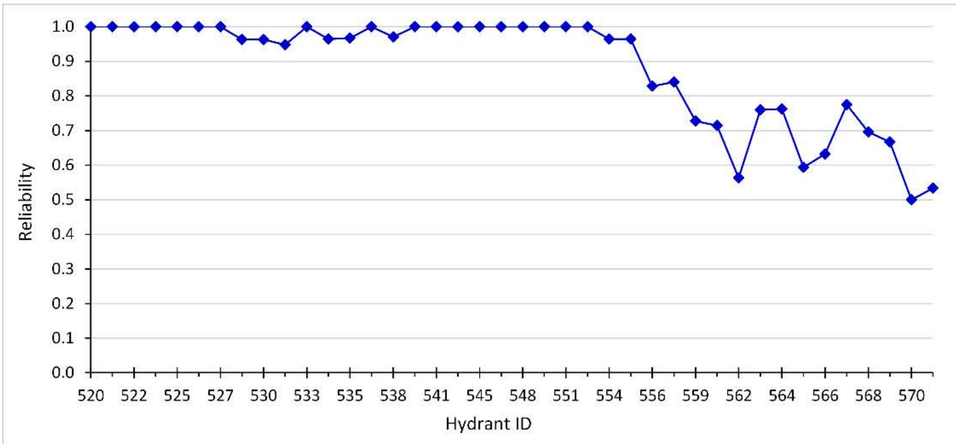

Fig. V-12. Reliability for the rehabilitated Sector 13 network (Case 3)

The three mentioned rehabilitation cases are summarized in Fig. V-13. The latter shows the cost of rehabilitation and the associated pressure deficit recorded at the most unfavourable hydrant in the network. This study obviously revealed that it is worthwhile to consider the automatic looping in the optimization of PIDNs rehabilitation as it provides much better results (case 1). These results confirm the work of Lamaddalena et al. (2015) and Fouial et al. (2016). It is well known that looped networks are used in urban WDSs because of their reliability. PIDNs have usually been branched networks due to their lower investment costs. However, it was proven from this work that using localized loops where improvement is mostly needed provides great cost savings for the rehabilitation of branched PIDSs. By comparing case 1 and case 2, even though the two solutions provided the same magnitude of improvement to the network, a cost saving of about 77% is obtained by choosing case 1 as the rehabilitation solution.

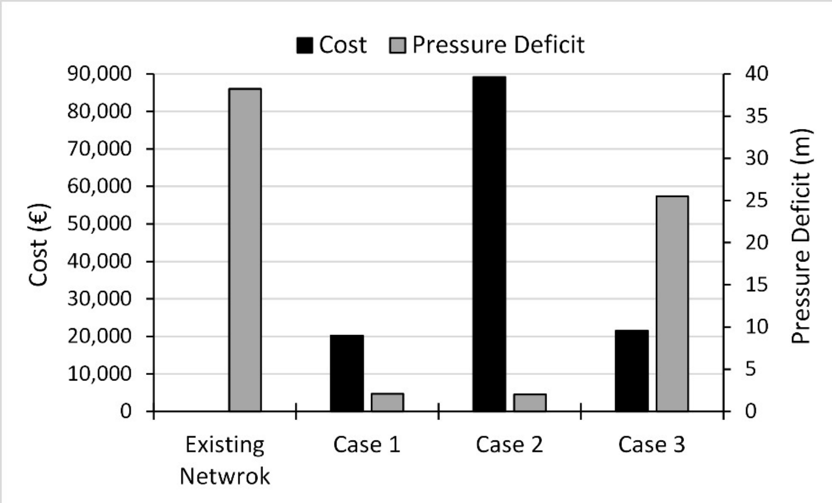

Fig. V-13. Pressure deficits and associated rehabilitation costs

V.4 Conclusions

The objective of this work was to develop a comprehensive optimization module to assist planners and decision makers in the determination of the most cost-effective strategy for the rehabilitation of PIDNs. For this purpose, an optimization module was developed and tested on a medium-size network. The developed module is equipped with an innovative automatic search operator for the localization of looping position, according to pre-defined conditions, that may improve the overall performance of the network. It also uses NSGA-II, a popular MOEA, to find the best trade-off between the minimization of pressure deficit at the most unfavourable hydrant in the network and the total cost of rehabilitation. Two optimization of the irrigation network rehabilitation were carried out. The first one included the option of adding loops by using the automatic looping operator and the second one excluded that option. The obtained results clearly indicate that it is worthwhile to consider the localized loops option. A selected solution considering this option provided a rehabilitation cost saving of about 77% compared to a solution, which provided similar improvement but excluded the looping option.

The developed module can easily be modified to use alternative objective functions. It can also be used for the design of new distribution networks by assigning an initial pipe diameter of 0 to all pipes. During this work, Energy costs were not explicitly considered because the network in the case study is operated by gravity. However, it can be easily incorporated into the cost objective function. It is interesting to adapt this module for networks with pumps to explore the impact of including looping option, in the rehabilitation, on energy saving.

Annex V-1. Pipe diameters in the existing network and the selected rehabilitation cases

ID	Initial Node	Final Node	Diameter (mm)	New Pipe Diameters (mm)		
				Case 1	Case 2	Case 3
520	19	520	250	250	**315**	250
521	520	521	250	250	**315**	250
522	521	522	250	250	250	250
523	522	523	250	250	250	250
524	523	524	180	**250**	180	**200**
525	524	525	180	180	180	180
526	525	526	180	180	180	180
527	526	527	180	180	180	180
528	527	528	180	180	180	180
529	528	529	180	180	180	180
530	529	530	180	180	180	180
531	530	531	180	180	180	180
532	531	532	140	140	140	140
533	528	533	180	180	180	180
534	533	534	180	180	180	180
535	534	535	180	180	180	180
536	535	536	180	180	180	180
537	536	537	140	140	140	140
538	537	538	140	140	140	140
539	523	539	250	250	250	250
540	539	540	250	250	250	250
541	540	541	140	140	140	140
542	541	542	140	140	140	140
543	542	543	125	125	125	125
544	540	544	250	250	250	250
545	544	545	140	140	140	**160**
546	544	546	250	250	250	250
547	546	547	140	140	**180**	**180**

ID	Initial Node	Final Node	Diameter (mm)	New Pipe Diameters		
				Case 1	Case 2	case 3
548	546	548	250	250	250	250
549	548	549	250	250	250	250
550	549	550	200	200	**250**	200
551	550	551	200	200	**250**	200
552	551	552	200	200	**250**	200
553	552	553	180	180	**250**	**200**
554	553	554	180	180	**225**	**200**
555	554	555	180	180	**225**	**200**
556	555	556	180	180	**200**	180
557	556	557	180	180	**200**	180
558	557	558	180	180	**200**	180
559	558	559	180	180	180	180
560	559	560	180	180	180	180
561	560	561	180	180	180	180
562	560	562	180	180	180	180
563	562	563	180	180	180	180
564	558	564	180	180	**200**	180
565	564	565	180	180	180	180
566	565	566	180	180	180	180
567	566	567	180	180	180	180
568	567	568	180	180	180	180
569	568	569	180	180	180	180
570	569	570	180	180	180	180
571	570	571	180	180	180	180
Suggested Loops						
1	557	535	0	0	0	0
2	557	536	0	**125**	0	0
3	557	537	0	0	0	0
4	557	538	0	0	0	0
5	564	538	0	**160**	0	0

V.5 References

Aliod, R., González, C., 2008. A computer model for pipe flow irrigation problems, in: Garcia-Navarro, P., Playán, E. (Eds.), Numerical modelling of hydrodynamics for water resources. Proceedings of the Conference on Numerical Modelling of Hydrodynamic Systems. Taylor & Francis, London. pp. 293-313., Zaragoza, Spain, 18-21 June 2007., pp. 293-313.

Artina, S., Bragalli, C., Erbacci, G., Marchi, A., Rivi, M., 2012. Contribution of parallel NSGA-II in optimal design of water distribution networks. Journal of Hydroinformatics 14, 310-323. doi:10.2166/hydro.2011.014

Babayan, A., Kapelan, Z., Savic, D., Walters, G., 2005. Least-cost design of water distribution networks under demand uncertainty. J. Water Resour. Plann. Manage. 131, 375-382. doi:10.1061/(ASCE)0733-9496(2005)131:5(375)

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6, 182-197. doi:10.1109/4235.996017

Farmani, R., Abadia, R., Savic, D., 2007. Optimum design and management of pressurized branched irrigation networks. Journal of Irrigation and Drainage Engineering 133, 528-537. doi:doi:10.1061/(ASCE)0733-9437(2007)133:6(528)

Farmani, R., Walters, G., Savic, D., 2006. Evolutionary multi-objective optimization of the design and operation of water distribution network: total cost vs. reliability vs. water quality. Journal of Hydroinformatics 8, 165-179. doi:10.2166/hydro.2006.019

Fernández García, I., Creaco, E., Rodríguez Díaz, J.A., Montesinos, P., Camacho Poyato, E., Savic, D., 2016. Rehabilitating pressurized irrigation networks for an increased energy efficiency. Agric. Water Manage. 164, Part 2, 212-222. doi:10.1016/j.agwat.2015.10.032

Fouial, A., Khadra, R., Daccache, A., Lamaddalena, N., 2016. Modelling the impact of climate change on pressurised irrigation distribution systems: Use of a new tool for adaptation strategy implementation. Biosystems Engineering 150, 182-190. doi:10.1016/j.biosystemseng.2016.08.010

Giustolisi, O., Berardi, L., 2009. Prioritizing pipe replacement: From multiobjective genetic algorithms to operational decision support. J. Water Resour. Plann. Manage. 135, 484-492. doi:10.1061/(ASCE)0733-9496(2009)135:6(484)

Goldberg, D.E., 1989. Genetic algorithms in search, optimization and machine learning. Addison-Wesley Longman Publishing Co., Inc., USA.

Lamaddalena, N., 1997. Integrated simulation modeling for design and performance analysis of on-demand pressurized irrigation systems, Instituto Superior de Agronomia. Universidade Técnica de Lisboa, Lisboa.

Lamaddalena, N., Khadra, R., Fouial, A., 2015. Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig Sci 33, 453-468. doi:10.1007/s00271-015-0481-5

Murphy, L.J., Dandy, G.C., Simpson, A.R., Gransbury, J.C., 1998. Optimisation of irrigation infrastructure rehabilitation using genetic algorithms, National Conference, Irrigation Association of Australia, Brisbane, Australia.

Nicolini, M., 2004. Evaluating performance of multi-objective genetic algorithms for water distribution system optimization, Sixth International Conference on Hydroinformatics. World Scientific Publishing Company, pp. 850-857.

Olsson, R.J., Kapelan, Z., Savic, D.A., 2009. Probabilistic building block identification for the optimal design and rehabilitation of water distribution systems. Journal of Hydroinformatics 11, 89-105. doi:doi:10.2166/hydro.2009.047

Reca, J., Martínez, J., 2006. Genetic algorithms for the design of looped irrigation water distribution networks. Water Resour. Res. 42, W05416. doi:10.1029/2005WR004383

Roshani, E., Filion, Y.R., 2014. Water distribution system rehabilitation under climate change mitigation scenarios in Canada. J. Water Resour. Plann. Manage. 141, 04014066. doi:10.1061/(ASCE)WR.1943-5452.0000450

Saleh, S.A., Tanyimboh, T., 2013. Coupled Topology and Pipe Size Optimization of Water Distribution Systems. Water Resour. Manage. 27, 4795-4814. doi:10.1007/s11269-013-0439-4

Savic, D.A., 2002. Single-objective vs. multiobjective optimisation for integrated decision support, in: Rizzoli, A.E., Jakeman, A.J. (Eds.), Integrated Assessment and Decision Support, pp. 7-12.

Savic, D.A., Walters, G.A., 1997. Genetic algorithms for least-cost design of water distribution networks. J. Water Resour. Plann. Manage. 123, 67-77. doi:doi:10.1061/(ASCE)0733-9496(1997)123:2(67)

Simpson, A.R., Dandy, G.C., Murphy, L.J., 1994. Genetic algorithms compared to other techniques for pipe optimization. J. Water Resour. Plann. Manage. 120, 423-443. doi:doi:10.1061/(ASCE)0733-9496(1994)120:4(423)

Tanyimboh, T.T., Seyoum, A.G., 2016. Multiobjective evolutionary optimization of water distribution systems: Exploiting diversity with infeasible solutions. Journal of environmental management 183, Part 1, 133-141. doi:10.1016/j.jenvman.2016.08.048

Wang, Q., Creaco, E., Franchini, M., Savić, D., Kapelan, Z., 2015. Comparing low and high-level hybrid algorithms on the two-objective optimal design of water distribution systems. Water Resour. Manage. 29, 1-16. doi:10.1007/s11269-014-0823-8

White, T., He, S., 2012. An empirical comparison of several recent multi-objective evolutionary algorithms, in: Iliadis, L., Maglogiannis, I., Papadopoulos, H. (Eds.), Artificial Intelligence

Applications and Innovations: 8th IFIP WG 12.5 International Conference, AIAI 2012, Halkidiki, Greece, September 27-30, 2012, Proceedings, Part I. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 48-57.

Wu, W., Maier, H.R., Simpson, A.R., 2013. Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions. Water Resour. Res. 49, 1211-1225. doi:10.1002/wrcr.20120

Zitzler, E., Deb, K., Thiele, L., 2000. Comparison of multiobjective evolutionary algorithms: Empirical results. Evolutionary Computation 8, 173-195. doi:10.1162/106365600568202

CHAPTER VI

MODELLING THE IMPACT OF CLIMATE CHANGE ON PRESSURIZED IRRIGATION DISTRIBUTION SYSTEMS: USE OF A NEW TOOL FOR ADAPTATION STRATEGY IMPLEMENTATION*

VI.1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2013), global mean temperatures are continuing to rise and some regions of the world will experience increases in the frequency, duration and magnitude of hot extremes, which will particularly affect food security. The Mediterranean region has been identified as one of the most prominent climate response Hot-Spots, where potential climate change impacts on agricultural systems can be evident (Giorgi, 2006; Iglesias et al., 2007; Olesen et al., 2011). The region will experience an increase in drought, decreased water availability, deterioration of water quality and increase in irrigation needs (Iglesias and Garrote, 2015). In a semi-arid area such as the Mediterranean, climate change is likely to affect agriculture in two distinct ways (Schlenker et al., 2007). The first one is the direct effect of climate on crop growth. In addition, changes in temperature, precipitation and solar radiation may negatively affect the demand for irrigation water, the crop yield (Olesen and Bindi, 2002; Zhao et al., 2015) and the availability of water for irrigation.

Irrigation infrastructures, such as PIDSs, play an important role for the intensification of agricultural production in the semi-arid Mediterranean region, with positive effects on the rural economy and the sustainability of agriculture. Therefore, in order to assess the potential effect of climate change on irrigated crops, it is indispensable to consider not only the direct effects of climate on crop yields but also its effects on the performance of infrastructures that deliver irrigation water. Many studies have assessed the impacts of climate change on irrigation water

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demands, with inputs of future climate projections obtained from several Global Circulation Models (GCMs), for various crops in the Mediterranean region (García-Garizábal et al., 2014; Rodríguez Díaz et al., 2007; Saadi et al., 2015; Tanasijevic et al., 2014; Yano et al., 2007). Results from these studies have predicted an increase in irrigation water demands and, consequently, an increase of the gap between demand and supply. However, only few studies have considered the consequences of these results on the performance of PIDSs (Daccache et al., 2010; Pérez Urrestarazu et al., 2010).

The design of these systems must be adequate to convey the demand for water during the peak period, guaranteeing the minimum pressure at the hydrants for conducting adequate on-farm irrigation. PIDSs, if properly designed, provide an efficient use of water and allow for on-demand delivery schedules, which offer a greater potential profit as compared to other schedules (Lamaddalena and Sagardoy, 2000). Due to the expected increase in irrigation water demands, PIDSs will have to be designed for longer and higher peaks in water demand which may also cause problems in some of the already existing systems (Rodríguez Díaz et al., 2007). According to Fader et al. (2016), the Mediterranean region may face an increase in gross irrigation requirements between 4% and 18% only from climate change effect and consequently distribution and conveyance systems might not be adequate for such higher volume to be distributed.

Therefore, long-term as well as short-term adaptation measures have to be taken to overcome problems facing some of the existing PIDSs. From an engineering point of view, expensive adaptation strategy, involving the replacement of old and undersized pipes can be implemented to increase the capacity of these systems. Also, the installation of pumping stations or the increase of the pumping capacity of existing pumps could be used to improve the performance of some of these systems. However, these solutions require high investment and energy costs. Non-engineering based solutions are much cheaper but more difficult to implement, and less efficient if not well managed (Daccache et al., 2010). These solutions may require changes in the cropping pattern, sectoring of the irrigation system or the change of delivery schedule from on-demand to rotational. However, all these adaptations limit the flexibility and freedom of the farmers.

The main objective of this paper is to assess the impact of potential climate change scenarios on the sustainability of existing PIDSs and to propose possible solutions to face such impact. An example of an existing irrigation system located in Southern Italy will be analysed and discussed hereafter. This is achieved by evaluating the vulnerability and sensitivity as well as the adaptive capacity of the existing system, considering alternative adaptation strategies, which provide the best solutions to cope with future irrigation demands increase.

Climate change impacts are assessed using the new scenarios of future forcing developed for the Fifth Assessment Report (AR5) of the IPCC (IPCC, 2013). The Representative Concentration Pathways (RCPs) (Moss et al., 2010) provides a quantitative description of concentrations of the climate change pollutants in the atmosphere over time, as well as their radiative forcing in 2100. Compared to the previous SRES scenarios, RCPs have no fixed sets of assumptions related to population growth, economic development or technology associated. Instead, different socioeconomic futures can lead to the same level of radiative forcing. This enables researchers to test various permutations of climate policies and social, technological, and economic circumstances. The four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5) (IPCC, 2013). RCP2.6 (overall impact of 2.6 W/m2 by 2100) assumes a peak between 2010 and 2020 of the global annual GHG emissions to be followed by a substantial decline. Emissions in RCP4.5 and RCP6 peak around 2040 and 2080 respectively while emissions in the worst case scenario (RCP8.5) will continue to rise throughout the 21st century (Meinshausen et al., 2011).

VI.2 Study area

The Apulia region, Southern Italy, has a typical semi-arid Mediterranean climate characterized by hot, dry summers and mild, wet winters. For this reason, the study is conducted on district 4 network described in section IV.3. The irrigated crops are summarized in Table IV-1.

VI.3 Methodology

In this study, the estimation of irrigation requirements was attained using the irrigation demand and scheduling module, while the hydraulic analysis of District 4 network was carried out using the hydraulic analysis module. The first is used for the estimation of the total volumetric water demand of the entire district depending on the cropping pattern and the irrigation need of each individual crop. The second module is used to analyse the hydraulic performance of the system during peak demand time. Fig. VI-1 illustrates the various calculation steps followed to attain the objectives of this study.

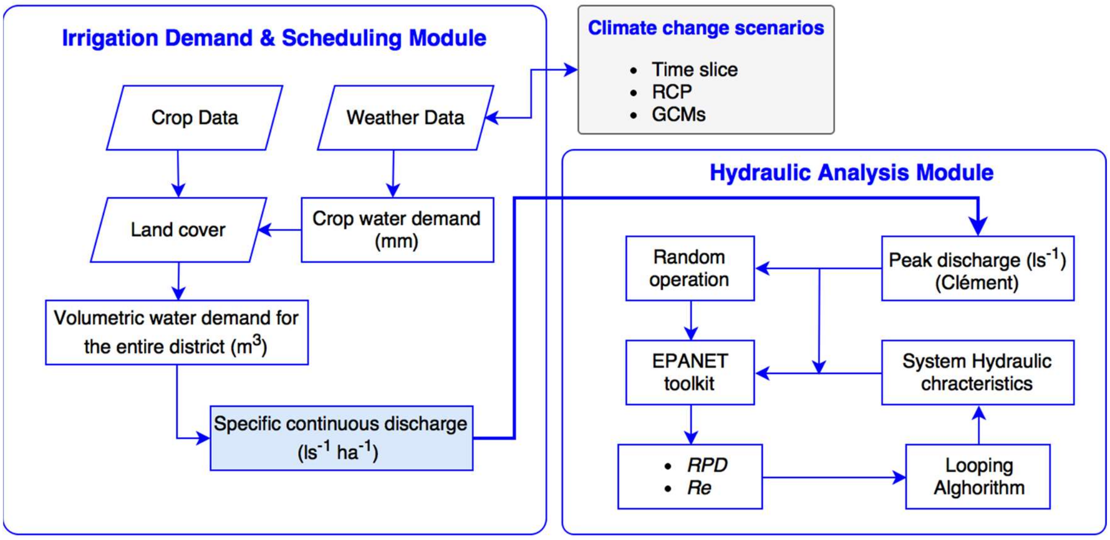


Fig. VI-1. Flowchart summarizing various calculation steps within DESIDS

VI.3.1 Climate change scenarios

Impact assessments of climate change on irrigation demands require daily data of weather variables for the study location, for both the current climate and a range of future possible scenarios. The direct use of climate predictions from multi-model ensemble could be problematic. This is because GCM predictions are typically available as monthly means or changes in monthly means of climatic variables on a coarse spatial resolution (Semenov et al., 2010). Several downscaling techniques have been used to support local-scale impact assessments such as statistical downscaling and weather generators (Kilsby et al., 2007; Semenov and Barrow, 1997). In this study, future data are generated using MarkSim GCM, a

GCM downscaler employing both stochastic downscaling and climate typing (Jones and Thornton, 2013). The basic algorithm of MarkSim is a daily rainfall simulator that uses a third-order Markov process to predict the occurrence of rainy days. It also estimates daily maximum and minimum air temperatures and daily solar radiation values. The generated data are obtained using an ensemble mean of 17 total GCMs (Annex VI-1). The use of the multi-model ensemble mean provides the most accurate basis for making best estimate projections of future climate (Reifen and Toumi, 2009). The outputs, used for the estimation of irrigation demands, are divided into three time series: i) Present, ii) 2050s and iii) 2080s, and for the two scenarios RCP2.6 and RCP8.5 used in AR5, representing respectively, low (GHG emissions reductions over time) and high emissions (business as usual).

VI.3.2 Irrigation water requirements

Irrigation water requirements (*GIR*) in the study area, is computed using a simplified water balance based on the difference between ET_c and effective rainfall (P_{eff}). P_{eff} is calculated as 80% of the total precipitation (mm), K_c is obtained from a series of field experiments conducted locally (Ciollaro et al., 1993), and ET_0 (mm day^{-1}) is estimated using the empirical formula of Hargreaves-Samani equation (Eq. II-2).

Using the current cropping pattern of District 4 (assuming an unchanged cropping pattern for the future) and the derived climate datasets for the Present and each of the two RPCs scenarios, the total volumetric water demand of the entire district is calculated. From which, the specific continuous discharge (ls^{-1} ha^{-1}) during peak demand period is obtained. The peak demand discharge is then calculated based on a probabilistic approach (Clément, 1966) where, the number of hydrants simultaneously opened is considered to follow a binomial distribution. A detailed description of Clément model can be found in Lamaddalena and Sagardoy (2000).

VI.3.3 Hydraulic analysis

Using the upstream peak demand discharge obtained with the probabilistic approach of Clément, a number of hydrants simultaneously operating (configurations) are automatically and randomly chosen. For each configuration, the hydraulic analysis module calculates the pressure head of each hydrant. Accordingly, two indicators are used to assess the performance of the system at hydrant level, the *RPD* (Eq. II-8) and *Re* (Eq. II-9). Using the two indicators, each hydrant is classified into classes of performance according to Table VI-1 (Khadra and Lamaddalena, 2010).

Table VI-1 System performance classified by RPD and hydrants Re indicators

Indicator	Performance			
	Good	Fair	Poor	Bad
RPD	$RPD \geq 0$	$0 > RPD \geq -0.3$	$-0.3 > RPD > -1$	$RPD \leq -1$
Re	$1 \geq Re \geq 0.8$	$0.8 > Re \geq 0.5$	$Re < 0.5$	

VI.3.4 Adaptation strategy

In response to the projected worsening of the performance of PIDSs, an adaptation strategy has to be implemented either through engineering or management solutions or both. Engineering solutions can be easily managed and implemented (Daccache et al., 2010). The capacity of the network to convey higher water volume can be implemented by increasing the size of the pipes or the capacity of the pumps to avoid new hydrants failure.

In this study, a cost effective solution is proposed. The solution consists of creating localised loops (Lamaddalena et al., 2015) connecting hydrants to compensate for pressure deficit and improve performance of the entire system.

VI.4 Results and discussions

VI.4.1 Impact of climate change on ET_0 and rainfall

Due to the combined effects of temperature increase and rainfall decrease, the water requirements for the available cropping pattern will increase in the future. In this work, the impact of temperature on the length of the growing season was not taken into consideration. Also planting date was assumed to remain the same in the future despite the rain and temperature patterns change. To avoid such methodological limitation a well calibrated and validated biophysical crop growth model with early planting option to reduce heat and prolonged drought effect on crop productivity are needed. For simplicity, these limitations were accepted in order to reduce the complexity of the work presented.

Changes in annual ET_0, irrigation requirements (*GIR*) and rainfall under the two considered future climate change scenarios RCP2.6 and RCP8.5 for the years 2050s and 2080s are presented in Fig. VI-2. ET_0 is shown to increase for both scenarios. In 2050s, ET_0 increased by about 6% for RCP2.6 and around 9% for RCP8.5. However, predictions for 2080s resulted in bigger difference in ET_0 increase between the two scenarios. RCP8.5 reached an increase of around 16% while the increase for RCP2.6 stayed at the same level as in 2050s. Similar pattern is shown for the predictions of future rainfall. For RCP2.6, the decrease in rainfall is about 4% for both time slices. Contrarily for RCP8.5, the decrease in 2080s is double that of 2050s reaching a drop of 22%. As a result, of the magnitude of changes in ET_0 and rainfall, there is a significant difference in the annual *GIR* between RCP2.6 and RCP8.5. The latter resulted in the highest *GIR* increase of about 34% in 2080s and around 20% in 2050s. Conversely, 2050s show a slightly higher increase of *GIR* (12%) compared to that of 2080s (around 10%) for the RCP2.6 scenario. This is due to the expected reduction of greenhouse gas for this scenario in the future. The projected increase of ET_0 and decrease of rainfall are unevenly distributed throughout the months of the year as depicted in Fig. VI-3.

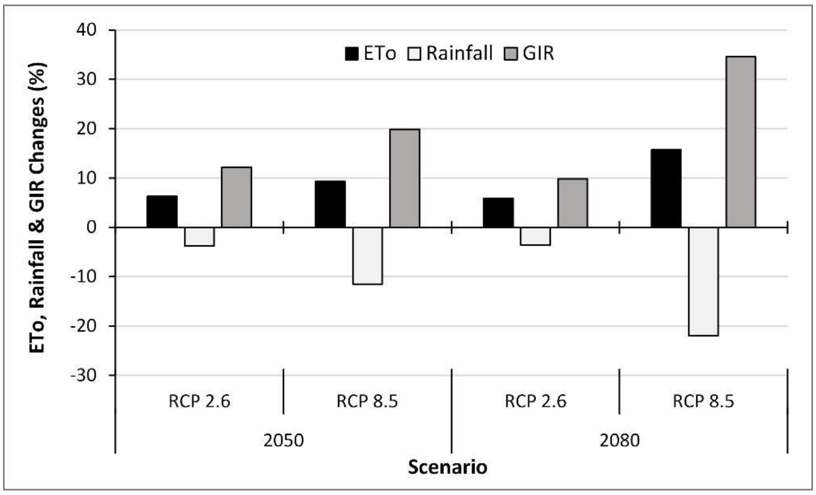


Fig. VI-2. Projected future changes (2050s and 2080s) in ET_0, GIR and rainfall using RCP2.6 and RCP8.5 scenarios

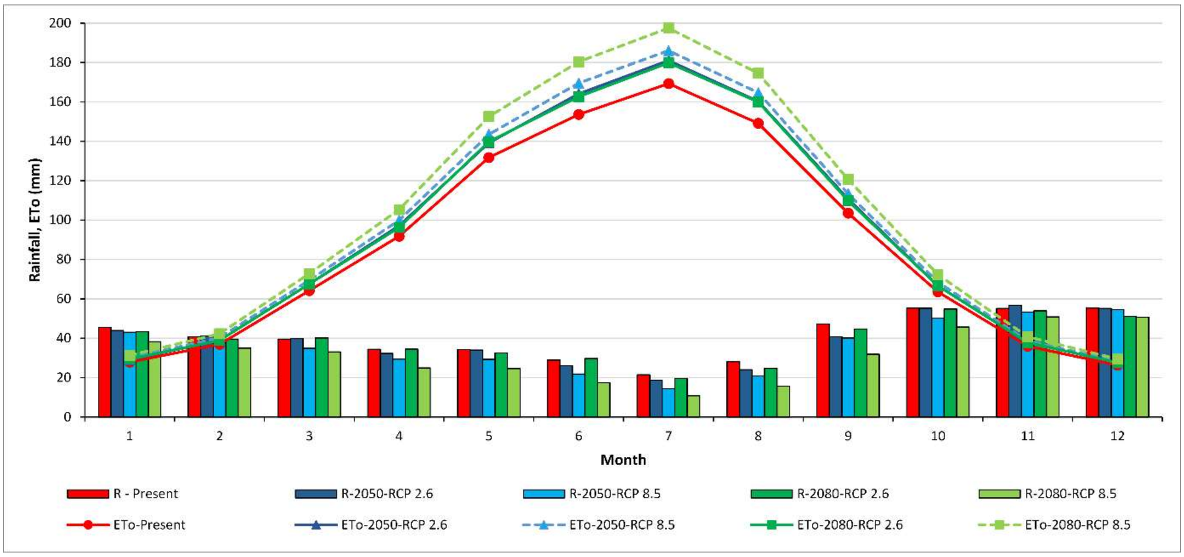


Fig. VI-3. Current and future (2050s and 2080s) monthly ET_0 and rainfall using RCP2.6 and RCP8.5 scenarios

Monthly ET_0 values increase at similar magnitude for RCP2.6 scenario in both time slices 2050s and 2080s. However, scenario RCP8.5 shows similar trend for both time slices but with sharper increase in 2080s. Most of the significant increases are recorded between the months of May and October for all scenarios as compared to the Present. Concerning monthly rainfall, the distribution of monthly projected changes in rainfall is different among the simulated scenarios. The maximum decreases for RCP8.5 are recorded in the month of July, which is the peak period, with values of around 50% and 33% for 2080s and 2050s, respectively, compared to the Present. However, the maximum decreases for RCP2.6 are recorded in the month of June with values of about 15% and 12% for 2080s and 2050s, respectively.

The peak water demand to satisfy the crops of District 4 is estimated through the calculation of the specific discontinuous discharge for the peak period. The results are used then to compute peak upstream discharge of the District as shown in Table VI-2.

Table VI-2. Specific continuous discharge and peak upstream discharge under present and future (2050's and 2080's) climate with RCP2.6 and RCP8.5 scenarios

	Present	2050		2080	
		RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Specific discontinuous discharge ($l\ s^{-1}\ ha^{-1)}$)	0.37	0.41	0.43	0.40	0.47
Upstream discharge ($l\ s^{-1}$)	1270	1400	1460	1370	1590

VI.4.2 Performance of the distribution system

Performance analysis of the existing network was carried out by generating 3000 random configurations of simultaneously opened hydrants. The maximum reservoir piezometric elevation is 143 m a.s.l, and the minimum required pressure head at hydrants (H_{min}) for appropriate on-farm irrigation is 20 m. The maximum upstream discharges used for the analysis are listed in Table VI-2.

Fig. VI-4 illustrates the 90% envelope curve (10% probability of exceedance) for the values of *RPD* resulting from the analyses corresponding to the peak water demand in the district for the Present and the two scenarios RCP2.6 and RCP8.5 for 2050s and 2080s. Regarding 2050s, the number of hydrants with good *RPD* fell from 541 to 471 and 432 for RCP2.6 and RCP8.5, respectively, whereas the number of hydrants labelled as bad increased from 10 to 45 and 60 for RCP2.6 and RCP8.5, respectively. Concerning 2080s, RCP2.6 scenario shows similar results as 2050s for the same scenario, with 481 hydrants classified as good and 45 hydrants categorised as bad. However, scenario RCP8.5 indicates an even worse situation with 376 good hydrants and 96 hydrants labelled as bad. This change has also affected the reliability of the District 4 network. The number of hydrants with good reliability decreased from 595 to 527 and 502 in 2050s and to 540 and 436 in 2080s for the scenarios RCP2.6 and RCP8.5, respectively.

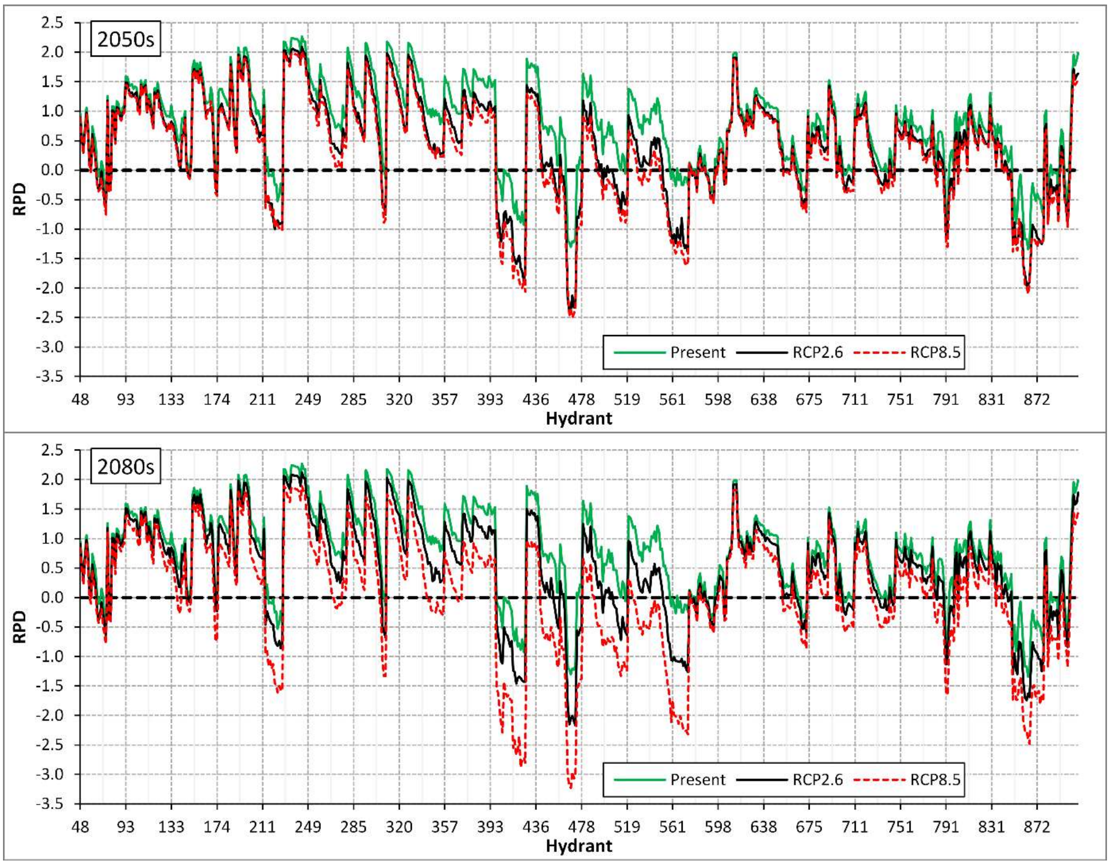


Fig. VI-4. RPD envelope (90%) under current and future climate (2050s and 2080s) using RCP2.6 and RCP8.5 scenarios

VI.4.3 Adaptation to climate change

In this study, by assuming an unchanged cropping pattern, upstream discharge increased between 8% and 25% depending on the selected emission scenarios (RCP2.6 and RCP8.5), for the time slices 2050s and 2080s. To tackle this increase in water demand, localised loops in the failure areas are proposed as shown in Fig. VI-5. The performance of localised loops solution which costs 677,000 € is compared to the optimised rehabilitation solution for the whole network with a total cost of 3.8 Million €.

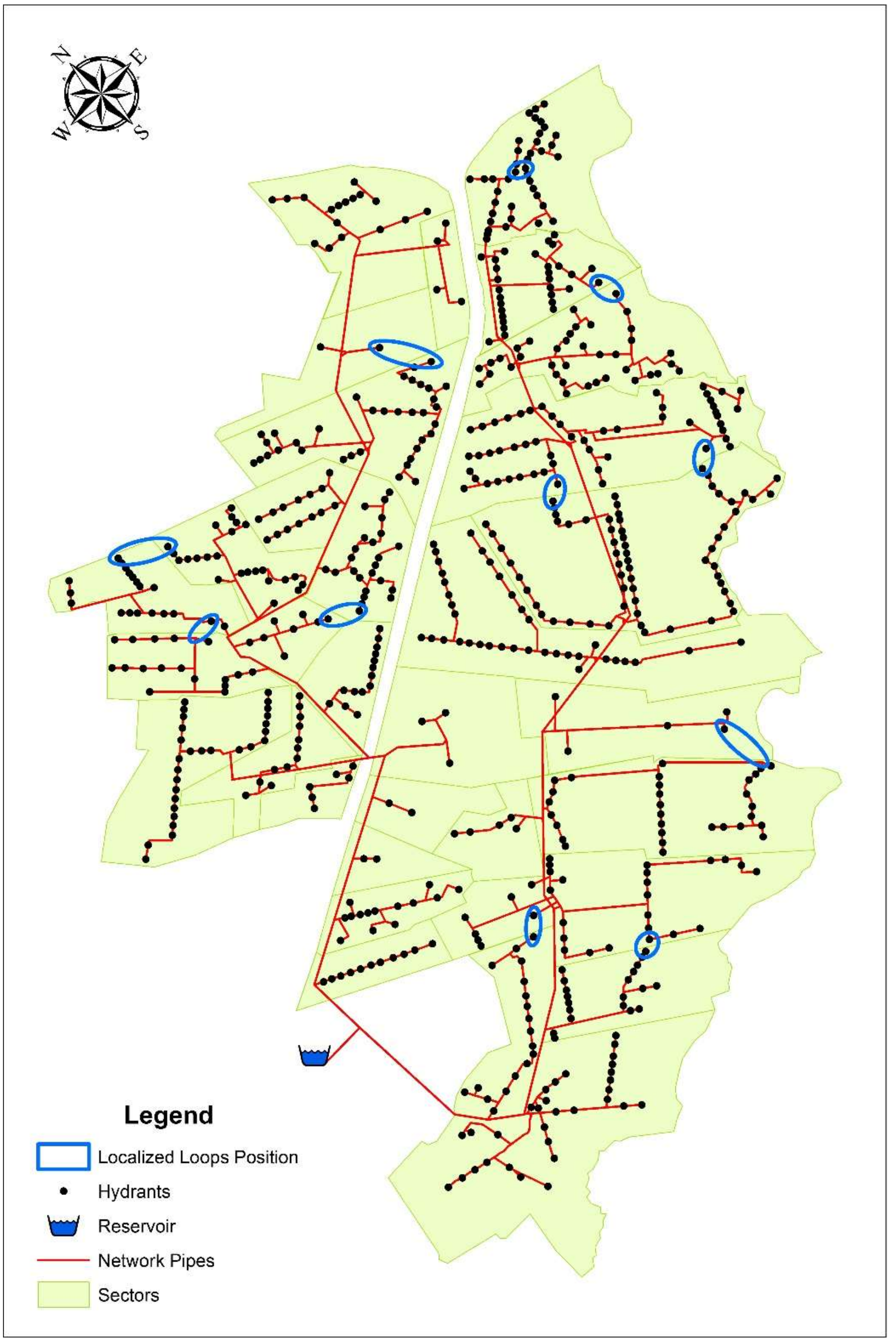
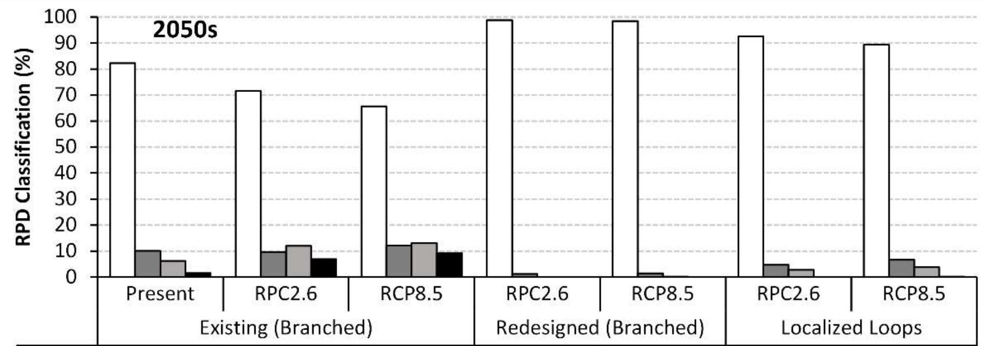


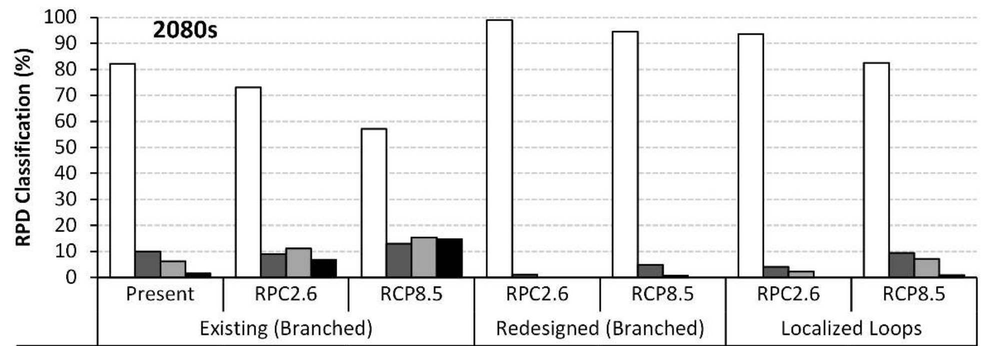
Fig. VI-5. Location of the loops proposed to improve the current and future performance of District 4 network

Fig. VI-6 and Fig. VI-7 illustrate the comparison between the results of *RPD* and reliability, respectively, from the hydraulic analysis (90% curve) of the existing District 4 network and the two adaptation strategies, optimised rehabilitation (pipe diameters increase) and localised loops.

For 2050s, the results show that for the RCP2.6 scenario, hydrants with good *RPD* increased by 27% using optimised rehabilitation of the whole network and 21% using localised loops, compared to the Present. In addition, both adaptations eliminated hydrants with bad *RPD* in the network. Hydrants with good reliability also increased by 19% and 16%, respectively, for the two considered strategies compared to the Present. Regarding RCP8.5 scenario, the optimised rehabilitation and localised loops increased the good *RPD* hydrants by 33% and 24%, respectively. They also increased hydrants with good reliability by 23% and 19%, respectively.



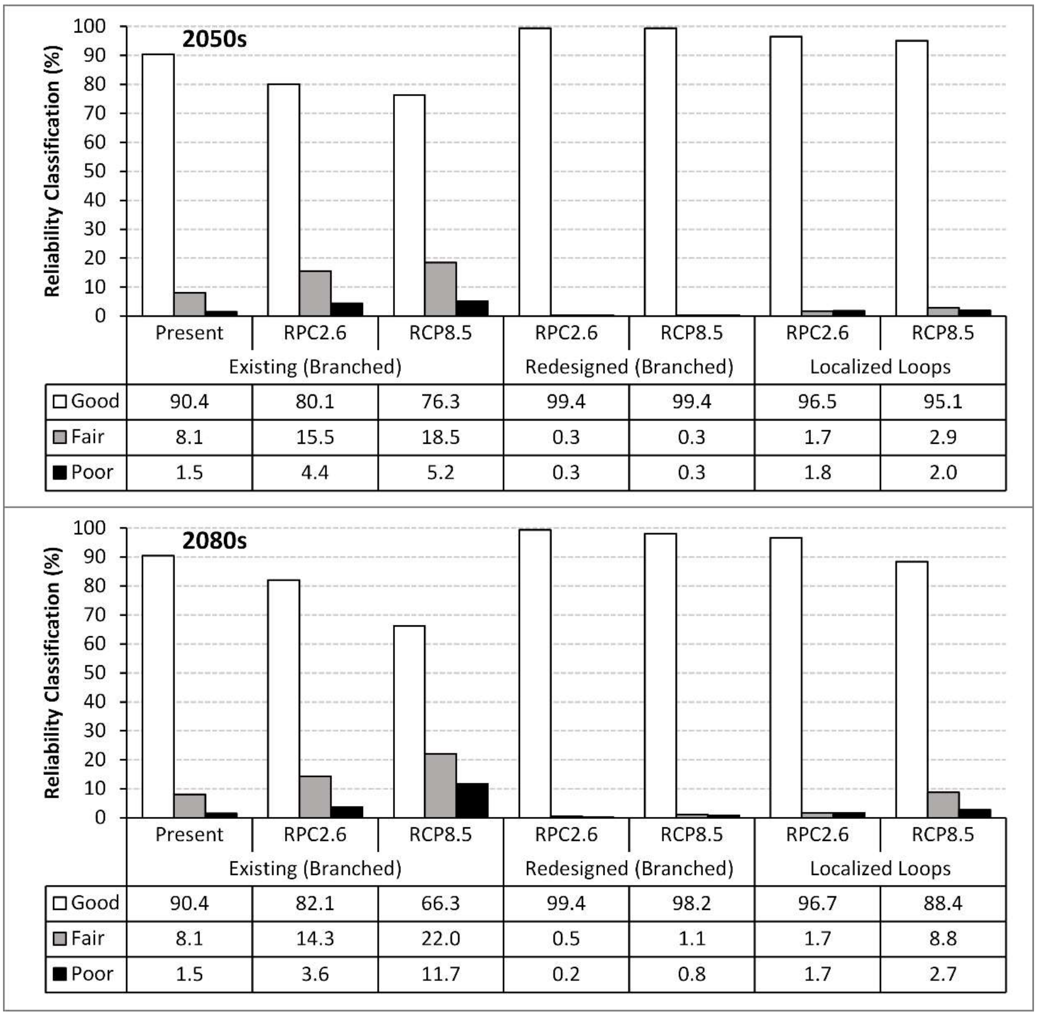
	Present	RPC2.6	RCP8.5	RPC2.6	RCP8.5	RPC2.6	RCP8.5
	Existing (Branched)			Redesigned (Branched)		Localized Loops	
Good	82.2	71.6	65.7	98.8	98.5	92.6	89.4
Fair	10.0	9.6	12.2	1.2	1.4	4.7	6.7
Poor	6.2	12.0	13.1	0.0	0.2	2.7	3.8
Bad	1.5	6.8	9.1	0.0	0.0	0.0	0.2



	Present	RPC2.6	RCP8.5	RPC2.6	RCP8.5	RPC2.6	RCP8.5
	Existing (Branched)			Redesigned (Branched)		Localized Loops	
Good	82.2	73.1	57.1	98.9	94.5	93.6	82.5
Fair	10.0	9.0	12.9	1.1	4.9	4.1	9.4
Poor	6.2	11.1	15.3	0.0	0.6	2.3	7.1
Bad	1.5	6.8	14.6	0.0	0.0	0.0	0.9

Fig. VI-6. Current and future performance of District 4 with existing, redesigned and localized loop solutions as evaluated using RPD indicator

For 2080s, hydrants labelled as good *RPD* increased by 26% and 21% in the RCP2.6 scenario when applying optimised rehabilitation and localised loops, respectively, while the good reliability hydrants increased by 17 and 15% (from 82 to 99 and 97%), respectively. Concerning the RCP8.5 scenario, optimised rehabilitation and localised loops increased hydrants with good *RPD* by 37 and 25%, respectively. Hydrants with good reliability also increased by 32 and 22% using both strategies, respectively.



	Present	RPC2.6	RCP8.5	RPC2.6	RCP8.5	RPC2.6	RCP8.5
	Existing (Branched)			Redesigned (Branched)		Localized Loops	
Good	90.4	80.1	76.3	99.4	99.4	96.5	95.1
Fair	8.1	15.5	18.5	0.3	0.3	1.7	2.9
Poor	1.5	4.4	5.2	0.3	0.3	1.8	2.0

	Present	RPC2.6	RCP8.5	RPC2.6	RCP8.5	RPC2.6	RCP8.5
	Existing (Branched)			Redesigned (Branched)		Localized Loops	
Good	90.4	82.1	66.3	99.4	98.2	96.7	88.4
Fair	8.1	14.3	22.0	0.5	1.1	1.7	8.8
Poor	1.5	3.6	11.7	0.2	0.8	1.7	2.7

Fig. VI-7. Current and future performance of District 4 with existing, redesigned and localized loop solutions as evaluated using hydrants reliability indicator.

VI.5 Conclusion

The assessment of the impact of climate change under two future scenarios RCP2.6 and RCP8.5 for time slices, 2050 and 2080, shows an increase in water demand between 8% and 25%, with the assumption of unchanged cropping pattern. The projected water demand can increase even further in the case where crops with higher water demand are used in the district. An adaptation strategy was investigated using localised loops to increase the capacity of the gravity-fed system without affecting the operational freedom of farmers (on-demand schedule). The implemented adaptation strategy proved its ability to improve the hydraulic performance of the system under higher future demand and even provided slightly better performance than the existing system under Present demand. This improvement solution also offers a saving of over 82% of improvement cost compared to the optimised rehabilitation solution. Further investigation is recommended to assess climate change for different cropping patterns to evaluate this adaptation strategy under higher demand, and to implement it in other systems with pumping stations to evaluate the possibility of energy saving.

Annex VI-1. List of the GCMs used by MarkSim GCM® to project future climate

	Model	Institution	Resolution Lat x Long
1	BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125
2	BCC-CSM 1.1(m)	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125
3	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence	1.875 x 1.875
4	FIO-ESM	The First Institute of Oceanography, SOA, China	2.812 x 2.812
5	GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
6	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
7	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5
8	GISS-E2-H	NASA Goddard Institute for Space Studies	2.0 x 2.5
9	GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 x 2.5
10	HadGEM2-ES	Met Office Hadley Centre	1.2414 x 1.875
11	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	1.875 x 3.75
12	IPSL-CM5A-MR	Institut Pierre-Simon Laplace	1.2587 x 2.5
13	MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125
14	MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125
15	MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	1.4063 x 1.4063
16	MRI-CGCM3	Meteorological Research Institute	1.125 x 1.125
17	NorESM1-M	Norwegian Climate Centre	1.875 x 2.5

VI.6 References

Ciollaro, G., Lamaddalena, N., Altieri, S., 1993. Analisi comparativa fra consume idrici stimati e misurati in un comprensorio irriguo dell'Italia meridionale [A comparative Analysis of estimated and measured water use in a Southern Italy irrigation Scheme] Rivista di Ingegneria Agraria 4, 234-243

Clément, R., 1966. Calcul des débits dans les réseaux d'irrigation fonctionnant à la demande. La Houille Blanche, 553-576

Daccache, A., Weatherhead, K., Lamaddalena, N., 2010. Climate change and the performance of pressurized irrigation water distribution networks under Mediterranean conditions: Impacts and adaptations. Outlook on Agriculture 39, 277-283. doi:10.5367/oa.2010.0013

Fader, M., Shi, S., von Bloh, W., Bondeau, A., Cramer, W., 2016. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrol. Earth Syst. Sci. 20, 953-973. doi:10.5194/hess-20-953-2016

García-Garizábal, I., Causapé, J., Abrahao, R., Merchan, D., 2014. Impact of climate change on Mediterranean irrigation demand: Historical dynamics of climate and future projections. Water Resour. Manage. 28, 1449-1462. doi:10.1007/s11269-014-0565-7

Giorgi, F., 2006. Climate change hot-spots. Geophysical Research Letters 33, L08707. doi:10.1029/2006GL025734

Iglesias, A., Garrote, L., 2015. Adaptation strategies for agricultural water management under climate change in Europe. Agric. Water Manage. 155, 113-124. doi:10.1016/j.agwat.2015.03.014

Iglesias, A., Garrote, L., Flores, F., Moneo, M., 2007. Challenges to Manage the Risk of Water Scarcity and Climate Change in the Mediterranean. Water Resour. Manage. 21, 775-788. doi:10.1007/s11269-006-9111-6

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, P.G., Thornton, P.K., 2013. Generating downscaled weather data from a suite of climate models for agricultural modelling applications. Agricultural Systems 114, 1-5. doi:10.1016/j.agsy.2012.08.002

Khadra, R., Lamaddalena, N., 2010. Development of a decision support system for irrigation systems analysis. Water Resour Manage 24, 3279-3297. doi:10.1007/s11269-010-9606-z

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A., Wilby, R.L., 2007. A daily weather generator for use in climate change studies. Environmental Modelling & Software 22, 1705-1719. doi:10.1016/j.envsoft.2007.02.005

Lamaddalena, N., Khadra, R., Fouial, A., 2015. Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig Sci 33, 453-468. doi:10.1007/s00271-015-0481-5

Lamaddalena, N., Sagardoy, J.A., 2000. Performance analysis of on-demand pressurized irrigation systems. FAO Irrigation and Drainage Paper 59. Food and Agriculture Organization of the United Nations, Rome, Italy.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, 213. doi:10.1007/s10584-011-0156-z

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747-756. doi:10.1038/nature08823

Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Europ. J. Agronomy 16, 239-262. doi:10.1016/S1161-0301(02)00004-7

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Europ. J. Agronomy 34, 96-112. doi:10.1016/j.eja.2010.11.003

Pérez Urrestarazu, L., Smout, I., Rodríguez Díaz, J., Carrillo Cobo, M., 2010. Irrigation distribution networks' vulnerability to climate change. J. Irrig. Drain Eng. 136, 486-493. doi:10.1061/(ASCE)IR.1943-4774.0000210

Reifen, C., Toumi, R., 2009. Climate projections: Past performance no guarantee of future skill? Geophysical Research Letters 36, L13704. doi:10.1029/2009GL038082

Rodríguez Díaz, J.A., Weatherhead, E.K., Knox, J.W., Camacho, E., 2007. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. Reg. Environ. Change 7, 149-159. doi:10.1007/s10113-007-0035-3

Saadi, S., Todorovic, M., Tanasijevic, L., Pereira, L.S., Pizzigalli, C., Lionello, P., 2015. Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. Agric. Water Manage. 147, 103-115. doi:10.1016/j.agwat.2014.05.008

Schlenker, W., Hanemann, W.M., Fisher, A., 2007. Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California. Climatic Change 81, 19-38. doi:10.1007/s10584-005-9008-z

Semenov, M., Barrow, E., 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change 35, 397-414. doi:10.1023/A:1005342632279

Semenov, M., Donatelli, M., Stratonovitch, P., Chatzidaki, E., Baruth, B., 2010. ELPIS: a dataset of local-scale daily climate scenarios for Europe. Clim. Res. 44, 3-15. doi:10.3354/cr00865

Tanasijevic, L., Todorovic, M., Pereira, L.S., Pizzigalli, C., Lionello, P., 2014. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. Agric. Water Manage. 144, 54-68. doi:10.1016/j.agwat.2014.05.019

Yano, T., Aydin, M., Haraguchi, T., 2007. Impact of climate change on irrigation demand and crop growth in a Mediterranean environment of Turkey. Sensors 7, 2297-2315. doi:10.3390/s7102297

Zhao, G., Webber, H., Hoffmann, H., Wolf, J., Siebert, S., Ewert, F., 2015. The implication of irrigation in climate change impact assessment: a European-wide study. Glob. Change Biol. 21, 4031-4048. doi:10.1111/gcb.13008

CHAPTER VII

GENERAL CONCLUSIONS

VII.1 Conclusions

The decision-making processes associated with collective PIDSs is very complex, and require thorough consideration and analysis. These processes include (i) the determination of the existing problems to be solved and the targeted objectives; (ii) analysis of the current operation processes (mainly the links between the manager's and the farmers' decisions); (iii) definition of management plans; (iv) and assessment of possible operation and management strategies and their expected impact on farmers. Nowadays, irrigation district managers are in need of several tools to assess the performance and the management of PIDSs, such as hydraulic models and DSSs, which are available, but as independent elements.

Therefore, there is a need to provide an integrated solution, a DSS that is based on a real 'need' services that help irrigation district managers with the complex intertwined processes mentioned above. To this end, a comprehensive DSS called DESIDS has been developed in the framework of this research to deal with the different components related to PIDS, such as planning, performance analysis, management and rehabilitation. DESIDS was developed with the idea to provide an effective DSS that incorporates, simultaneously, all these components with enough flexibility to adjust to any new requirements and changes needed by irrigation district managers and decision makers. Thus, prodigious care has been taken in creating a flexible, relatively easy to handle DSS, which also offers an effective platform for managers to understand and evaluate the impact of their decisions on the overall performance of PIDS and on the quality of services provided to farmers.

DESIDS is a comprehensive DSS that encompasses four separate, yet easily integrated modules:

1. *The irrigation demand and scheduling module*: used for the calculation of CWRs, irrigation demand, irrigation scheduling for an entire irrigation district, and generates operating hydrants configurations. The latter capability is a vital information for district managers to simulate realistic operations of PIDS. Hence, helps in the prediction of the performance of

a system throughout the irrigation season, which is imperative in the decision-making process for better management. This module was tested in a case study in Southern Italy to generate hourly operating hydrants configurations, by estimating the irrigation scheduling for each field served by the considered PIDS, using climatic, crop and soil data. Results showed that this tool provides irrigation district managers with great flexibility and the ability to assess the operation of PIDSs at any period during the irrigation season;

2. *The operation and management module*: used to provide optimal operation strategies to achieve the best services (demand and pressure) to farmers. This module includes an optimization tool that uses GA to assign each operating hydrant in a PIDS to an irrigation period during the day considering as objective function of the optimization problem, the minimization of pressure deficit at the most unfavourable hydrant. The module was tested on a large-scale PIDS showing management solutions that successfully improve the hydraulic performance of the failing system, ensuring the satisfaction of CWRs in all hydrants. These solutions were also able to overcome a significant increase in the upstream discharge;
3. *The design and rehabilitation module*: this module considers the possibility that in some cases, improving management alone (using the previous module) does not considerably cause an improvement in PIDSs hydraulic performance unless combined with structural rehabilitation. Hence, this module offers a comprehensive optimization tool to assist planners and decision makers in the determination of the most cost-effective strategy for the rehabilitation of PIDNs. This tool uses NSGA-II to find the best trade-off between the minimization of pressure deficit at the most unfavourable hydrant in the network and the total cost of rehabilitation. It is also equipped with an innovative automatic search operator for the localization of looping position, according to pre-defined conditions. This module was tested on a medium-sized network in Southern Italy and showed to provide a wide range of rehabilitation solutions. However, the obtained results clearly indicated that it is worthwhile to consider the localized loops option included in the tool. A selected solution considering this option provided a rehabilitation cost saving of about 77% compared to a solution, which provided similar improvement but excluded the looping option.
4. *The hydraulic analysis module*: this is the core of DESIDS, as it is the tool used to evaluate the hydraulic performance of PIDS and to assess the impact of the decisions taken using

the abovementioned modules. This module was tested in the different case studies used in this research, as it is the core that links all modules in DESIDS. The module uses two types of analyses, namely DDA and PDA. The latter is usually ignored when dealing with PIDSs. However, it was proven in this research that this type of analysis is vital to determine not just pressure deficiencies in a network but also the impact of these deficiencies on the supplied discharges from hydrants. Thus, it estimates the potential negative impact of the overall performance of a PIDS on crops yield. This information is imperative as it gives irrigation district managers the ability to extend the management of the PIDS beyond the distribution structure and understand the real effect of their decisions on crops yield, thus farmers income. The results of this module can be displayed on the incorporated GIS to facilitate the localization of the failing areas in the considered PIDS.

An Integrated DSS was developed in the framework of this research and tested in several case studies. It was demonstrated that this is a vital tool that includes innovative components to help irrigation district managers and decision makers in addressing the key issues and challenges often found in PIDS, including planning, analysis, operation, management and rehabilitation processes. Four discrete modules were developed in a decoupled fashion to maximize their use in the previously mentioned processes and to support future expansions and integrations in DESIDS. It is worth mentioning that in all the case studies used in this research, energy uses and costs were not explicitly considered because this subject is extensively researched and widely available in the literature. However, this can be easily incorporated and analysed in the mentioned modules. It is interesting though to apply this DSS on networks with pumps to explore the impact of the decisions taken by irrigation district managers using DESIDS on energy saving. Nevertheless, the developed DSS is an important tool that can be used as a platform for future integrations and improvement of the overall efficiency of the integrated processes.

VII.2 Published and presented works

Fouial, A., Fernández García, I., Bragalli, C., Lamaddalena, N., Rodríguez Diaz, J.A. Multi-objective optimization model based on localized loops for the rehabilitation of pressurized irrigation networks. Submitted for review to Water Resources Management.

Fouial, A., Fernández García, I., Bragalli, C., Brath, A., Lamaddalena, N., Rodríguez Diaz, J.A., (2017). Optimal operation of pressurised irrigation distribution systems operating by gravity. Agric. Water Manage. 184, 77-85. doi:10.1016/j.agwat.2017.01.010

Fouial, A., Khadra, R., Daccache, A., & Lamaddalena, N. (2016). Modelling the impact of climate change on pressurised irrigation distribution systems: Use of a new tool for adaptation strategy implementation. Biosystems Engineering, 150, 182-190. doi:10.1016/j.biosystemseng.2016.08.010

Lamaddalena, N., Khadra, R., Fouial, A., (2015). Use of localized loops for the rehabilitation of on-demand pressurized irrigation distribution systems. Irrig. Sci. 33, 453-468. doi:10.1007/s00271-015-0481-5

Fouial, A., Khadra, R., and Lamaddalena, N. (2015) Impact of climate change on irrigation infrastructures: Use of localized loops as an adaptation strategy. Paper presented at the IX International Workshop on Planning and Evaluation - Strategies for the Environment: Evaluating and Planning for Extreme Events - AESOP. Mediterranean Agronomic Institute of Bari, Valenzano (Bari), Italy. 16-17 March 2015.