A Methodology to Conduct Diagnostic Performance Assessment and Simulation of Deliveries in Large-Scale Pressurized Irrigation Systems

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A METHODOLOGY TO CONDUCT DIAGNOSTIC PERFORMANCE
ASSESSMENT AND SIMULATION OF DELIVERIES IN LARGE-SCALE PRESSURIZED IRRIGATION SYSTEMS

by

Daniele Simone Alessio Zaccaria

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Irrigation Engineering

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2011
ABSTRACT

A Methodology to Conduct Diagnostic Performance Assessment and Simulation of Deliveries in Large-Scale Pressurized Irrigation Systems

by

Daniele Simone Alessio Zaccaria, Doctor of Philosophy

Utah State University, 2011

Major Professor: Dr. Christopher M.U. Neale
Department: Civil and Environmental Engineering, Irrigation Engineering Division

A methodology was developed to conduct diagnostic performance assessment and simulation of alternative delivery scenarios in pressurized irrigation distribution networks. It consists of three components, an agro-hydrologic model able to forecast peak water demand hydrographs, a hydraulic model with capability of simulating the network behavior under different flow configurations, and a set of performance indicators for conducting assessments of performance achievements relative to specified targets.

As a preliminary work, the current delivery schedule of an existing pressurized irrigation network (system 1) and the resulting effects on crop irrigation management were analyzed by simulating soil water balance and irrigation scheduling at field level. Simulations allowed analyzing the on-farm irrigation management under the current rotation deliveries, and comparing it with an alternative flexible irrigation scheduling to maximize crop yields. Results at field level were up-scaled to the entire command area of the system, showing the usefulness of soil water balance and of irrigation scheduling as
analytical tools to demonstrate the inconsistency between the current water delivery and crops’ and farmers’ requirements. This preliminary work also allowed highlighting the need for modernizing the irrigation management in the first of the two study areas considered for the present research work (system 1 located in the province of Taranto, southern Italy).

An existing agro-hydrological model conceived to forecast water demand hydrographs in pressurized delivery networks was enhanced through several refinements and amendments of the computation algorithms. The refined model was applied for validation at different management levels on an existing pressurized irrigation system (system 2) located in the province of Foggia, southern Italy, where water withdrawals by farmers and the main hydraulic parameters are recorded on a continuous basis for monitoring purposes.

Results from validation showed that the model is capable of forecasting with good accuracy the timing of peak-demand periods, the seasonal demand irrigation volumes, as well as the hydrographs of hourly flow rates demanded by farmers during these peak periods, especially when it is applied to large multi-cropped command areas.

Performance indicators, originally conceived for diagnostic assessment in canal systems, were modified for application to pressurized distribution networks, and reference standard values were proposed. These indicators were then applied for validation to the second study area (irrigation system 2), where records of water deliveries are available, and showed their usefulness for diagnostic performance assessments.
Finally, the proposed methodology for diagnostic assessment and simulation of deliveries was applied to two tail-end districts of the first study area (irrigation system 1) and enabled the analysis of networks performances under different flow configurations. This application showed the usefulness of the combined analysis and simulation tools for addressing physical and operational aspects of modernization of poor performing delivery networks.

(191 pages)
DEDICATION

To my dear parents, Luigi and Anna, for giving me the precious gifts of life and vision to the future, and for their unconditional support during the long and demanding period of work necessary for the completion of this program.
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CHAPTER 1
INTRODUCTION

Background

Worldwide, 70% of the water resources extractions are due to agricultural water use, but agriculture is considered as the least water-efficient sector and several analyses showed that irrigated agriculture utilize effectively only 45% of the available water supply. Overall losses of 55% are reported (source: FAOSTAT statistic database, 2008) as cumulative from inefficiencies at the level of water distribution system (15%), at field application (25%) and at farm distribution (15%).

Water distribution to farms is accomplished by means of large-scale irrigation systems, which in the past played a significant role in developing, stabilizing and diversifying agricultural production in rural areas. At present, large-scale irrigation systems have the major objective of enabling the effective and equitable distribution of limited water resources that otherwise would only be accessible to few (Lamaddalena and Sagardoy 2000).

As indicated by IWMI (2007), at present and most likely in the near future, new investments focus much more on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes, rather than on expanding irrigated areas. Irrigation will need to adapt to serve an increasingly productive agriculture and technical and institutional efforts will be needed to adapt yesterday’s systems to today’s and tomorrow’s needs.
In the arid and semi-arid regions of the Mediterranean basin, fresh water supplies are being increasingly demanded for municipal, industrial and touristic uses. Water is therefore progressively been transferred from irrigated agriculture to higher valued industrial and urban uses and there is also a call for more water to be reserved for environmental purposes (Bos et al. 2005). According to IWMI (2007), as competition for water from other sectors intensifies, irrigation is increasingly being under pressure to release water for higher valued water uses, and the reduction of water availability for agriculture and water scarcity represent the major incentives for irrigation systems to perform better. Small and Svendsen (1992) reported that in many areas of the world irrigation projects perform far below their potential and poor performances of conveyance and delivery systems were also documented by several other authors and institutions (Plusquellec et al. 1994; UNESCO 2003) as mainly due to unrealistic designs, to rigid water delivery schedules, to operational problems or to inconsistencies between the systems management and the needs of users. D’urso (2001) pointed out that irrigation agencies and water users’ organizations are being questioned about the current level of efficiency in water use and are continuously asked to improve the performance of their irrigation delivery systems. For doing so, performance assessments should be periodically conducted on existing systems to benchmark the actual achievements with respect to current and future water management objectives.

As pointed out by several authors (Murray-Rust and Snellen 1993; Small and Svendsen 1992; Burt and Styles 2004) in the domain of irrigation system management there is a remarkable lack of analytical frameworks to support irrigation managers and auditors in evaluating performance achievements and in identifying feasible ways to
enhance performance in the future. Therefore, diagnostic methodologies are needed to analyze system behavior, assess current and future performances, and identify critical aspects and weaknesses in the operation of existing irrigation systems.

**Problem Formulation**

The International Commission on Irrigation and Drainage defined Modernization of irrigation systems as “the process of improving and enhancing an existing project to meet new performance criteria.” According to the ICID perception, the process includes changes in existing facilities, operational procedures, management, and institutional aspects. These changes are designed to enhance economic and social benefits of the users and the region (Price 1999).

FAO (2007) pointed out that irrigation modernization is often misunderstood and associated exclusively with high technology or costly automation. Modern irrigation management is instead essentially concerned with responding to the needs of current users with the best use of the available resources and technologies, as well as with a sense of anticipating the future needs of the scheme. Extensive studies conducted by international institutions reported that effective management improvements in many irrigation systems can largely be achieved without major physical investments (Murray-Rust and Snellen 1993).

In several Mediterranean countries a first phase of modernization of existing irrigation schemes occurred during 1980’s and mainly concerned physical aspects. Large investments were made to incorporate improvements in conveyance, regulation, water control, automation and measurement, and to transform open-channel schemes into pressurized piped networks. Several positive impacts on rural economies, on crop
production and on water conservation in the serviced command areas were prospected to
decision-makers and stakeholders as resulting from physical improvements in storage,
conveyance and distribution systems. In many cases, modernization programs relied upon
the assumption that the availability of ameliorated structures would have always enabled
the management staff of irrigation systems to fully and effectively achieve a set of well
defined project objectives. Nevertheless, in many cases the anticipated potential benefits
were not achieved and actual performances of the modernized systems are lower than
what had been forecasted or adequate water delivery services are not provided to farmers,
often resulting in inequitable and unreliable distribution.

During modernization programs, the lack of diagnostic methodologies and
simulation tools did not allow investigating the causes of poor performance, analyzing
systems operation under different scenarios and appraising the likely effectiveness of
different improvement options prior to decide the specific measures to be implemented in
the systems under study. In addition, often not much attention was paid to training and
capacity building of staffs to enhance the flexibility and reliability of water service
provision and to better respond to users’ needs.

There are few published studies on how managers should operate existing
systems, evaluate operational requirements and performance, and allocate resources and
efforts to optimize system achievements. A study conducted by the International Food
Policy Research Institute (IFPRI) in conjunction with the International Irrigation
Management Institute (IIMI) reported that assessment of irrigation performance is often
seriously neglected. In many schemes, a mixture of rule of thumb and local experience is
the basis for operational decision-making (Renault and Makin 1999).
Several research institutions and working groups have put their efforts in conceiving general methodological frameworks for diagnostic studies to address modernization of irrigation systems. Small and Svendsen (1992) highlighted that conflicting objectives considered by irrigation agencies and water users are often the main cause of complexity in system management and operation, and that the multiplicity of approaches for assessing performance makes the task also confusing and difficult to be tackled.

A sound consideration made by ICID (Price 1999) is that a lot of changes often occur in irrigation schemes over their life span. Changes in land use, cropping patterns, irrigation methods and farming practices, market trends, and environmental conditions may create situations that make the original objectives difficult, unwanted or unfeasible to achieve. When such impacts occur, modifications of the project objectives should be also conducted to serve a different combination of water users’ needs. Where the objectives of a project have changed, a key facility or structure that was adequate for the original purposes may in fact result inadequate. In other words, periodic reviews of project objectives should be conducted by the project management.

According to the International Commission on Irrigation and Drainage (Price 1999), evaluating the condition and adequacy of existing facilities is crucial for the quality and reliability of service to water users over the entire project areas. Performance assessment is the central part of modern service-oriented management and any modernization program should be based upon the outcomes from diagnostic performance assessment. Bos et al. (2005) highlighted that performance assessment in irrigation and
drainage projects entails the systematic observation, documentation and interpretation of activities related to irrigated agriculture with the objective of continuous improvement.

From reviewing previous works conducted in the domain of irrigation systems modernization, it can be inferred that there is still a lack of diagnostic methodologies to analyze irrigation systems behavior under different conditions, assess the systems performance, identify the causes of poor performance, investigate the room for improvement, and simulate the likely effectiveness of modernization options. A sound methodology for analysis of the existing irrigation schemes should entail a diagnostic component to determine and analyze the behavior of the system, and a simulation component for evaluating the system response following alternative modifications or correcting measures. In both components, the analyses should be conducted on the basis of a set of properly chosen performance indicators able to account for the main variables effecting operation and management and for synthetically representing the state of the system with respect to specific management objectives, both in its current state and after improvements.

The present research thus focused on developing and validating an analytical methodology for conducting diagnostic performance assessment and simulation of alternative management scenarios on large-scale pressurized irrigation systems.

This methodology could be used by irrigation managers and auditors to first get a good understanding of the systems behavior under different operating conditions and then utilize simulation and management-support tools to take or recommend consistent decisions. The application of such a methodology would represent an analytical basis to
orient decision-making either in modifying operation of existing structures as well as in evaluating the need for modernization of irrigation delivery systems.

**Study Objectives**

In order to address the need identified and described in the previous section, the proposed study focused on developing the capability to conduct diagnostic analyses, simulation of alternative delivery scenarios and evaluation of performance achievements on pressurized irrigation delivery networks.

The specific tasks envisioned to accomplish the general objective of the study are listed hereafter:

1. to modify an existing agro-hydrologic simulation model in order to enhance the capability of forecasting peak water demand hydrographs and flow configurations in pressurized irrigation delivery systems. The enhanced model performs simulations of flow hydrographs based upon the spatial and time distributed irrigation demand patterns as estimated over the cropped areas supplied by the distribution networks. This task also entailed testing the simulation model on a modern pressurized irrigation delivery network for validation purposes.

2. to develop and test a set of performance indicators and related ranges of reference values, with the aim of providing the analytical framework for conducting diagnostic performance assessments;

3. to apply the enhanced agro-hydrologic model in combination with an existing hydraulic simulation model and with the proposed indicators and test their
applicability for simulating alternative operational scenarios and for assessing performance achievements in existing pressurized distribution systems;

4. to provide suggestions for action about operation, evaluation and modernization of pressurized water distribution networks, based on actual and target achievements relative to performance objectives.

These tasks were accomplished through four papers presented as chapters of this dissertation. Each chapter contains the necessary background and literature review related to the specific aspects described and addressed in the paper.

Chapter 2 describes a preliminary study conducted on an irrigation system of southern Italy (study area 1) to analyze the current operation of the delivery network and the resulting effects on crop irrigation management and on aquifer salinity increase. This preliminary work aimed at documenting how the soil water balance and irrigation scheduling approaches can be used as analytical tools to frame a typical water distribution problem, i.e. the mis-match between current water deliveries, crops irrigation requirements and farmers’ needs. The analyses carried out in the Chapter 2 enabled the detailed description of the baseline scenario on the first study area where the proposed methodology for diagnostic analysis and evaluation of performance achievements was finally applied to address modernization issues of district delivery networks.

Chapter 3 corresponds to the second paper, which is related to task 1, and provides a detailed description of the refinements, amendments and modifications implemented to the existing agro-hydrologic model to forecast flow hydrographs and flow configurations in irrigation delivery networks during peak demand periods. The main components, algorithms and calculation procedures of the enhanced model are
explained and their scientific basis is also provided in this paper. The paper included in Chapter 4 illustrates the testing and validation of the enhanced agro-hydrologic model through applications to different management levels (district, sectors, hydrants) of an existing irrigation delivery network (study area 2) where service-oriented irrigation management is conducted on a regular basis. Both Chapter 3 and 4 specifically address task 1. Chapter 5 corresponds to the fourth paper and describes the set of performance indicators selected and specifically adapted to pressurized irrigation delivery networks and their application for validation to two sectors of the modern irrigation system (study area 2). In the same chapter, a detailed description of the proposed methodology for diagnostic performance assessment and for simulation of alternative delivery scenarios is provided. Finally, the applications of the entire methodology to two district delivery networks of an existing poor-performing system (study area 1) are illustrated. The paper contained in Chapter 5 thus addresses the tasks 2, 3, and 4.

**Significance of the Research**

Evaluating and enhancing the performance of irrigation structures constitute major goals for improving water resources management in the arid and semi-arid agricultural areas of the Mediterranean basin. The accomplishment of these tasks requires the analysis of operation of irrigation systems with respect to current and future performance objectives. In turn, this entails evaluating the main physical processes that govern the irrigation systems by monitoring a set of operational parameters, or alternatively, using properly calibrated simulation models able to reproduce the systems’ behavior under different operating conditions.
The operation of water delivery networks may become complex due to conflicting objectives by the management agency and the users. This complexity is particularly evident in pressurized systems and during periods of water limitation. The proposed research represents a step forward for achieving better understanding of the processes and aspects affecting performance in large-scale pressurized irrigation systems. The diagnostic component in combination with the simulation capability will facilitate understanding systems behavior and the resulting performance achievements under several water management scenarios.

Most of the studies available in literature in this domain concern optimizing operation in open channel irrigation systems. Also, almost all of the works conducted on performance indicators, performance assessment and modernization of irrigation systems refer to specific applications conceived for gravity networks, which are very prevalent in irrigation schemes. In the last years pressurized irrigation systems received increasing attention and a considerable number of them were designed and constructed in the Mediterranean countries, but also in several other parts of the world, as alternative or enhancements of gravity systems. Many of the previous studies focused on design and optimization of such systems. Analyzing the hydraulic performance of pressurized systems, whose operation is complex due to their constantly varying flow conditions, require analytical and simulation models, but also the selection of adequate performance indicators and of reference performance standards.

In this perspective, the uniqueness of the proposed research with respect to previous studies can be found in the following aspects:
1. development of the capability to forecast peak flow demand hydrographs and configurations with higher accuracy relative to random generation approaches. Simulation of flow demand is the most relevant and uncertain aspect in the analysis of operation of large-scale irrigation systems serving multi-cropped heterogeneous areas.

2. The modification of indicators, originally conceived for performance assessment in open channel networks, enabled to tailor these performance indicators for diagnostic studies on pressurized irrigation systems with the aim of evaluating the compliance of the performance achievements with the specified performance objectives.

3. Simulating the demand flow configurations and the conditions required for adequate performance of such networks is a relevant scientific and technological challenge to foster the judicious use of water resources and sustain production system in irrigated agriculture under scarcity conditions.

References


CHAPTER 2
FLEXIBLE DELIVERY SCHEDULES TO IMPROVE FARM IRRIGATION AND REDUCE PRESSURE ON GROUNDWATER: A CASE STUDY IN SOUTHERN ITALY

Abstract This study was conducted on an irrigated area of southern Italy to analyze the current operation of a large-scale irrigation delivery system and the effects of the operation procedures on crop irrigation management and aquifer salinity increase. The area is characterized by relatively high levels of groundwater salinity in the summer that are probably due to intensive groundwater pumping by farmers during periods of peak irrigation demand, with the resulting seawater intrusion. Two alternative delivery schedules, namely the rotation delivery schedule and the flexible delivery schedule, referred to as RDS and FDS, respectively, were simulated using a soil-water balance model under different combinations of crop, soil and climatic conditions. The first set of simulations concerned the farm irrigation management constrained by the rotational delivery used by the local water management organization. The second scenario simulated the farm irrigation schedule most commonly used by growers in the area for maximizing crop yields. Based on crop irrigation management under RDS and FDS, two alternative operational scenarios were also developed at the scheme level and then compared for evaluation. Winter and summer salinity maps of the aquifer were developed by interpolating salinity measurements of the groundwater samples collected during the 2006 irrigation season. From these maps a close relationship can be inferred among

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1 Coauthored by Daniele Zaccaria, Ines Oueslati, Christopher M.U. Neale, Nicola Lamaddalena, Michele Vurro and Luis S. Pereira.
delivery schedule, aquifer exploitation and salinity increase, which justifies the need for implementing a flexible delivery schedule that might reduce the groundwater demand for irrigation.

2.1 Introduction

Matching irrigation demand and supply is usually a difficult task in many Mediterranean irrigation systems. This is due not only to water scarcity but often to inappropriate delivery schedules (Lamaddalena et al. 1995). Poor irrigation management is often the problem (Hargreaves and Zaccaria 2007). Clemmens (2006) reported that one of the major problems of poorly performing irrigation systems is that their operation is not tied to productivity or conditions enabling farmers to achieve target yields. In the same work, Clemmens also indicated that in irrigation systems where distribution is carried out using a static operating plan (such as fixed rotation), the water management body often shows little concern about the production that comes from this water, or whether the delivery has any influence on its effective use.

Clemmens and Molden (2007) stressed the importance of flexibility and quality of delivery service on the economic viability of irrigation projects. Styles and Mariño (2002) conducted a study on 16 irrigation projects that had already been partially modernized in hardware and/or managerial aspects, and observed a positive correlation between improving the flexibility of an irrigation project and an economic performance indicator, namely the "potential production indicator". They found that increased yields are positively correlated with increased level of water delivery service, expressed in terms of flexibility of flow rate, duration and frequency (see also Styles 2001). Sanaee-Jahromi et al. (2001) clarified that the delivery schedule performance relates to how well
the water delivery schedule matches the irrigation requirements, whereas the *operation performance* refers to the ability of the system to supply water according to the schedule.

Merriam et al. (2007) emphasized that the essence of the concept of flexible water distribution is to endow the farmer with the management control of the frequency, the rate and the duration of irrigation water deliveries. Burt and Styles (2000) collected data from 61 irrigation districts in the western U.S. and developed a Flexibility Index (FI) to characterize the degree of water delivery flexibility in terms of frequency, flow rate and duration provided by irrigation districts.

Styles (1997) and Merriam and Freeman (2002) documented that accurate on-farm control of irrigation water deliveries can contribute to reducing drainage and salinity problems on the project scale caused by excess, inadequate and non-uniform applications. Appropriate delivery schedules are essential for improving the irrigation performance on the farm and system scale (Clemmens 2006; Pereira 1999; Pereira et al. 2002). Styles (1997) also reported that in several areas of the world a significant increase in the number of farmers using irrigation wells has been observed during the last decades in response to the lack of flexible deliveries from the irrigation districts. This occurred even where less expensive irrigation water was available from the districts. Kijne et al. (1998) pointed out that salinity problems in irrigated agriculture may result from seawater intrusion into coastal areas where the water tables have been lowered by the mining of groundwater for irrigation purposes. Umali (1993) reported that poor water management by irrigation agencies is one of the leading grounds for irrigation-induced salinity in many agricultural areas.
Improving delivery modes in large-scale multi-cropped irrigated areas requires the use of simulation models, often adopting decision tools and multi-criteria analysis (Walker et al. 1995; Sanaee-Jahromi et al. 2001; Gonçalves et al. 2007). These improvements need to be based on appropriate irrigation scheduling assumptions relative to the crop patterns adopted. Irrigation scheduling (Heermann 1996) requires knowledge on (a) the crop water requirements and yield responses to water (Kang et al. 2003; Popova et al. 2006), (b) the constraints specific to each irrigation method and irrigation equipment (Pereira 1999; Liu et al. 2000), (c) the crop sensitivity to salinity when water of poorer quality is used (Rhoades et al. 1992; Minhas 1996), (d) the limitations relative to the water supply system (Goussard 1996; Lamaddalena et al. 2007), and (e) the financial and economic implications of the irrigation practice (Ali et al. 2007).

Several water distribution studies have been conducted for pressurized irrigation systems (e.g. Calejo et al. 2007; Khadra and Lamaddalena 2006; Plannels et al. 2007; Zaccaria et al. 2006b) but few refer to surface or low-pressure irrigation systems in the Mediterranean area. The case study presented in this paper refers to a system where conveyance is through a canal and distribution occurs through branched networks of low-pressure pipes. Enhancing delivery schedules in these systems is feasible when these pipe distributors are designed for a flexible delivery (Pereira et al. 2003a).

This study was conducted on the Sinistra Bradano irrigation system, located in the western part of the province of Taranto (southern Italy) and managed by a local Water User Organization (WUO), namely the “Consorzio di bonifica Stornara e Tara.” Several farmers from the command area were interviewed and stated that the irrigation delivery schedule enforced by the WUO is no longer suitable for the prevailing farming
conditions, in terms of flow rate, delivery frequency and pressure head at hydrants. According to many farmers the scheduled water delivery is too restrictive and not often timely to match the actual crop water requirements and farmers’ irrigation needs (Zaccaria et al. 2006a). As a matter of fact, if not properly tailored to match the crop irrigation requirements and farmers’ needs, the rigid rotation supply could result in wasteful water use as a consequence of improper application timings, over irrigation and runoff, thereby hindering the good management of the farm. As a result, in the last ten years a large number of farmers have developed groundwater resources by drilling farm tube-wells, since the aquifer is relatively shallow in the study area. This has led to the creation of a very large number of irrigation wells (INEA 1999), either licensed or unlicensed, which pump water from the aquifer during a large portion of the irrigation season.

Several interviews with extension agents (both from the WUO and the private sector) as well as with farmers’ representatives were also conducted to acquire information about farmers’ habits and irrigation management practices that are commonly applied at farm level.

Since the Sinistra Bradano irrigation scheme is located at an average distance of 7-8 km from the Ionian Sea, seawater intrusion into the aquifer occurs during periods of intensive groundwater pumping, leading to salinity build-up (Capaccionia et al. 2005). Some research works conducted in areas bordering the study site (Polemio and Ricchetti 1991; Polemio and Mitolo 1999; Polemio et al. 2002) revealed that seawater intrusion is progressively increasing in the whole Ionian coastal aquifer in Italy.
The objective of the present study is to analyze the farm irrigation management under the irrigation delivery that is currently-scheduled by the WUO and to compare it with an alternative irrigation scheduling aimed at maximizing crop yields, which could be achieved if more flexible deliveries are adopted. This paper includes results from simulation models and field data so as to understand in the best possible way shortcomings and externalities related to rigid irrigation delivery on a large-scale irrigation system. No attempt is made in this paper to conduct a surface water-groundwater balance of the study area. Also, the conjunctive use of surface and groundwater is beyond the scope of the present work.

Since water is distributed through pipes, higher flexibility in water delivery could be implemented in this irrigation scheme to allow for better use of the available water supply and reduce the actual demand on the aquifer. To support these analyses, winter and summer salinity maps were generated, from which a relationship among delivery schedules, aquifer exploitation and groundwater salinity can be inferred.

2.2 The Study Area

The Sinistra Bradano irrigation scheme (Fig. 2.1) is located in the western part of the province of Taranto and covers a total topographic area of 9,651 ha. This area was equipped for irrigation by the local WUO from 1968 to 1974 and extends over an alluvial plain having a land elevation that ranges between 24 and 54 m a.s.l. The system is divided into 10 operational districts the size of which ranges from a minimum of 353 ha (district # 7) to a maximum 1,675 ha (district # 5). Each district is subdivided into sectors consisting of grouped numbers of farms.
The water source is the San Giuliano reservoir located on the Bradano River in the nearby region of Basilicata. This reservoir has a capacity of 70 Mm$^3$ and supplies water to both the western and eastern sides of the Bradano River. The dam is operated by the Consorzio di bonifica Bradano e Metaponto, a WUO that is responsible for the distribution of water to irrigation systems located on the western side of the Bradano River, in the region of Basilicata. On the basis of yearly-agreed volumes and rates, the same WUO supplies water to that of “Consorzio di bonifica Stornara e Tara” for it to irrigate areas located on the eastern side of the Bradano river in Apulia region. Out of the reservoir’s total capacity, 35 Mm$^3$ are supposed to be available for irrigating the Sinistra Bradano system. On average only 23 Mm$^3$ are diverted to the Sinistra Bradano irrigation system.
system from the reservoir, out of which only 16.4 Mm$^3$ are delivered to cropped areas, due to conveyance and distribution losses that amount to 28.7% of the total diverted volume (INEA 1999).

Water travels for about 14 km from the San Giuliano reservoir to the study area through the main conveyance canal. Once the canal reaches the western limit of the irrigated area, it conveys water to 10 branched-district distribution networks located along its pathway, which runs along the northern boundary of the irrigation scheme for about 25 km. Water diversions from the main canal are controlled by cross-regulators and orifice-type undershot-gate offtakes, which are manually operated. The branched delivery networks of each district consist of gravity-fed buried pipelines that deliver water to farms with low pressure head. Pressure at farm hydrants results from the difference in elevation between the offtakes and the lower-elevation irrigated areas, minus the head losses occurring in the pipe network. The whole irrigation system was conceived and designed forty years ago for surface irrigation methods. That is why pressure heads at hydrants range between 0.3 and 0.6 bars, depending on their ground elevation relative to the canal offtakes. The average discharge-area ratio is around 5 l s$^{-1}$ for 3.5 ha of served area.

The total cropped area that can be irrigated amounts to 8,636 ha. Although the cropped area remained nearly constant over the years, the area irrigated by WUO-supplied water started decreasing in 1990 and further decreased during the last decade, with no significant changes in the cropping pattern. According to the records provided by the WUO, the area served by the WUO-supplied water passed from 2,128 ha (24.6 % of the irrigable area) in 1997 to 1,354 ha (15.7 % of the irrigable area) in 2003 and to 987 ha
(11.4 % of the irrigable area) in 2006. In the 2007 irrigation season only 921 ha out of a total of 8,636 ha were served by the large-scale distribution system, thus receiving irrigation water under rotation delivery schedule. But farmers irrigated the remaining 7,715 ha exclusively by means of groundwater pumping, thereby obtaining the required flexibility in on-farm irrigation scheduling. These 921 ha irrigated by rotation delivery are not concentrated in a specific zone but spread throughout the irrigation scheme. Major changes, instead, have characterized the farm irrigation methods, as growers shifted from surface irrigation to pressurized high-frequency irrigation, which is not compatible with the water delivery conditions provided by a system conceived in the 1960’s for surface irrigation methods.

The reduction in the area served by surface water from the WUO shows that the area irrigated by groundwater pumping has tremendously increased over the years, most probably as a consequence of poor conditions of water delivery with respect to farmers’ requirements. A comparison between two subsequent Regional Water Plans, namely the “Piano Regionale di Risanamento delle Acque” (Regione Puglia 1983) and the “Piano di Tutela delle Acque della Regione Puglia” (Regione Puglia 2007), issued in 1983 and 2007, respectively, shows that the area subjected to seawater intrusion has strongly increased. This increase is consistent with the strong increment of the agricultural wells that have been drilled during the last decades throughout the whole area.

During the entire irrigation season, the average Total Dissolved Solids (TDS) of the water conveyed from the San Giuliano reservoir equals 0.8 – 0.9 g l-1, which means that the water is slightly saline according to the classification provided by Rhoades et al. (1992).
The study area is characterized by abundant groundwater resources that are mainly used for agricultural purposes. Based on information concerning the hydrogeological set-up of the study area and on the outcomes of previous investigations (Piccirillo 2000), it can be inferred that groundwater is available from two aquifers: a shallow upper aquifer located in sands and marine terraced deposits, and a deeper aquifer confined in limestone formations. This sequence is due to the advance and regression of the coastal line during the geological eras, as reported by Cotecchia and Magri (1967) and Cotecchia et al. (1971).

The hydraulic conductivity of the shallow aquifer varies from medium to high and this water source is subjected to heavy utilization and therefore to seawater intrusion (Polemio et al. 2002). The deeper aquifer has a secondary permeability due to fractures and fissures. This resource represents an important water body for the Apulian area (Benedini et al. 1996). Between the two aquifers, two separate layers are found, composed of clays and calcarenites respectively and referred to as “Aquiclude” and “Aquitard.”

The most recent observations of the water table depth date back to 2004. These data were collected during a study for developing the piezometric map of the province of Taranto and show that the water table lies at a depth that ranges from 2 m (in the southwestern part) to 20 m (in the northeastern part) from the ground surface within the Sinistra Bradano irrigation system, confirming the easy access to the aquifer by farmers for irrigation purposes (Polemio et al. 2002; Regione Puglia 2007).

Polemio et al. (2002) reported that seawater intrusion upon coastal groundwater has become a real problem for the social and economic development of this area. The
results they obtained from the analysis of hydro-geological, chemical and physical data that was collected from boreholes in areas near the study site, hinted at quality degradation of coastal plain groundwater, owing to seawater intrusion in the shallow aquifer. This evidence is also supported by data collected in the period 2006-2007 within an on-going project aiming at monitoring groundwater parameters at regional level (Regione Puglia 2006).

The study area is characterized by semi-arid to sub-humid climate referred to as “Maritime-Mediterranean,” which is typical of the coastal areas of the Mediterranean region. Precipitation varies between a minimum of 400 mm in south-eastern part of the scheme and a maximum of 730 mm in the northern part of the scheme. The average yearly rainfall is around 550 mm, 35 % of which occurs in the winter months, 32 % in fall and 33 % in spring and summer. There is typically very little summer precipitation and irrigation is usually needed from April to September. Figure 2.2 shows the monthly values of the reference evapotranspiration (ETo) and rainfall (P) for the year 2006, averaged from three meteorological stations (Massafra, Ginosa Marina, and Castellaneta) located in territories that neighbor the study area.

The WUO usually starts distributing water in April and ends late in October. The distribution network is operated on a fixed rotation delivery schedule. The rotation is set for the entire irrigation season with a flow rate of 20 l s⁻¹ ha⁻¹ and 5 hours of delivery for each user as well as with a fixed delivery interval of 10 days. Before starting each irrigation season the WUO collects the farmers’ requests for water delivery according to the various crops and related areas to be served during the season. These requests are then processed by the WUO staff to define and publicize the rotation delivery schedule.
Farmers pay a fixed fee of 65 Euro/ha to the WUO for the water delivery service, whether they use water or not, and a rate for irrigation of 485 Euro/ha for the water that the WUO delivers during the irrigation season, regardless of the amount used and the crop grown. The average farm size is 3.5 ha.

At farm level, micro-irrigation is currently adopted in most of the irrigated area whereas sprinkler irrigation covers only 20% of the citrus acreage. Surface irrigation is no longer practiced due to high labour costs.

A typical on-farm irrigation system consists of a connection device to the closest hydrant (or to the farm well), a booster pump, fertigation equipment (mixing tank) and safety device, flow and pressure regulators, filters, supply line, a set of plastic manifolds and laterals equipped with emitters. All the components mentioned above are typical of a solid-set irrigation system. As to tree crops such as olives, stone-fruits, table-grapes, almonds and citrus, laterals are made of plastic pipes or drip-lines laid along the rows or between rows and are equipped with regularly spaced on-line or in-line emitters, whose nominal discharge may range between 4 and 30 l h⁻¹. The number of emitters per plant typically varies between 1 and 4. Some citrus orchards are still irrigated by sprinkler or micro-sprinkler systems consisting of buried plastic manifold and laterals, with 2 to 4 sprinklers or sprayers per plant. As for vegetables, laterals usually consist of drip-lines laid along rows and equipped with in-line emitters or drip-tapes with calibrated orifices.

In a few larger farms, small storage reservoirs are available to buffer timing and flow rates of delivery, thus enabling farmers to achieve higher flexibility in irrigation scheduling.
Fig. 2.2 Monthly rainfall and reference evapotranspiration for the year 2006 averaged from the three meteorological stations considered for the present study.

As reported by the extension agents and farmers’ representatives interviewed, when the water supply is flexible and shows no delivery constraints (i.e. storage reservoirs, holding ponds or groundwater pumping), growers usually tend to distribute small amounts of water to cropped fields by means of micro-irrigation systems with high frequency, which also varies during the irrigation season in response to perceived crop water needs.

As regards conditions of water delivery, a previous study showed that the current water distribution does not meet the farmers’ needs in terms of pressure head at the hydrants (Zaccaria and Lamaddalena 2005). Farmers need to use booster pumps downstream of the hydrants to feed properly their irrigation systems because the available pressure does not allow for the adequate operation of on-farm micro and sprinkler irrigation systems. At present, many farmers may prefer pumping groundwater rather
than paying water tariffs to the WUO and spending additional money to operate booster pumps to feed properly their pressurized farm irrigation systems, especially for crops characterized by long irrigation seasons.

Figure 2.3 presents the cropped areas and relative spatial distribution for the year 2006 (data was obtained from WUO records). The main crops are table-grapes, citrus, and summer vegetables. Soils result from alluvial deposits onto flat clayey plains that originated from the erosion of high lands consisting of terraces that emerged during the Pleistocene age. These alluvial areas were afterwards subjected to a long period of carbonate leaching.

Fig. 2.3 Cropping pattern of the Sinistra Bradano irrigation systems for 2006
This study groups cropped soils into five classes, according to the USDA soil textural classification. Most of the cropped areas are on loamy-sand. The values of electrical conductivity (EC) of soils range between 0.064 and 0.635 dSm\(^{-1}\) (Oueslati 2006).

2.3 Material and Methods

2.3.1 Soil water balance modelling

The climatic datasets were collected and processed on a daily time-step for the year 2006 with reference to three meteorological stations located in territories that belong to the towns of Ginosa Marina, Castellaneta, and Massafra, respectively, and that surround the irrigation system under study. The respective areas of influence of these three stations were identified using the Thiessen’s polygons method.

The cropping pattern map was intersected with the soil map and with the areas of influence of the meteorological stations using commercial GIS software (ArcGIS). This resulted in forty-two unique crop-soil-climate combinations that constitute the soil-water-balance simulation units used in this study.

The ISAREG model (Pereira et al. 2003b; Liu et al. 1998) was used on a daily time-step to simulate the soil-water balance for each unit. ISAREG was previously tested in the area (Al-Haj Hussein 2001) and validated for citrus irrigation under similar environmental conditions (Alba et al. 2003). The model performed the water balance and evapotranspiration computations following the methodology proposed by Allen et al. (1998).

The impacts of water stress on yields were assessed through the Stewart’s one-phase model (Stewart et al. 1976; Doorenbos and Kassam 1979). Although production
functions relating applied water to crop yields were developed in various forms by several authors in later works (Vaux and Pruitt 1983; Hargreaves and Samani 1984; Solomon 1985; English 1990; English et al. 1990; English and Raja 1996; English et al. 2002; Steduto et al. 2007), the Stewart’s model was used in this study owing to its wide applicability for simulation purposes and because specific production functions needed to be calibrated for the different crops under local conditions. Moreover, since the Stewart’s model is based on evapotranspiration rather than on water applied, it is more or less independent of spatially-related variables (actual deliveries from the distribution system, soils, farmers’ habits and practices in crop water management), which may influence the shape of the water-yield relationship (English 2002).

Simulations were performed for every crop-soil-climate combination to compare the amounts of water applied, crop evapotranspiration, delivery schedule performance and the related yield impacts when irrigation is performed under current rotational delivery schedule or if an alternative flexible delivery schedule is adopted. The delivery schedule performance is used in this work as an indicator of potential room for water conservation, although excessive water applications at farm level should not be necessarily considered as water losses, according to revised concept of irrigation efficiency provided by several authors in large-scale and basin-levels studies (e.g. Perry 1999; Keller et al. 1996; Willardson et al. 1994).

For the first simulation scenario, named rotation delivery scheduling (RDS), fixed irrigation dates and volumes were adopted to reproduce the current delivery operational rules (irrigation intervals of 10 days, flow rate of 20 l s⁻¹ha⁻¹ and 5 hours of delivery duration). For the second, named flexible delivery scheduling (FDS), the irrigation
schedules reproduce those that are commonly used by farmers when they rely on flexible or unconstrained water supply (i.e. on-farm storage reservoirs, holding ponds, or groundwater pumping), and according to the irrigation methods and practices utilized for each crop. The values of readily available water for different crops resulted from both the values of total available water of different soil types and crops’ rooting depths, and the soil moisture depletion factors for no stress (p), as reported in literature (Allen et al. 1998).

Input data for the model were organized as follows:

1. Meteorological files, including data on effective precipitation and reference evapotranspiration. The daily reference evapotranspiration (ETo) was estimated using the Hargreaves-Samani equation (Hargreaves and Samani 1985), given the limited climatic datasets of local weather stations.

2. Crop files, with dates of crop development stages and the related crop coefficients values (Kc), root depths (Zr) and soil moisture depletion factors for no stress (p), as reported in Table 2.1. Crop files were developed from data gathered during multi-annual field work (Rubino and Steduto 1999). The Kc values reported in Table 2.1 refer to the beginning of each crop development stage. Based on these specific Kc input values, the model generates a time-averaged crop coefficient curve by means of an internal procedure, thereby defining daily Kc values to be used within the soil-water balance computations on a daily time-step. Kc values for tree crops refer to bare soil surface conditions. Furthermore, the data collected by extension agents on the practices that are commonly adopted by farmers in the study area was used.
Crop files also include the yield response factor Ky required by the Stewart’s one-phase model. Ky values were based on those proposed by Doorenbos and Kassam (1979) after checking yield data provided by the local extension agents.

3. Soil files, including values of potential depth for root extraction and soil water content at field capacity and at wilting point. The data included in these soil files derives from analytical laboratory determinations on a set of soil samples collected during a survey conducted on the study area in 2003.

The simulated gross irrigation requirements were estimated from the computed net irrigation requirements considering an average application efficiency of 85%. Given the limited WUO’s data records on water measuring and accounting, this study could not reproduce the “baseline scenario” by documenting farmers and crops receiving canal water and those that have recourse to pumped groundwater. Instead, two different future operational scenarios were simulated at scheme level, considering both the whole irrigable area and all farmers as being served by the large-scale distribution system so as to accomplish alternatively the RDS or the FDS alternatively. These scenarios were generated by up-scaling the results of simulations from cropped fields to districts and system levels using GIS tools, and were then compared for evaluation.

The RDS scenario corresponds to the normal practices adopted by the WUO, and extended to the whole study area for operating the distribution system by fixed rotation delivery. In this scenario the aquifer is not deemed to be accessible to farmers owing to physical, technical, regulatory or economic reasons; therefore, no groundwater pumping would occur in the whole cropped area. As a matter of fact, in the near future
groundwater pumping for agricultural purposes should be forbidden in the study area, according to regulations set by Regional Water Plan (Regione Puglia 2007) issued in 2007 and not yet enforced.

The FDS scenario assumes the WUO’s wide, effective and economically-sustainable implementation of a flexible delivery schedule that meets farmers’ and crops’ needs.

**Table 2.1 Crop characteristics and growth stages used in the modeling**

<table>
<thead>
<tr>
<th>Development stages</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dates</td>
<td>10/04 to 25/04</td>
<td>25/04 to 20/05</td>
<td>20/05 to 25/06</td>
<td>25/06 to 10/08</td>
<td>10/08 to 30/09</td>
<td>30/09 on</td>
</tr>
<tr>
<td>Rooting depths (m)</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Crop Coefficient (Kc)</td>
<td>0.40</td>
<td>0.48</td>
<td>0.60</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>p (fraction)</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Yield factor (Ky)</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>

**Table grapes**

| Dates              | 10/03 to 25/03 | 25/03 to 20/04 | 20/04 to 30/06 | 30/06 to 30/10 | 30/10 to 15/12 | 15/12 on |
| Rooting depths (m) | 1.00    | 1.00    | 1.00    | 1.00    | 1.00    | 1.00    |
| Crop Coefficient (Kc) | 0.70   | 0.70    | 0.65    | 0.65    | 0.70    | 0.70    |
| p (fraction)       | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    |
| Yield factor (Ky)  | 0.90    | 0.90    | 0.90    | 0.90    | 0.90    | 0.90    |

**Citrus**

| Dates              | 15/03 to 30/03 | 30/03 to 20/04 | 20/04 to 20/05 | 20/05 to 30/06 | 30/06 to 15/08 | 15/08 on |
| Rooting depths (m) | 0.15    | 0.25    | 0.40    | 0.65    | 0.65    | 0.65    |
| Crop Coefficient (Kc) | 0.42   | 0.45    | 0.80    | 0.95    | 1.05    | 0.95    |
| p (fraction)       | 0.35    | 0.35    | 0.35    | 0.35    | 0.35    | 0.35    |
| Yield factor (Ky)  | 1.10    | 1.10    | 1.10    | 1.10    | 1.10    | 1.10    |

**Vegetables**

Stage A: from planting or beginning of green-up to beginning of fast vegetative growth
Stage B: from beginning of fast vegetative growth to beginning of flowering
Stage C: from beginning of flowering to start of yield formation
Stage D: from start of yield formation to beginning of ripening
Stage E: from beginning of ripening to harvesting (or end of irrigation)
Stage F: marking the beginning of harvesting or the end of irrigation season
2.3.2 Groundwater quality

Measurements of total dissolved solids (TDS) and electrical conductivity (EC) were conducted on groundwater samples collected in the Sinistra Bradano area during the irrigation season of 2006. Eighteen sites were sampled in 2006 throughout the study area. Two samples per site were collected, the first in February and the second in July. TDS values were determined by means of laboratory measurements using the gravimetric method, whereas EC values were obtained using a conductivity meter (Hanna Instruments, mod. HI 9835). Winter and summer salinity maps were generated by interpolation using the inverse weighted distance method embedded in the GIS software package. Seasonal changes in groundwater quality were assessed by comparing the aquifer salinity in winter and summer.

2.4 Results

2.4.1 Irrigation scheduling

Figure 2.4 presents the soil water balances simulated for the three main crops grown in the study area (vegetables, table-grapes and citrus) under the RDS and FDS scenarios. Section 1a of Fig. 2.4 refers to the RDS scenario applied to the simulation unit of spring-summer vegetables (mainly eggplant and bell pepper) grown on a sandy-loam soil, using weather data from Ginosa Marina meteorological station. The simulated irrigation scheduling shows that under RDS, over-irrigation occurs during the first half of the crop cycle whereas soil water deficits take place in the second half of the season. This schedule produces a net applied irrigation depth of 468 mm and indicates a relative yield loss of 13.5 % due to water stress. Alternatively, if farmers could rely on FDS, the irrigation management would be more effective at farm level and the net applied
irrigation depth would be reduced to 437 mm without incurring water stress and water excess (Fig. 2.4, section 1b).

Simulations concerning another sample unit, namely table-grapes grown on loamy-coarse sandy soil in the area of Massafra (Fig. 2.4, sections 2a and 2b), show that, when RDS is adopted, the net applied irrigation depth is 612 mm, which is much greater than the FDS applied depth that equals 385 mm. Under RDS, limited water stress occurs and the relative yield loss is negligible (0.5 %) but irrigation water that is surplus to requirements amounts to 216 mm. On the other hand, under FDS both water stress and excess application can be avoided, and therefore no yield loss will be generated.

The results of the simulation unit of citrus grown on a loamy-sand soil based on weather data from Massafra station are reported in sections 3a and 3b of Fig. 2.4 and are similar to those illustrated above. For citrus, the net applied seasonal irrigation depth is 792 mm (section 3a) under RDS whereas it equals 429 mm (section 3b) under FDS. No relative yield loss resulting from water stress is observed under RDS. On the contrary, an excessive irrigation application of 311.5 mm may occur under RDS thus leading to a delivery schedule performance (ratio between the consumed fraction and the net volume delivered) of 60.6 %. Neither water stress nor excessive irrigation is noted for citrus under FDS for the soil-climate combination considered in this specific simulation. Again, for the aforesaid crop, simulations were conducted in such a way as to reproduce local farmers’ irrigation management practices, under rigid and flexible water supply.

Table 2.2 summarizes the averaged results obtained from simulations for the three main crops under RDS and FDS scenarios.
Fig. 2.4 Simulated soil water balance for simulation units consisting of 1) vegetables grown on sandy-loam soil in the area of Ginosa Marina, 2) table-grapes grown on loamy-coarse sandy soil in the area of Massafra, and 3) citrus grown on loamy-sand soil in the area of Massafra, under the RDS (sections a) and FDS (sections b).
Table 2.2 also shows that the delivery schedule performances that can be achieved under the RDS imposed by the WUO are much lower than those that can be obtained under FDS.

Table 2.3 presents figures referred to the RDS and FDS operational scenarios at the scheme level. The results of all simulation units at field level under RDS and FDS were aggregated for the three largest irrigation districts (districts No. 1, 2, and 5) and for the whole scheme, on the basis of the acreages of each unit within these districts and within the scheme. Table 2.3 shows that if a flexible delivery was adopted and successfully implemented by the WUO in the whole cropped area, the overall seasonal irrigation water demand would decrease from 53.5 Mm$^3$ (as estimated under the rigid delivery scenario) to 33.7 Mm$^3$.

**Table 2.2** Simulated applied seasonal water depths, estimated evapotranspiration and yield decrease for the main crops under RDS and FDS (data for 2006 averaged from simulation units)

<table>
<thead>
<tr>
<th></th>
<th>Rotation Delivery Schedule, RDS (current)</th>
<th>Flexible Delivery Schedule, FDS (simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vegetables</td>
<td>Grapes</td>
</tr>
<tr>
<td><strong>Seasonal applied water depth (mm)</strong></td>
<td>468</td>
<td>612</td>
</tr>
<tr>
<td><strong>Soil Water at planting (mm)</strong></td>
<td>28</td>
<td>87</td>
</tr>
<tr>
<td><strong>Soil Water at harvesting (mm)</strong></td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td><strong>Water excess (mm)</strong></td>
<td>93</td>
<td>216</td>
</tr>
<tr>
<td><strong>Max ET (mm)</strong></td>
<td>604</td>
<td>523</td>
</tr>
<tr>
<td><strong>Actual ET (mm)</strong></td>
<td>530</td>
<td>519</td>
</tr>
<tr>
<td><strong>Delivery Schedule Performance (%)</strong></td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td><strong>Yield decrease (%)</strong></td>
<td>13</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 2.3 Simulated total irrigation volumes for the three largest districts and for the whole system under the RDS and FDS scenarios, and potential water conservation attainable when adopting the FDS in the study area

<table>
<thead>
<tr>
<th>District No.</th>
<th>Cropped area (ha)</th>
<th>RDS scenario Total irrigation volumes (Mm³)</th>
<th>FDS scenario Total irrigation volumes (Mm³)</th>
<th>Potential water conservation (Mm³)</th>
<th>Averaged potential water conservation (m³/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1204</td>
<td>6.5</td>
<td>4.8</td>
<td>1.8</td>
<td>1470</td>
</tr>
<tr>
<td>2</td>
<td>1032</td>
<td>6.3</td>
<td>4.0</td>
<td>2.2</td>
<td>2169</td>
</tr>
<tr>
<td>5</td>
<td>1675</td>
<td>10.3</td>
<td>6.2</td>
<td>4.0</td>
<td>2389</td>
</tr>
<tr>
<td>Total (whole system)</td>
<td>8636</td>
<td>53.5</td>
<td>33.5</td>
<td>19.6</td>
<td>2292</td>
</tr>
</tbody>
</table>

Figure 2.5 presents the two operational scenarios (sections a and b) in terms of disaggregated seasonal applied water depths. Also, Fig. 2.5 shows that, under the FDS scenario, the eastern part of the irrigation system is likely to be the most affected area in terms of seasonal water applied changing from RDS to FDS.

2.4.2 Groundwater quality

By comparing winter and summer salinity maps, which result from the spatial interpolation of point-measured values, it can be observed that groundwater salinity increased in 2006 from winter (Fig. 2.6 – section a) to summer (Fig.2.6 – section b). The increase in groundwater salinity mainly concerned the eastern part of the study area. Fig. 2.6 shows that the groundwater salinity, expressed in terms of TDS, which was measured in winter for the eastern part, ranged between 1.5 and 1.8 g l⁻¹, whereas it reached TDS values between 1.9 and 3.1 g l⁻¹ in summer. The western-most part of the study area showed no significant increment of groundwater salinity.
Fig. 2.5 Spatial distribution of simulated seasonal applied water depths in the study area under the RDS scenario (a) and FDS scenario (b) for weather data of 2006
2.5. Discussion

The results obtained from simulations of soil water balances for vegetables, table-grapes and citrus grown in the study area under the RDS and FDS scenarios clearly show that farmers are heavily bound by the present mode of operation of the water delivery system. If farmers irrigate in compliance with the fixed delivery currently scheduled by the WUO, the crops are likely to experience both water deficit and excess water. The comparison between both schedules explains why many growers prefer pumping groundwater to irrigate instead of relying on deliveries from the irrigation distribution networks.

As regards summer vegetables, the extension agents interviewed reported that, when using groundwater as irrigation source (thus under an unconstrained and flexible type of supply), growers usually irrigate the fields every 2-3 days by means of trickle systems, that is applying small water depths (20-25 mm). By managing irrigation under FDS farmers can easily prevent water deficit and water excess to the crops by applying a total amount of water which is slightly lower (6.5%) than that under RDS.

Likewise, for table-grapes extension agents from the WUO and farmers’ representatives reported that, when growers can rely on water supply with no limitations or delivery constraints, they usually tend to apply small amounts of water (20-25 mm of water per irrigation) through trickle systems. Moreover, they vary the frequency of applications during the irrigation season, from a minimum of 8-10 days to a maximum of 5-6 days during the peak demand period. Even for this crop, the FDS enables farmers to avoid water deficit and excess using nearly 40% less water than the amount applied under RDS.
As regards citrus, the extension agents reported that, under flexible water supply, growers usually apply 35-40 mm of water per irrigation by means of micro-sprayers, also varying the frequency of irrigation along the season up to a minimum irrigation interval of 8-10 days during the peak demand period. The FDS enables citrus growers to apply nearly 45% less water than the amount applied under RDS and to avoid water excess at the same time.

The simulation results are supported by information provided by the farmers interviewed. Growers reported that, under RDS, the on-farm water management is greatly limited, because the WUO’s scheduled water deliveries are restrictive and their timing is inadequate to meet the irrigation requirements and the farmers’ needs for most of the crops grown in the area. In order to achieve flexible irrigation management, many farmers rely on groundwater pumping, which in their perception represents an unconstrained and flexible water supply. Upon enforcement of the regulations of the Regional Water Plan in the area, farmers’ use of groundwater will be no longer uncontrolled as it is to date, but it will be strictly forbidden, or limited, and monitored.

In the current situation, many farmers pump water from the aquifer to offset the restrictions imposed by rigid rotation delivery and to achieve more effective irrigation timing. On top of that, under the current tariff system there is no incentive for water conservation at any system’s level, nor for efficient water use at farm level. If farmers have recourse to the water service supplied by the WUO, they must pay a fixed tariff to the WUO per irrigated area per season, regardless of the amount they actually receive during the irrigation season.
Fig. 2.6 Map of groundwater salinity in the Sinistra Bradano area during winter, (February) (a) and summer (July) (b) for the year 2006
In this situation, they may end up with applying the entire amount delivered during their turn to cropped fields, even though neither crops nor soils need it. This is clearly depicted by the simulated amounts of excess water that may result from irrigating different crops under the RDS scenario (Table 3.2).

As for the operational scenarios at scheme level, Table 3.3 and Fig. 2.5 show that FDS could allow for achieving a significant reduction (37 %) in the seasonal amount of water demanded at district and system level with respect to the RDS scenario. The overall seasonal irrigation demand under FDS would amount to 33.7 Mm$^3$. Given that, on average, 35 Mm$^3$ are seasonally available in the San Giuliano reservoir for the Sinistra Bradano irrigation system, implementing the flexible delivery in the study area would be feasible and might reduce or prevent groundwater pumping by farmers, as long as the service provided by the WUO proves to be adequate to fulfil farmers’ needs in terms of conditions of water delivery. However water storage and/or pressurization of the system would be required to allow for more frequent irrigation applications.

As far as groundwater quality is concerned, based on the analysis of simulation results and field information it can be inferred that if the WUO implemented a cost-effective FDS throughout the system, groundwater pumping by farmers would probably decrease, particularly in the eastern part of the study area. This area also corresponds to the zone where salinity increased most between winter and summer 2006 (Fig. 2.6) and where most probably the use of groundwater from the upper aquifer was higher during the irrigation season 2006 due to intensive agricultural withdrawals. The eastern part also happens to be the area where most of the citrus is found. Simulations of soil-water balance carried out on this crop showed the largest difference between RDS and FDS
(Fig. 2.4) as well as high potential for water conservation. Although these simulations showed that no water deficit would occur to citrus under RDS, field interviews with extension agents and local farmers revealed that groundwater pumping is the water source that citrus growers prefer. This is due to a combination of factors, including the fact that citrus growers start irrigating earlier (March) with respect to the beginning of water delivery by the WUO (April), that farmers need to get rid of the delivery constraints imposed by the WUO, not to mention the high irrigation requirements and the lowest profitability of citrus with respect to other crops.

All the aforesaid factors are likely to results in higher cost-effectiveness of groundwater pumping relative to the requirements of micro-sprinklers and trickle on-farm systems and to the water tariffs applied by the WUO. Local farmers and the WUO’s technical staff also reported that, in the eastern area, the distribution networks deliver water with the lowest pressure heads at hydrants, since this zone is characterized by relatively high land elevation and is served by the tail-end of the main canal, which in turn may negatively affect the dependability of the scheduled water delivery. Under these conditions, farmers living in the eastern part of the study area (especially those growing citrus) may find that groundwater pumping proves to be more appropriate to feed properly their pressurized on-farm systems for high-frequency irrigation.

Although the available data does not allow reliable assessment of the cause of increased groundwater salinity, it shows that increased summer pumping may lead to progressive salinization. Quantifying the water volume withdrawn by farmers from the aquifers is very difficult and not straightforward with the available data.
The low sensitivity of the western part to salinity increase may be due to lower intensity of groundwater pumping. Since this area is served by the upstream part of the main canal, the delivery service is probably more dependable than in the eastern area. Moreover, the river base-flow that amounts to an average flow rate of $7 \text{ m}^3 \text{ s}^{-1}$, is likely to exert some positive hydrodynamic pressure on the upper aquifer eastwards and southwards, given that the Bradano River flows along the western boundary of the irrigation scheme (Fig. 2.1). This may be due to the high hydraulic conductivity of sand and gravel deposits located near the river. The shallow aquifer in this zone is recharged by the Bradano River, where water has an average TDS value of 0.8 – 0.9 g l$^{-1}$. In this area, seawater intrusion seems to be lower than that found in the eastern part, where the over-exploitation of the aquifer is not mitigated by the hydraulic influences of the river.

2.6 Improving Water Delivery

The results obtained from simulations, along with data collected by field interviews, show the urgent need for improving the delivery of surface water to benefit farmers. A tentative enhancement of the current situations could be attained by modernizing the irrigation system from both the technical and the operational points of view. The Sinistra Bradano irrigation scheme is a multi-cropped heterogeneous area where the operation of the distribution system targeted to achieve homogeneous water delivery might represent a major cause of inefficiency.

Several measures could be implemented to improve the flexibility of water distribution with the aim of fostering efficiency of water use in the study area. Tailoring deliveries to different irrigation districts and sectors and for different periods along the irrigation season could be a feasible solution to meet crop irrigation requirements in the
best possible way and to improve the overall quality of delivery services provided to users. To this end, the WUO’s managers need an in-depth understanding of the spatial and temporal water distribution and of management requirements. Simulation modeling should be used to generate a set of possible flow hydrographs at sector, district and scheme level for the different delivery schedules that are technically feasible with the existing irrigation network. A special delivery schedule could then be arranged at each distributor. For this to be done, cropped areas must be known in the command area that is served by each district and sector off-takes, and the irrigation calendars need to be arranged for each group of farmers. Through simulation modeling and the participation of the groups of farmers concerned, this solution could be viable, even in the short term.

A detailed investigation is also needed to evaluate the potential imbalance between water demand and supply over time, for decadal or monthly time-steps. This would require collecting and analyzing multiannual time-series of water supply. In the event of surface water shortage in the study area, developing a sound plan for conjunctive use of surface and groundwater, as well as eventually centralizing the water pumping from the aquifer, could be feasible alternatives for improving the management of water resource and monitor both the aquifer exploitation and groundwater salinity. Under the assumption of improved delivery scheduling, the pumping of groundwater would be regarded as an additional, though limited, water supply with respect to that distributed by the WUO through the delivery network, in case the latter does not fully meet the farmers’ needs in specific periods of the irrigation season. When necessary, the excessive amounts of water (water that is not withdrawn from the network or not applied to the fields) could
be stored either at the farm level in holding ponds, or in district reservoirs that need to be properly sized and constructed at the upstream ends of the distribution networks.

In order to test whether the flexible delivery schedule fits technically the existing irrigation network, a detailed hydraulic analysis should be conducted by means of hydraulic simulation models at sector, district and scheme level. These simulations could allow for identifying the performances achievable by the existing network under different modes of operation, the weaknesses of the system with respect to the simulated hydrographs and to the existing capacity of the network, and the main structural and operational correcting measures.

Finally, as regards tariff rules, they should be modified into volumetric charges and vary according to the seasonal volumes consumed by farmers, in order to promote a more responsible use of the available water thereby avoiding inefficiencies at farm level.

2.7 Conclusions

All simulations, information gathered by means of field interviews and the results reported proves that the rotation delivery serving the study area does not allow for an efficient use of the available supply, since both the amount and timing of water delivered to farmers do not match the estimated crop irrigation requirements. As a result, some significant water deficits and surpluses may characterize different cropped areas that are served by the irrigation system. The rotation delivery schedule encourages many farmers to pump water from the aquifer at their convenience so as to avoid the rigidity and the restrictions imposed by the fixed rotation and to prevent water deficits resulting from inadequate canal water deliveries.
The operation of the system could be considerably enhanced if only water deliveries were better tailored to crop requirements and farmers’ needs. This would lead to the reduction of the existing demand on aquifer as well as to positive impacts on the environment and the economic sustainability of irrigated agriculture in the study area.

References


CHAPTER 3
SIMULATION OF PEAK-DEMAND HYDROGRAPHS IN PRESSURIZED IRRIGATION DELIVERY SYSTEMS USING A STOCHASTIC MODEL
PART I: MODEL DEVELOPMENT

Abstract This paper describes a model named HydroGEN that is based on a stochastic methodology conceived for simulating hydrographs of daily volumes and hourly flow rates during peak-demand periods in pressurized irrigation delivery networks with on-demand operation. The model is composed of a set of computational procedures that allow reproducing the crop irrigation management practices followed by farmers and simulating the soil-water balance and irrigation events for all cropped fields supplied by each delivery hydrant in a distribution network. The input data include weather, crop and soil parameters, as well as information on irrigation practices followed by local farmers. The model outputs are generated flow hydrographs during the peak-demand period that enable the subsequent analysis of performance achievable under different scenarios. The model can be applied either for system design or re-design, as well as for analysis of operation and evaluation of performance achievements of on-demand pressurized irrigation delivery networks. Results from application of HydroGEN to a real pressurized irrigation system at different scales are presented in Chapter 4 (Model Applications).

3.1 Background and Previous Work
In several Mediterranean countries, a first phase of modernization of existing irrigation systems was carried out during the 1980’s and mainly concerned physical

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1 Coauthored by Daniele Zaccaria, Nicola Lamaddalena, Christopher M.U. Neale, and Gary P. Merkley
aspects of the infrastructure. Although modernization processes should include changes in physical facilities, operational procedures, water management, and institutional aspects for properly upgrading an existing irrigation project to meet new performance criteria (Price 1999), in many cases large investments were made during the 1980’s and 1990’s only to transform open-channel water delivery schemes into pressurized networks. This type of physical modernization usually offers great potential to enhance the overall management of irrigation systems, with tangible benefits for crop production and water conservation (Merriam and Davis 1986) due to the fact that pressurized networks, when properly designed and operated, have the significant advantage of allowing more flexible delivery schedules (Lamaddalena and Zaccaria 2004).

Although during many modernization programs positive impacts on rural economies were proposed to decision-makers and stakeholders, the anticipated benefits were not always achieved and actual performance of newly modernized systems are often lower than expected. While developing modernization programs, little attention was paid to the analysis of future system operation under different delivery scenarios prior to deciding upon the specific measures to be implemented.

To this end, the determination of demand flow rates is one of the most relevant and uncertain aspects in the analysis of operation of large-scale pressurized irrigation systems, as the configuration of flows in the network affects both the design and operating conditions. Specifically, in pressurized delivery networks, simulating the daily demand volumes is relevant to allow accurate management of the available water supply, whereas forecasting hourly flow rates during the peak demand periods would enable the
Lamaddalena (1997) emphasized that in pressurized systems flows are subjected to relevant time variability and are affected by spatial heterogeneity and uncertainties related to crops, soils, meteorological conditions, on-farm irrigation efficiency, and farmers’ practices. Other authors, such as Pulido-Calvo et al. (1998) and Reca et al. (1999), reported the variability over time and uncertainty of flowrate demands in pressurized systems as being also related to different energy costs during daytime hours, network operation and management requirements, and farmers’ habits. In designing new irrigation systems, as well as in modernizing and re-engineering existing ones, design engineers have often overcome the uncertainty of flow demand by over-sizing hydraulic works with respect to current or projected operational requirements. Pereira et al. (2003) and Moreno et al. (2007) reported that in pressurized irrigation delivery networks the demand discharge at hydrants must take into consideration the variable decisions of farmers relative to the timeliness, duration, and frequency of irrigations, as well as farmers’ habits and behaviors.

From earlier research on this topic it can be inferred that accurate operational analysis in pressurized distribution networks requires estimating high spatial and temporal resolution irrigation demand patterns in order to simulate flow configurations. This is a challenging task when the complexity of large and heterogeneous multi-cropped irrigated areas is considered. Specific problems include the accurate quantification of cropped areas, characterization of the spatial and temporal variability of parameters that
affect the crop water demand, and reproducing the irrigation management strategy followed by farmers.

The discharges flowing into each section of pressurized distribution networks may be computed or simulated by using probabilistic approaches, in which the Gaussian distribution of discharges is hypothesized (Clement 1966; Clement and Galand 1979). With these methods a single peak-flow is used for design and a risk-threshold is accepted, i.e. during the operation of the system, discharges higher than those assumed at design may occur with low probability (Calejo et al. 2008). Alternatively, the simulation of flow distribution in pressurized irrigation delivery networks can be better performed using the “Several Flow Regimes” (SFR) approach as proposed by Labye et al. (1988), or generating the irrigation demand by performing a soil water balance at each delivery hydrant in combination with a stochastic approach to account for farmers’ behavior (Lamaddalena 1997; Calejo et al. 2005; Khadra and Lamaddalena 2006; Moreno et al. 2007; Lozano and Mateos 2008). The SFR approach involves the random generation of K hydrants simultaneously opened among the total number of hydrants, R, of the network (with K < R) and the discharge in the sections of the network is thus calculated as the sum of the discharges withdrawn from the downstream hydrants that are in simultaneous operation (Lamaddalena and Sagardoy 2000), with the simplifying assumption that each open hydrant always delivers the nominal flow rate.

In the past, a single value of peak discharge, as computed from the “First Clement Formula” (Clement 1966), was typically used to design and size large-scale irrigation systems operating on-demand, but this approach does not account for the variety of flow configurations occurring in the pipe network, which are very relevant to performance
analysis. Lamaddalena (1997) and Lamaddalena and Pereira (1998) demonstrated that, even when the design discharges are not exceeded, very low hydraulic performance could occur in the network during its operation due to seasonal and daily variation in farm demand, and to different configurations of hydrants in simultaneous operation. As a result, a large spatial and temporal variability of pressure and discharge available at hydrants may occur, and this can affect network performance (Lamaddalena et al. 2007).

Both the SFR and the soil water balance approach account for the temporal variability of the discharges flowing into the irrigation network and the performance analysis and design, or modernization, can then be conducted by evaluating the values of performance indicators that result at the system and hydrant levels from the generated flow configurations.

Several simulation models have been proposed to forecast water demand in large-scale irrigation systems. Maidment and Hutchinson (1983) modeled the demand pattern over a large irrigation scheme taking into account the service area, soil types, cropping patterns, the adopted irrigation strategies, and weather variations. However, in their approach the demand hydrograph had to be averaged over time in order to avoid unrealistic water demands which were highly variable from one day to the next. Some simulation models utilize queuing theory (Abdellaoui 1986), and other models estimate the water requirements for each field by maintaining a soil water balance, subject to individual field characteristics and weather conditions, based on a chosen method of irrigation scheduling (Walker et al. 1995; Lozano and Mateos 2008). Although these models were applied to command areas of existing irrigation systems and aggregate demands were estimated with reasonable accuracy (Prajamwong et al. 1997; Yamashita
and Walker 1994; Walker et al. 1995), they consider a single peak discharge demand in the network. Moreover, these models were conceived to assist irrigation project managers in operating surface irrigation projects at the turnout level.

D’urso (2001) proposed a deterministic model to simulate demand in existing irrigation systems assuming the hydrograph as limited by the hydraulic capacity of the distribution networks. In his model, there are no means to account for the variability due to farmers’ behavior and local practices in crop irrigation management, as the model only considers the deterministic components given by the soil water budget in the root-zone.

Two other models were developed to perform extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. The first is called EPANET (Rossman et al. 1993; Rossman 2000) and tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank or reservoir, and the concentration of a substance flowing into the network during a multi-time period simulation. The EPANET model requires the demand hydrograph at each node as input data. The second model is called Random Generation Model, RGM, (Lamaddalena and Sagardoy 2000) and generates the flow distribution in the different pipe branches for fixed values of the discharge at the inlet of a pressurized irrigation system operating on-demand, using a random generation algorithm for simulating the opening and operation of hydrants. More recently, several other authors (Khadra and Lamaddalena 2006; Zaccaria et al. 2006; Rodriguez Diaz et al. 2007; Moreno et al. 2007) presented models and methodologies to simulate demand flows in pressurized irrigation systems, highlighting that the distribution of flows in each section of the delivery network will most likely vary from one period to another.
Simulating the conditions required for adequate performance of the irrigation network during its life period is the major task to be accomplished for accurate design or re-engineering of irrigation systems. The model presented by Lamaddalena and Sagardoy (2000) and by Khadra and Lamaddalena (2006) can generate several possible discharge configurations and would enable the design of systems capable of achieving good performance for the life span of the project, considering possible scenarios changes that may occur. Khadra and Lamaddalena (2006) conducted a detailed analysis of the demand hydrographs and demonstrated that, in the flow generation process, both deterministic and stochastic components need to be considered. The parameters of the soil-water balance in the root-zone constitute the deterministic component of the flow demand that is based on the combination of crop, soil and weather parameters related to the actual crop evapotranspiration process. The stochastic component accounts for uncertainties and for sources of variability related to the crop cycle (sowing, development and maturity), to the initial soil water reserve, and to the habits and irrigation management practices of the farmers.

The HydroGEN model presented in this paper results from the enhancement of the aforesaid model presented by Khadra and Lamaddalena (2006) and includes refinements and amendments of several internal computational procedures. The enhanced model simulates the soil-water balance for each cropped field supplied by water delivery hydrants and generates the demand hydrographs both at the hydrant level and at the inlet of the distribution network.

The overall objective of the present study consists in testing the applicability and reliability of the HydroGEN model for operational analysis and planning, as well as for
modernization of existing large-scale pressurized irrigation systems. In the following sections, the conceptual methodological approach and its main components are illustrated. A companion paper (Part II: Model Applications) illustrates the applications of the HydroGEN model to a real-case pressurized irrigation system at different operational scales.

3.2 Modeling and Simulation Approach

The approach utilized by the HydroGEN model for generating the flow demand hydrographs is outlined in Fig. 3.1.

Modeling crop irrigation demand to forecast flow hydrographs in pressurized systems entails a deterministic component, which is represented by the soil-water balance equation, and a stochastic component that accounts for uncertainties and variability of some parameters related to crops and their response to weather, initial soil water content at the beginning of crop growth cycle and farmers’ habits and practices.

With regards to the deterministic component, daily water balances are simulated for individual cropped fields supplied by the water distribution network, based upon crop evapotranspiration estimated from daily climatic and rainfall data, crop type and stage of development, soil properties, and farm irrigation methods.

Soil evaporation and crop transpiration are estimated separately on the basis of the dual crop coefficient approach (Allen et al. 1998), of canopy development in the different growth stages, which in turn can be measured or estimated in the field through the fraction of soil covered by the green canopy (fraction or percentage of ground cover), of daily meteorological data and of simulated daily available soil water.
The stochastic component enables the determination of some parameters of relevance to the computation of crop irrigation requirements and of timings of irrigation events, such as the sowing or green-up dates, crop phenology, and the initial soil water content at the beginning of the growing season. All the above parameters are strongly affected by uncertainties related to weather variables and farmers’ decisions. In HydroGEN these parameters are determined by means of random generation within specific user-defined ranges, as described below.

In HydroGEN, both the deterministic and stochastic components were refined and amended with respect to the earlier version of the model presented by Khadra and Lamaddalena (2006), by introducing improved algorithms so as to integrate or enhance the following computational procedures:
1. Estimation of effective rainfall

2. Estimation of daily fractional canopy cover

3. Calculation of basal crop coefficient for the mid-season at peak plant size or height

4. Correction of basal crop coefficients of mid-stage for local climatic conditions

5. Estimation of actual soil evaporation and crop transpiration

6. Determination of timing of irrigation events, either under full or regulated irrigation practices

7. Computation of irrigation depths to be delivered at irrigation events

8. Calculation of hourly discharges during the peak-demand period

### 3.2.1 Simulation of daily irrigation volumes

By maintaining a root-zone soil water budget for the cropped fields served by each delivery hydrant, the deterministic and stochastic components jointly allow generating disaggregated information on soil water deficits, and thus on timing and volumes of irrigation demand, both under conditions of full replenishment of crop irrigation requirements and under regulated and/or deficit irrigation strategies. The ability to simulate demand flow hydrographs under regulated and deficit irrigation scenarios represents a major new feature with respect to the earlier version of the model presented by Khadra and Lamaddalena (2006).

The irrigation depths resulting from simulating the daily water balance and irrigation events are then summed up for all the cropped fields supplied by each hydrant, and afterwards aggregated for all hydrants of the network, thus enabling the generation of
a daily hydrograph of irrigation demand volumes. The aggregation can be conducted up to different system management levels, thus producing hydrographs at the hydrant, at single branches of the distribution network, sector, district, or at the entire system level.

3.2.2 Rationale for stochastic processing in simulating hourly discharge hydrographs

The simulation of hourly discharge hydrographs is affected by uncertainties due to farmers’ decisions about irrigation timing and duration, as well as farmers’ habits and their irrigation management strategy. Once the daily volumes demanded at the inlet of the distribution network are simulated and the peak-demand period is identified through some deterministic and stochastic procedures, further stochastic processing is required in order to account for these sources of uncertainties while simulating the discharge hydrographs. In the following, the theoretical basis which justifies the need of the stochastic processing is illustrated through the analysis of demand hydrographs recorded in a real pressurized distribution network.

The hourly flow rates withdrawn from an irrigation delivery system located in southern Italy (network of District 10 of the Sinistra Ofanto irrigation system in the Foggia province) and operated on-demand were monitored and recorded for the entire 2008 irrigation season by means of a venturi-type flow meter installed at the upstream end of the distribution network.

Based on the recordings, the 10-day peak irrigation demand period was identified and the values of the average hourly flow rate were computed by Eq. 3.1.

\[
\mu_i = \sum_{d=1}^{10} \frac{Q_{t,d}}{10} \quad (3.1)
\]
where $\mu_t$ are the mean hourly flow rates withdrawn during the peak demand period; and, $Q_{t,d}$ is the flow rate withdrawn from the delivery system at an hour $t$ during day $d$.

For the 10-day peak demand period, a 240-record matrix was thus populated with values of hourly flow rate, and afterwards the average flow rate withdrawn during the same period was computed by Eq. 3.2:

$$\mu_{AVE} = \frac{1}{24} \sum_{t=1}^{24} \mu_t$$  \hspace{1cm} (3.2)

Provided that the distribution network under monitoring is operated by limited-rate demand, in order to understand farmers’ behavior during the peak demand period, as well as during the daytime, the whole set of discharge recordings were processed to draw the auto-correlation function (ACF) of water withdrawals by farmers, by means of Eq. 3.3:

$$F_{A,t} = \sum_{t=1}^{N_p-t_1} \frac{(Q_t - \bar{Q})(Q_{t+t_1} - \bar{Q})}{\sum_{t=1}^{N_p} (Q_t - \bar{Q})^2}$$  \hspace{1cm} (3.3)

Figure 3.2 reports the ACF ($F_{A,t}$) of withdrawals during the 2008 irrigation season from the monitored delivery system. From the figure, it can be observed that there is a sinusoidal pattern of the autocorrelation function, showing that farmers usually take water from the system at their convenience, but commonly at the same times during the day.

To better understand and explain the farmers’ behavior, it is assumed that water withdrawals from the distribution network follow a combination between a deterministic component and a random component. In other words, the time series of withdrawals are assumed to be regulated by the following rule:

$$Q_{h,d} = \mu_h + re_{h,d}$$  \hspace{1cm} (3.4)
where $Q_{h,d}$ are values of hourly flow rate recorded at the upstream end for the identified 10-day peak-demand period (hour by hour, for each of the 10 days of peak irrigation demand); $\mu_h$ are the average hourly flow rates (calculated as average of the 10 values of the flowrate related to each of the 24 hours in a day); and, $r_{e,h,d}$ are the residuals obtained from the difference between $Q_{h,d}$ and $\mu_h$.

From this step of data processing, a set of 240 values of $r_{e,h,d}$ was obtained and the auto-correlation function of the residuals was thus computed (Fig. 3.3) with the aim of investigating the pattern of the random component in the time series of water withdrawals by farmers from the water delivery network. From Fig. 3.3 it can be inferred that the value of the autocorrelation function becomes very close to zero after the initial time period of about 10-12 hours, thus showing that after that time lapse the data are not correlated.

![Auto-correlation Function](image)

**Fig. 3.2** Auto-correlation function of withdrawals during the 2008 irrigation season from the monitored delivery system
Within the initial 12-14 hours, the fact that $\text{ACF} \neq 0$ shows the existence of correlation between data, which can be explained by the fact that, when needing to irrigate their fields, farmers give the command to the hydrant to start the water withdrawal and to keep it in operation for the necessary time (or until the necessary water volume is delivered) to refill the root zone. Micro irrigation is currently the most commonly used irrigation method in the monitored system, and the majority of hydrants has a nominal flow rate of 10 l s$^{-1}$, but usually operates at much lower discharges due to very small land holdings, a time of 10-12 hours represents a typical operation time of hydrants for drip irrigation events during the peak-demand period. Therefore, it is assumed that the time series of residuals is affected by an inertial component represented by the common hydrants operation time, and by a purely random component.

![Fig. 3.3 Auto-correlation function of the residuals between the hourly flow rates and the average hourly flow rates withdrawn during the 10-day peak-demand period of the 2008 irrigation season in the monitored delivery system](image)
This can be also inferred by observing the auto-correlation of residuals drawn on the same system on discharge data collected during the irrigation season 1999, which is reported in Fig. 3.4. At that time, sprinkler and mini-sprinkler irrigation was commonly utilized by farmers for most of the crops, so the typical hydrant operation times (inertial component), as seen in Fig. 3.4, were on average shorter (7-8 hours) than those observed during the 2008 irrigation season, when trickle irrigation was instead the preferred irrigation method by nearly all farmers.

For a deeper understanding of the system’s behavior through water withdrawals, the time series of the residual, $r_{e_h,d}$, for the data collected during the 2008 season was further analyzed with respect to the values at the previous instant $r_{e_h-1,d}$, through a regression analysis, which is presented in Fig. 3.5, yielding the Eq. 3.5.

Fig. 3.4 Auto-correlation function of the residuals between the hourly discharges withdrawn and the average hourly discharges during a 10-day peak demand period in the 1999 irrigation season from the monitored delivery system
\[ re_{h,d} = R_A + R_B \ast re_{h-1,d} + R_{h,d} \] (3.5)

where \( R_A \) and \( R_B \) are regression coefficients (whose values were determined to be 0.7528 and 0.267, respectively); and, \( R_{h,d} \) are the random residuals.

On the basis of this additional data processing step, the auto-correlation function of the random residual was calculated and is presented in Fig. 3.6. From this figure it can be noticed that, when the inertial component related to the residuals at the previous instant \( (re_{h-1,d}) \) is discarded, the ACF is very close to zero, showing that no correlation exists among the random residuals. In conclusion, from the analyses carried out it can be stated that the time series of water withdrawals from the delivery network are affected by a deterministic component, which is related to the different terms of the soil water balance, and by a stochastic component related to the hydrants’ nominal discharge, the irrigation methods utilized by farmers, the size of irrigated fields, and to the farmers’ decisions on crop irrigation management resulting from their strategy, and from crop quality targets pursued by them.

The combination of deterministic and stochastic components yields a stochastic phenomenon, so the deterministic component \( \mu_h \) of the process can be considered to be proportional to the probability distribution function of water withdrawals during the peak irrigation demand period.

In HydroGEN, for simulating the hourly flow rates during peak-demand periods on the basis of the generated daily irrigation volumes, an additional stochastic procedure and a related algorithm is proposed as an alternative to the one presented in the earlier version of the model.
Fig. 3.5 Regression analysis of the residuals with respect to those relative to the previous instant for the monitored delivery system in the 2008 irrigation season

\[ y = 0.7528x + 0.267 \]
\[ R^2 = 0.5687 \]

Fig. 3.6 Auto-correlation function of the isolated random residuals for the water withdrawals during the 2008 irrigation season from the monitored delivery system

The former procedure entails a stochastic approach which allows determining the operation start-time of each hydrant (time of hydrant’s opening) by using the probability
distribution function of hourly irrigation withdrawals during the peak demand periods. As described by Khadra and Lamaddalena (2006), this function can be derived by analyzing and processing datasets of hourly discharges recorded during the peak-demand period at the upstream end of the distribution networks under analysis or of other networks operated under similar delivery scheduling and operation conditions. Once hydrant operation start times are determined by the former procedure, the model computes the duration of water delivery for all hydrants in simultaneous operation on the basis of the irrigation volumes to be supplied to fully or partially replenish crop requirements, and considering the hydrants’ nominal discharge. Finally, the model aggregates the demand flow rates upwards on an hourly basis to generate the daily hydrograph for each day of the peak-demand period.

The proposed alternative procedure allows deriving the hourly hydrograph by processing a series of recorded hourly discharges through several computational steps, which also include the generation of series of random numbers with uniform distribution. In other words, through this alternative procedure, the model still relies on the probability distribution function of withdrawals but the uncertainty related to farmers’ behavior is accounted for by means of a newly-introduced simplified stochastic algorithm which is described in the following sections.

### 3.2.3 Estimation of crop irrigation requirements

Net irrigation requirements for each cropped field are computed with a daily time step based upon the soil water balance equation expressed in a simplified form as follows:

\[
I_n = ETa - R_{ef}f - GW + SRO + DP + \Delta Ws
\]  

(3.6)
where \( I_n \) is net irrigation requirement; \( \text{ETa} \) is actual crop evapotranspiration; \( \text{Reff} \) is effective rainfall; \( \text{GW} \) is groundwater contribution; \( \text{SRO} \) is surface runoff; \( \text{DP} \) is deep percolation of water below the root zone; and, \( \Delta \text{Ws} \) is the change in soil water content from the previous time period (day).

A detailed description of all the computational steps carried out by HydroGEN for estimating crop water requirements and for generating flow hydrographs, with specific reference to all improvements and refinements introduced, is provided in the following sub-sections.

### 3.2.3.1 Crop evapotranspiration

HydroGEN utilizes a dual crop coefficient approach (Allen et al. 1998) to determine crop transpiration (\( T \)) and soil evaporation (\( E \)) separately, by multiplying the reference evapotranspiration (\( \text{ETo} \)) by the various crop coefficients (\( K_c \)). The dual crop coefficient approach was recently introduced in the computational procedures in order to enhance the accuracy of estimation with respect to the single crop coefficient methodology utilized in the earlier version of the model.

When the soil water in the root zone is not limited, HydroGEN estimates crop transpiration and soil evaporation as occurring at their potential rate through the following relationship:

\[
\text{ETc} = (\text{Ke} + \text{Kcb}) \times \text{ETo} = (\text{Ke} + \text{Kcb}) \times \text{ETo}
\]

where \( \text{ETc} \) is potential crop evapotranspiration (mm \( \text{d}^{-1} \)), \( \text{ETo} \) is reference evapotranspiration, or evaporative demand of the atmosphere (mm \( \text{d}^{-1} \)); and, \( \text{Ke} \) and \( \text{Kcb} \) are, respectively, the coefficients for soil evaporation and crop transpiration.
When insufficient water is available in the root zone to match the evaporative demand of the atmosphere, the model considers that crop transpiration and soil evaporation drop below their potential rates. For simulating these conditions, the potential crop transpiration is multiplied by a water stress coefficient (Ks), and the potential soil evaporation is multiplied by a reduction coefficient (Kr):

\[ \text{ETa} = (\text{Kr}\times\text{Ke} + \text{Ks}\times\text{Kcb})\times\text{ETo} \]  

(3.8)

### 3.2.3.2 Potential and actual soil evaporation

The model estimates Evaporation (E) from the exposed soil as occurring first in an *energy limiting stage* and afterwards in a *falling rate stage*. The energy limiting stage takes place when the soil surface is wet following rainfall or irrigation, and the evaporation rate is calculated as a function of the energy available at the soil surface. Within this stage, HydroGEN calculates soil evaporation as taking place at its maximum (potential) rate from a thin top-soil layer in contact with the surrounding atmosphere according to Eq. 3.9:

\[ \text{E}_{\text{pot}} = \text{K}_e \times \text{ETo} = \left([\left(1-\text{CC}^*\right) \times \text{Kc}_{\text{wet bare soil}} \times \text{Pw}]\right) \times \text{ETo} \]  

(3.9)

where \( \text{E}_{\text{pot}} \) is the potential soil evaporation (mm d\(^{-1}\)); \( \text{CC}^* \) is the effective fraction of the soil surface covered by green canopy; \( \text{Pw} \) is the fraction of wetted soil; and, \( \text{Kc}_{\text{wet bare soil}} \) is the crop coefficient for a wet and unshaded soil surface. For \( \text{Kc}_{\text{wet bare soil}} \) the model takes value of 1.10, as suggested by Allen et al. (1998).

When the upper evaporating soil surface layer becomes dry, HydroGEN assumes, in compliance with outcomes from soil water models and with empirical evidences, that water flows upwards from subsurface layers to the top-soil layer and that evaporation occurs at a falling rate, which depends not only on the available energy but also on the
hydraulic properties of the soil. In this falling-rate stage, HydroGEN considers the evaporation rate as decreasing with time and with the relative water content, due to the fact that the water flow to the upper (evaporating) soil surface layer becomes reduced as the available soil water in the profile decreases, as described by Raes et al. (2009).

HydroGEN requires inputting the values of the actual fraction of soil surface covered by green canopy (CC) at beginning and end of each growth stage which compose the crop cycle, as well as the duration (days) of each growth stage. These input values of CC are then corrected and increased to CC* (effective fraction) to account for the sheltering effect of the canopy, according to Eq. 3.10, as suggested by Raes et al. (2009), which is based on experimental data from Adams et al. (1976) and Villalobos and Fereres (1990).

\[
CC^* = 1.72 \, CC + CC^2 + 0.30 \, CC^3 \geq 0 \tag{3.10}
\]

where CC* is the effective fraction of the soil surface which is covered; and, CC is the green canopy cover or fraction of the soil surface covered by green canopy measured (or estimated) near solar noon.

Although other equations are available in the literature for describing the effect of canopy density on shading (Fereres 1981; Allen et al. 1998; Snyder and Eching 2005; Allen and Pereira 2009) Eq. 3.10 simplifies the estimation of the effective fraction of ground covered or shaded by vegetation from the fraction of soil surface covered by green canopy (CC), without considering other parameters such as the mean angle of the sun, the latitude of the location, the solar declination, or the solar time angle. After the correction of input data, the model then calculates the daily value of CC* by means of a
computational procedure which approximates the rate of change of CC* with time through the use of a linear variable.

CC is a simple parameter to estimate in the field. The sheltering effect results less available energy for soil evaporation, while more energy becomes available for crop transpiration, due to a micro-advection phenomenon and to a larger use of solar radiation by the canopy.

For estimating the actual evaporation rate, HydroGEN takes into consideration the maximum amount of water available in the top-soil layer, which is a given parameter for the different soil types, as reported by Allen et al. (1998). When all the available water is extracted from the upper (evaporating) soil layer, the actual evaporation is estimated to be below the potential rate by means of the following relationship:

$$E_{\text{act}} = K_r \cdot E_{\text{pot}}$$

(3.11)

where $E_{\text{act}}$ is the actual evaporation; and, $K_r$ is a dimensionless evaporation reduction coefficient.

The value of $K_r$ ranges between 0 and 1 according to the amount of water depleted from the top soil layer during the previous time period. The value of $K_r$ is taken as 1 when the top soil is wet and the evaporation is not reduced due to water depletion; as the soil water depletion progresses, the value of $K_r$ decreases nonlinearly to 0.

The value of the reduction coefficient, $K_r$, is computed by HydroGEN through the following exponential expression, as suggested by Raes et al. (2009):

$$K_r = \frac{\exp^{f_k W_{rel}} - 1}{\exp^{f_k} - 1}$$

(3.12)

where $f_k$ is a decline factor; and, $W_{rel}$ is the relative water content of a lower soil layer contributing water to the top soil surface layer where evaporation occurs.
A value of 4 is used for the exponential decline factor, $f_K$. This value is reported by Raes et al. (2009) as enabling the simulation of evaporation during the falling rate stage with a good fit with respect to the soil evaporation model by Ritchie (1972). Instead of using a linear reduction of $K_r$ with time on the basis of a Ritchie-type approach, through the above relationship HydroGEN considers not only the time but also the relative water content ($W_{rel}$) of the soil for determining $K_r$. In other words, in the determination of the evaporation reduction coefficient ($K_r$), the model accounts for the amount of water extracted from the top soil by transpiration, as well as for the contributions to soil water due to weather parameters.

The maximum thickness of the soil surface layer ($Z_{\text{surface layer}}$) and the soil depth from which water is moved upward to the evaporating surface layer are calculation parameters that can be defined by the user based on site-specific soil characteristics. Usually, the value of $Z_{\text{surface layer}}$ should be in the range of 0.10 – 0.15 m, as suggested by Allen et al. (1998), whereas the soil depth contributing with water flow to the evaporating surface layer should be within the range of 0.15 to 0.50 m, as suggested by the developers of other soil evaporation models (Ritchie 1972; Saxton et al. 1974; Raes 1982; Ritchie and Crum 1989).

The relative water content ($W_{rel}$) depends on the amount of water in the evaporating soil layer and specifically on the relative water depletion with respect to the amount of water that can be readily evaporated (REW). Its value may range between 0 and 1 and is computed by HydroGEN through the following relationships taken from Raes et al. (2009):

$$\text{if } Depl_{Ev,i-1} \leq REW \text{ then } Wrel_i = 1$$

\[ (3.13) \]
else \( W_{rel,i} = \frac{(TEW - Depl_{EV,i})}{(TEW - REW)} \geq 0 \) \hspace{1cm} (3.14)

where \( TEW \) is the Total Evaporable Water expressing the maximum depth of water that can be evaporated from the evaporating soil layer when it was initially saturated (mm); \( REW \) is the Readily Evaporable Water which expresses the maximum amount of water (mm) that can be easily evaporated from the evaporating soil layer; and, \( Depl_{EV,i} \) is the water depletion from the evaporating soil layer on day \( i \), whereas \( Depl_{EV,i-1} \) is the water depletion from the evaporating soil layer at the end of the previous day \((i-1)\).

\( TEW \) can be estimated with the relationship in Eq. 3.15, as suggested by Allen et al. (1998):

\[
TEW = 1000 \left( \theta_{FC} - 0.5 \theta_{WP} \right) Z_{surface\ layer}\] \hspace{1cm} (3.15)

where \( \theta_{FC} \) and \( \theta_{WP} \) are the soil water contents at field capacity and at wilting point, respectively; and, \( Z_{surface\ layer} \) is the depth of the surface soil layer that is subject to drying by way of evaporation.

\( REW \) is estimated based on the Available Water Content of the soil \( (AWC) \) through Eq. 3.16:

\[
REW = -0.4865 \ast AWC^2 + 17.73 \ast AWC - 63.76 \] \hspace{1cm} (3.16)

The variable \( AWC \) in the above equation is expressed in mm m\(^{-1}\) and is calculated as the difference between the soil water content at field capacity and at wilting point \( (\theta_{FC} \) and \( \theta_{WP} \)). Equation 3.16 was developed and introduced in HydroGEN within the procedure for estimating soil evaporation on the basis of evaporation parameters \( (REW \) and \( TEW) \) provided for the different soils types by the FAO guidelines for computing crop water requirements (Allen et al. 1998).
3.2.3.3 Potential and actual crop transpiration

When the root zone is wet as a result of rain or irrigation, the model assumes crop transpiration as occurring at its potential (maximum) rate. Allen and Pereira (2009) suggested that when the vegetation amount of the agricultural system is highly variable (a typical condition in an area with a large number of small land holdings), it is advisable to base estimates of crop transpiration on the fraction of ground covered or shaded by canopy. Based on this suggestion, HydroGEN calculates the potential crop transpiration ($T_{pot}$) as proportional of the effective fractional canopy cover through the following equation 3.17 provided by Raes et al. (2009):

$$T_{pot} = \left(CC^* \times K_{cb\ full}\right) \times ETo$$

(3.17)

where $K_{cb\ full}$ is the value of the basal crop coefficient during the mid-season at peak plant size or height, expressed for well-watered vegetation having full effective ground cover or LAI > 3 and corrected for local climate and for plant height; and, $CC^*$ is the effective crop canopy cover.

The value of $K_{cb\ full}$ is computed in HydroGEN using typical values of basal crop coefficients during the mid-stage, $K_{cb\ mid}$, taken from the literature or from field measurements (when available) for sub-humid and calm-wind conditions ($RH_{min} \approx 45\%$, $u_2 \approx 2\ m\ s^{-1}$). As reported by Allen et al. (1998) and by Allen and Pereira (2009), $K_{cb\ full}$ represents a general upper limit on $K_{cb\ mid}$ for tall vegetation having full ground cover and a non-limiting water supply. Corrections for plant height and for the site-specific climatic conditions are applied in the computation of $K_{cb\ full}$, i.e. when the climatic conditions deviate from those reported above as typical, by means of the following equation suggested by Allen et al. (1998):
\[ K_{cb_{\text{full}}} = K_{cb_{\text{mid}}} + \left[ 0.04 \times (u_2 - 2) - 0.004 \times (RH_{\text{min}} - 45) \right] \times \left( \frac{h}{3} \right)^{0.3} \]  

(3.18)

where \( u_2 \) is the mean value for wind speed at 2 m height during the mid-season (m s\(^{-1}\)); \( RH_{\text{min}} \) is the mean value for minimum daily relative humidity (%) during the mid-season; and, \( h \) is the maximum plant height (m).

Typical values of \( K_{cb_{\text{mid}}} \) for non-stressed well-managed crops in sub-humid climates are provided by Allen et al. (1998). The *mid-season* stage corresponds to the period when the crop canopy reaches its maximum evapotranspiration rate (effective full cover), until the beginning of canopy decrease, senescence, yellowing, or leaf drop (late-season stage). Based on the procedure used for calculating the daily effective crop canopy cover, which is reported in the following sections and Eq. 3.27, HydroGEN identifies the mid-season period (day of start and relative duration in days), within which it then computes the mean value for wind speed \((u_2)\) at 2-m height and the mean value for minimum daily relative humidity \((RH_{\text{min}})\), after reading the daily records values of these two parameters from the meteorological file required by the model as input. The calculation of \( K_{cb_{\text{full}}} \) is then performed by the model using Eq. 3.18 starting from the value of \( K_{cb_{\text{mid}}} \) provided by the user.

The actual rate of crop transpiration strongly depends on the amount of water available in the root zone. As the water stored in the root zone drops below a certain threshold, or when the water depletion in the root zone exceeds a certain fraction \((p)\) of the total available water \((TAW)\), known as Readily Available Water \((RAW)\), the crops face water stress and crop transpiration is reduced below its potential value. Under these conditions, HydroGEN computes the actual rate using Eq. 3.19:
where $K_s$ is a dimensionless reduction coefficient (water stress coefficient) accounting for crop water stress.

The parameter $K_s$ describes the effect of water stress on crop transpiration and is dependant on the available soil water in the root zone. $RAW$ is crop-specific and is a function of the parameter $p$, namely the depletion fraction for no stress, which, besides crop factors, is also affected by the evaporation potential of the atmosphere. The values for $p$ reported in the literature ($p_{\text{literature}}$) apply for $ETa \approx 5$ mm day$^{-1}$, which is a typical value. HydroGEN carries out a numerical approximation of $p_{\text{literature}}$ to $p$ for different values of $ETa$ according to the following equation:

$$p = p_{\text{literature}} + 0.04 \times (5 - ETa)$$ (3.20)

The level of water stress below the threshold of water depletion is expressed by the relative depletion ($Depl_{rel}$). When sufficient water remains in the root zone, HydroGEN uses $K_s = 1$ and transpiration is assumed to occur at the potential rate. When water is depleted from the root zone beyond the $RAW$, the water extracted by the crop becomes limited and the model takes $K_s < 1$, as the crop is expected to face water stress. At the wilting point, i.e. when the water depletion from the root zone has reached the total amount of water available in the soil, HydroGEN assumes $K_s = 0$ and the effect of water stress on transpiration is considered as occurring at its full strength. In other words, HydroGEN considers the variation of $K_s$ as linear between the above-mentioned limits and the wilting point. Therefore, the magnitude of effect of water stress ($K_s$) on the transpiration process can be quantified as proportional to the relative water depletion through Eq. 3.21:
\[ Ks = (1 - Depl_{rel}) \quad \text{with} \quad 0 \leq Ks \leq 1 \] (3.21)

In HydroGEN the relative water depletion \((Depl_{rel})\) in the root zone is calculated from the following three equations:

\[ Depl_{rel(t)} = 0 \quad \text{if} \quad SMD_{root\ zone(t-1)} \leq RAW \] (3.22)

\[ Depl_{rel(t)} = 1 \quad \text{if} \quad SMD_{root\ zone(t-1)} > TAW \] (3.23)

\[ \text{else} \quad Depl_{rel(t)} = \frac{(SMD_{root\ zone(t-1)} - RAW)}{(TAW - RAW)} \] (3.24)

where \(SMD_{root\ zone(t-1)}\) is the soil moisture depletion in the root zone on the previous day (t-1).

The whole set of above algorithms within the procedures for estimating soil evaporation and crop transpiration were introduced in HydroGEN as improvements to the earlier version of the model by Khadra and Lamaddalena (2006).

3.2.4 Weather and rainfall data

The root-zone water balance for each cropped field requires inputs of daily weather and rainfall data, crop data, and information related to soil physical features, as well as water holding capacity. Daily weather and rainfall data are necessary for the calculation of reference evapotranspiration, \(ETo\), and effective rainfall, \(Reff\), as well as for some intermediate calculations to determine correction coefficients to be used in estimating crop irrigation requirements and timing of irrigations.

The FAO-56 Penman-Monteith method is used for estimating \(ETo\), as recommended by the International Commission of Irrigation and Drainage (ICID) and by the Food and Agriculture Organization of the United Nations (Allen et al. 1989; Allen et
The daily effective rainfall is calculated from daily rainfall data on the basis of potential rain infiltration estimated from the simulated water depletion in the root zone at the end of the previous day. If the amount of daily rainfall exceeds the SMD in the root zone at the end of the previous day, on day \( t \) the effective rainfall is calculated as:

\[
R_{\text{eff},t} = SMD_{(t-1)} \quad \text{if} \quad \text{Rain}_t \geq \text{SMD}_{(t-1)}
\]

(3.25)

where \( \text{Rain}_t \) is the rainfall at the day \( t \) and \( SMD_{(t-1)} \) is the soil moisture depletion in the root zone at the end of the previous day \( (t-1) \).

In all other cases, the model considers the entire amount of rainfall as effective:

\[
R_{\text{eff},t} = \text{Rain}_t
\]

(3.26)

The above algorithm for estimating effective rainfall was introduced to replace the original procedure included in the earlier version of the model, which estimated the effective rainfall as a fixed percentage of the daily rainfall values.

### 3.2.5 Crop data

HydroGEN requires crop files defining input data and parameters for the irrigated crops being modelled. The following values are required: 

- **a)** crop type;  
- **b)** rooting depths (minimum and maximum) and duration of root development cycle;  
- **c)** timing of vegetation growth cycle (sowing date for annual crops or date of green-up and/or blossoming for perennial crops and stone-fruit orchards);  
- **d)** duration of the irrigation season;  
- **e)** depletion fraction for no stress;  
- **f)** maximum crop height;  
- **g)** percentage shaded area by green canopy (fractional canopy cover) at beginning and end of the different growth stages and their relative durations as a function of crop age, cultivar, plant spacing, canopy development and farming practices,  
- **h)** basal crop coefficient of mid
stage, $K_c b_{mid}$ from literature or from experimental field measurements; $i$) percentage of wetted area by irrigation, as a function of the on-farm irrigation systems, and of farming practices; $l$) management allowable depletion (MAD) in the different growing stages and relative duration of these stages; and, $m$) percentage of water replenishment by irrigation application relative to the soil water depletion, or to TAW.

The parameters indicated at the points $e$ through $m$ were introduced in HydroGEN to enable several improved calculation procedures related to the soil water balance with respect to the earlier version of the model. The whole set of crop parameters are relevant for identifying reduction coefficients to be used in the empirically-calculated net irrigation requirements and to further adjust these coefficients to the actual site-specific conditions. The basic information on crop type, crop age, plant spacing and percentage shaded area can be estimated with good accuracy by means of high-resolution multi-spectral airborne or satellite imagery, eventually supported by a ground-truthing campaign and by a supervised classification process.

### 3.2.5.1 Fraction of ground cover for the different growth stages

The values of both evaporation and transpiration $K_c$ coefficients depend on the daily value of fractional canopy cover, as crop transpiration is proportional to the fractional canopy cover ($K_c_{\text{transpiration}} \sim CC$) and soil evaporation is proportional to the portion of the soil surface not shaded by the canopy ($K_c_{\text{evaporation}} \sim (1-CC)$).

As mentioned above, the fraction of soil surface covered by green canopy is corrected to the effective fraction of canopy cover, $CC^*$, to account for the sheltering effect of the canopy cover, according to Eq. 3.10.
As part of the crop file input generation, the plant cycle is subdivided into several stages according to the canopy development, each being characterized by initial and final values of fractional canopy cover and by a typical duration in days. Based on these data, the rate of change of the effective fraction of canopy cover with time is assumed to be linear. For each growth stage (GS = 1, 2, ….) having duration of \( d_{GS} \), the daily value for \( CC^* \) is calculated through the following equation:

\[
CC^*_{t, GS} = CC^*_{1, GS} + t_{GS} \cdot \frac{(CC^*_{2, GS} - CC^*_{1, GS})}{d_{GS}}
\]  

where \( CC^*_{t, GS} \) is the effective canopy cover at day \( t \); \( CC^*_{1, GS} \) is the effective canopy cover at the first day of the current growth stage; \( CC^*_{2, GS} \) is the effective canopy cover at the last day of the current growth stage; \( t_{GS} \) is the day of the year in the current growth stage; and, \( d_{GS} \) is the duration in days of the current stage.

The algorithm for computation of the daily fraction of ground cover was developed and introduced within HydroGEN as improvement with respect to the earlier version of the model to enable higher accuracy in estimating crop irrigation requirements.

3.2.5.2 Beginning of vegetative growth

The beginning date of vegetation growth, \( V_d \), (date of emergence for annual crops or green-up for perennial crops and/or blossoming timing for stone-fruit orchards) depends on the crop physiology and on weather variables, as well as, to a certain extent, on farmers’ decisions (sowing date for annual crops and farming practices for perennial crops). To account for this source of variability, HydroGEN can determine vegetation/green-up start dates randomly within a user-defined range, from a minimum to a maximum based on the following equation:

\[
V_d = V_{d,\text{min}} + u_d \cdot (V_{d,\text{max}} - V_{d,\text{min}})
\]  

(3.28)
where $V_{d,\text{min}}$ is the minimum day for vegetation start as day of the year (1 is Jan 1st); $V_{d,\text{max}}$ is the maximum day for vegetation start as day of the year; and, $u_d$ is a randomly-generated number that ranges from 0 to 1.

### 3.2.5.3 Root development

The rate of root development is a relevant crop parameter for water budgeting in the root-zone, as it affects the volume of soil reservoir available for water storage. Root development is assumed to be linear from the 1st day of vegetation to day $t_x$ by considering a constant rate of development from the day $t_{x+1}$ to the end of the crop development ($D_{\text{end}}$). The daily root depth $R_{d,t}$ for a day $t$ is computed following the expressions from Doorembos and Pruitt (1977):

\[
R_{d,t} = R_{d,\text{min}} + \frac{(R_{d,\text{max}} - R_{d,\text{min}})}{t_x} t \quad \text{for} \quad 0 < t < t_x
\]

\[
R_{d,t} = R_{d,\text{max}} \quad \text{for} \quad t_{x+1} < t < D_{\text{end}}
\]

where $R_{d,\text{min}}$ is the root depth (m) at the beginning of root development; $R_{d,\text{max}}$ is the root depth (m) at the end of root development; and, $D_{\text{end}}$ is the duration in days of the entire root development cycle.

### 3.2.6 Soil data

#### 3.2.6.1 Available soil water at the beginning of a crop cycle

The available soil water in the root zone at the beginning of the crop growth cycle is a relevant parameter for daily soil water budgeting and, in large and multi-cropped agricultural areas, is usually affected by the large spatial variability of soil physical properties, the crop type, and the antecedent moisture conditions, which are a function of the soil moisture remaining at the end of the previous crop cycle and of the effective
precipitation since that point in time. To account for this variability and uncertainty, HydroGEN performs a stochastic procedure, described by Khadra and Lamaddalena (2006), for randomly determining the initial soil water conditions for each cropped field within a range of possible values from a minimum to a maximum according to the following equation:

\[ W_{s,\text{ini}} = W_{s,\text{min}} + u_d \times (W_{s,\text{max}} - W_{s,\text{min}}) \] (3.31)

where \( W_{s,\text{ini}} \) is the soil water content at the beginning of crop cycle, whereas \( W_{s,\text{min}} \) and \( W_{s,\text{max}} \) are, respectively, the soil water content at wilting point and at field capacity expressed in mm m\(^{-1}\), and \( u_d \) is a randomly-generated number ranging between 0 and 1, following a uniform distribution.

3.2.6.2 Calculation of the daily soil water

The model performs the computation of the soil water balance for each day \( t \) of the period ranging from the first to the last day of available weather records, for every crop \( i \) downstream each delivery hydrant \( j \). The daily soil water content is estimated using the following soil water balance equation expressed in terms of soil moisture depletion in the soil root zone:

\[ SMD_{t,i,j} = SMD_{t-1,i,j} + ETa_{t,i,j} - R_{eff,t,i,j} + SRO_{t,i,j} - I_{n,t,i,j} + DP_{t,i,j} - GW_{t,i,j} \] (3.32)

where \( W_{t,i,j} \) and \( W_{t-1,i,j} \) are, respectively, the soil water content on the day \( t \) and at end of the previous day; \( ETa_{t,i,j} \) is the actual crop evapotranspiration on day \( t \); \( R_{eff,t,i,j} \) is the effective rainfall on day \( t \); \( SRO_{t,i,j} \) is the surface runoff; \( I_{n,t,i,j} \), is the net irrigation depth applied on day \( t \); \( DP_{t,i,j} \) is the deep percolation on day \( t \); \( GW_{t,i,j} \) is the groundwater contribution on day \( t \); and, \( SMD_{t,i,j} \) and \( SMD_{t-1,i,j} \) are, respectively, the soil moisture
depletions on day $t$ and at the end of the previous day, all related to crop $i$ downstream of hydrant $j$, and expressed in mm day$^{-1}$.

As necessary data for simulating the daily soil water balance, HydroGEN computes the daily value of Allowable Soil Moisture Depletion ($SMD_{AL}$) for each crop $i$ downstream of hydrant $j$ based on the MAD values of the different stages of the crop growth cycle, and on the calculated daily values of the root depth. The $SMD_{AL}$ expresses the maximum amount of water that can be extracted from the root zone without causing unplanned crop water stress or excessive reduction of soil water relative to that needed to achieve crop quality targets, and is calculated by Eq. 3.33:

$$SMD_{AL,i,j} = TAW \times Rd_{t,i,j} \times MAD_{t,i,j}$$

(3.33)

where $Rd_{t,i,j}$ is the root depth of crop $i$ downstream of hydrant $j$ and on the day $t$; and, $MAD_{t,i,j}$ is the management allowable depletion for the crop $i$ downstream the hydrant $j$ on day $t$ as included in the stage $s$. The MAD value is referred to the specific stage of the crop cycle, in case regulated irrigation is followed by farmers, else the model assumes the value of MAD to be equal to the crop-specific value of the parameter $p$ (no stress depletion fraction).

HydroGEN calculates all the above parameters on a daily time-step and updates the soil water content to the end of each day.

3.2.7 Timing and depths of irrigation events

The model computes the $SMD$ and the $SMD_{AL}$ for each crop $i$ downstream from each hydrant $j$ for each day $t$ using Eqs. 3.32 and 3.33 and, then satisfies the following conditions:

$$if \ SMD_{t,i,j} < SMD_{AL,t,i,j} \ \text{irrigation is not required, thus } \ I_n = 0$$

(3.34)
if \( SMD_{t,i,j} \geq SMD_{A_t,i,j} \) irrigation is required, thus \( I_n > 0 \) \hspace{1cm} (3.35)

The net irrigation depth to be supplied by growers on the day \( t \), by hydrant \( j \) to crop \( i \), is given by:

\[
I_{n\ t,i,j} = SMD_{t,i,j} \ast Perc_{irr} \hspace{1cm} (3.36)
\]

where \( Perc_{irr} \) is the percentage of water replenishment by irrigation application (0 – 100\%) with respect to the soil water depletion of the day \( t \), which accounts for the irrigation management strategy followed by farmers, or for local farming practices.

\( Perc_{irr} \) is an irrigation management parameter commonly under farmers’ control for crop quality targets or water management purposes and can be varied along the irrigation season together with the values of \( MAD \) that can be adjusted within the different growth stages. It was introduced in HydroGEN to refine the computation of irrigation depths in compliance with the irrigation management practices followed by the farmers.

The gross irrigation amount (mm) to be delivered at each irrigation is then given by:

\[
I_{g\ t,i,j} = I_{n\ t,i,j} / Ea \hspace{1cm} (3.37)
\]

where \( Ea \) is the on-farm application efficiency of the irrigation method used for crop \( i \), downstream of hydrant \( j \).

As for the duration of hydrant operations, in order to satisfy the irrigation requirement \( I_g \) of crop \( i \), on day \( t \), hydrant \( j \) must remain open for a time period given by Eq. 3.38:

\[
t_{irr} = I_{g\ t,i,j} / q_j \hspace{1cm} (3.38)
\]
where \( q_j \) is the nominal flowrate (l s\(^{-1}\)) of hydrant \( j \). Conversion equations are applied to calculate irrigation volumes in cubic meters and irrigation times in hours.

By aggregating the irrigation demand resulting from the soil water balances conducted in each field, the model can determine the number of hydrants that need to be in operation each day, as well as the duration of delivery for each irrigation application. Through this step, HydroGEN generates the hydrograph of daily irrigation volumes for the whole distribution network and for the entire period from the first day of the year to the last day of available weather input data.

As a follow up step, the model identifies the 10-day peak-demand period by applying the method of the moving averages, to the set of simulated daily irrigation demands.

### 3.2.8. Computation of hourly demand discharges

As reported by Lamaddalena (1997) and by Khadra and Lamaddalena (2006), the simulation of hourly discharge hydrographs is affected by uncertainties due to irrigation management practices adopted by farmers and according to farmers’ habits. Two alternative stochastic approaches are provided to account for these uncertainties in the generation of the hourly discharge hydrographs for the identified 10-day peak-demand period.

In the first approach, described in details by Khadra and Lamaddalena (2006) and referred in this paper to as the “Long” approach (L), the model utilizes a probability distribution function of withdrawals recorded at the inlet of the delivery network during the peak demand period in order to determine the most likely timing of hydrants’ openings and shut-offs during the daytime. Based on the above determination, the
number of hydrants in simultaneous operation hour-by-hour can be simulated, and the hydrographs of hourly flow rates can be generated by aggregating the flow rate demanded from these hydrants on an hourly basis. The probability distribution function is calculated by the model on the basis of a complete set of frequency versus opening-time data which must be provided by the user. This dataset can be derived by processing hourly discharges recorded at the headwork of the distribution network under analysis or of networks operated under similar delivery conditions.

The second stochastic approach, referred in this paper to as the “Short” approach (S), was developed and introduced in HydroGEN as a further improvement to the earlier version of the model. By using this alternative approach, HydroGEN evaluates the recorded daily flow distribution and accounts for the hourly variability of flows by generating random numbers within the calculated confidence interval of the recorded discharges. In other words, when using the “Short” stochastic algorithm, HydroGEN performs several computational steps on the dataset of recorded hourly flow rates in order to derive the values of the average \( (\mu_h) \), standard deviation \( (\sigma_h) \), the 95 % confidence interval \( (CI_h) \), the ranges of possible variation of hourly flow rates \( (A_h) \) and the simulated values of hourly flow rates, \( QS_{d,h} \), for each of the 24 hours during the 10-day peak period, according to Eqs. 3.39 through 3.43, given below.

Given \( QR_{d,h} \) as the hourly flow rate recorded at hour \( h \) of day \( t \), the average hourly discharges during the 10-day peak period, \( \mu_h \), are calculated as:

\[
\mu_h = \frac{\sum_{d=1}^{10} \sum_{t=1}^{24} QR_{d,h}}{10}
\]  
(3.39)
The values of standard deviations, $\sigma_h$, for each of the 24 hours during the 10-day peak period are then computed as:

$$\sigma_h = \sqrt{\frac{\sum (QR_{d,h} - \mu_h)^2}{10}}$$  \hspace{1cm} (3.40)

The values of the 95% confidence intervals, $CI_h$, are determined according to Eq. 3.41:

$$CI_h = \mu_h \pm z_{\alpha/2} \left( \frac{\sigma_h}{\sqrt{10}} \right)$$  \hspace{1cm} (3.41)

where $z_{\alpha/2}$ is the critical value, while $\alpha$ is the significance level to calculate the confidence; for 95% confidence, $\alpha = 0.05$ and $z_{\alpha/2} = 1.96$.

The ranges of possible variation of hourly flow rates, $\Delta_h$, are computed as:

$$\Delta_h = [(\mu_h + CI_h) - (\mu_h - CI_h)]$$  \hspace{1cm} (3.42)

By means of the “Short” algorithm, HydroGEN then generates a set of random numbers, $u_{d,h}$, ranging from 0 to 1 that are then used to simulate the hourly flow rates, $QS_{d,h}$, through Eq. 3.43:

$$QS_{d,h} = \mu_h + [(u_{d,h} * \Delta_h) - CI_h]$$  \hspace{1cm} (3.43)

In this way, HydroGEN simulates the hydrograph of hourly flow rates based on the simulated farmers’ behavior observed through the dataset of recorded water withdrawals from the network during the actual peak-demand period.

### 3.3 Summary and Conclusions

A new version of a simulation model named HydroGEN was developed on the basis of a stochastic methodology to forecast the demand flows during peak periods in pressurized delivery networks operated on-demand. Several refinements and amendments
of computational procedures were carried out with respect to the earlier version of the model, with the aim of enhancing the capability of the model to reproduce the on-farm irrigation practices and to generate demand hydrographs with higher accuracy. The model generates disaggregated information on soil water deficits, and on timing and volumes of irrigation demand for the cropped areas serviced by the delivery network. Soil evaporation and crop transpiration are estimated separately using the dual crop coefficient approach and as a function of fractional canopy cover. The simulated openings of hydrants and the resulting water withdrawals by farmers are then aggregated upstream to generate the overall flow hydrograph at the inlet of the distribution network for the peak water demand period during the irrigation season. Simulations can be performed to replenish crops water requirements as well as to reproduce deficit or regulated irrigation conditions. Through its main deterministic and stochastic components, the enhanced model accounts for the temporal variability of discharges flowing into the irrigation delivery network as a result of variations in farm demand.

The model was defined to facilitate the analysis of operation of large-scale pressurized irrigation systems, which in turn is relevant to the evaluation of a system’s performance under different operating conditions.

HydroGEN can be applied to large multi-cropped irrigation systems at different management levels to forecast the timing of peak-demand periods, the overall demanded irrigation volumes during the season, as well as to generate the hydrographs of daily volumes and hourly flow rates withdrawn by farmers during these peak-demand periods. The simulated peak-demand hydrographs can then be inputted in some hydraulic simulation models to evaluate the network’s delivery performance under several possible
flow configurations. In this perspective, the model can be utilized as a useful tool for designing and sizing new irrigation delivery systems as well as for modernizing and re-engineering low performing systems, but also for assisting the management of irrigation schemes in developing operational plans and in avoiding situation of poor performance in water delivery.

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CHAPTER 4
SIMULATION OF PEAK-DEMAND HYDROGRAPHS IN PRESSURIZED IRRIGATION DELIVERY SYSTEMS USING A STOCHASTIC MODEL
PART II: MODEL APPLICATIONS

Abstract A stochastic model named HydroGEN was developed, as described in Chapter 3 (Model development), to enable the simulation of demanded daily volumes and hourly flow rates during peak periods in pressurized irrigation delivery networks. The model was applied to a pilot irrigation system located in southern Italy with the intent of testing its reliability in analyzing the operation of large-scale pressurized delivery systems. Daily data on rainfall, temperature, solar radiation, wind speed and relative humidity were obtained from a meteorological station located within the study area, whereas information on local irrigation management practices were collected through interviews with farmers and extension specialists. The model was tested at different management levels, from district to sector and hydrants. The validation was supported by the use of high-resolution remote sensing imagery acquired on a single overpass date in 2006 and then classified and recoded following a ground-truthing campaign conducted during the same year. Simulations were performed to identify the 10-day peak-demand period and to generate the hydrographs of daily volumes and of hourly flow rates. Results from the different simulations were compared with historical datasets of irrigation volumes and discharges recorded at the upstream end of the irrigation network during the 2008 and 2009 seasons, at a sector level during the 2007 season, and at selected delivery hydrants during the 2005 season. Some discrepancies between simulated and recorded data were noted, that can be

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1 Coauthored by Daniele Zaccaria, Nicola Lamaddalena, Christopher M.U. Neale and Gary P. Merkley
related to small errors in estimating crop and soil parameters, application efficiency at field level, as well as to large variability in irrigation management practices followed by local farmers. Overall, the validation results showed that the model is capable of forecasting with good accuracy the timing of peak-demand periods, the irrigation volumes demanded during the season, as well as the hydrographs of daily volumes and hourly flow rates withdrawn by farmers during these peak-demand periods, especially when it is applied to large multi-cropped command areas.

4.1 Introduction

The common practice of considering only a single value of the peak demand discharge purposes is not appropriate in case of design or modernization of pressurized irrigation delivery systems operating on demand, and this is due to the fact that large temporal discharge variability may occur as a result of uncertainties related to crops, soils, meteorological conditions and farmers’ behavior. Lamaddalena (1997) and Lamaddalena and Pereira (1998) reported that low delivery performance could occur in pressurized irrigation networks even when the design discharges are not exceeded, as a consequence of variations in farm demand and under certain flow configurations, i.e. different combinations of hydrants being in simultaneous operation. Lamaddalena et al. (2007) also pointed out that these demand variations may lead to large spatial and temporal variability of pressure and discharge available at hydrants, and thus affect the performance of the networks.

This chapter provides a detailed description of the results obtained from applications of the HydroGEN model to a large-scale pressurized irrigation system. The model was developed on the basis of a stochastic methodology conceived for simulating
the flow hydrographs during peak demand periods, accounting for the temporal variability of the discharges flowing into pressurized delivery networks operated on-demand. Chapter 3 provides details on the development of the model and on its main components, as well as on the computational algorithms and procedures utilized.

The HydroGEN model was applied and tested at different management levels and the results obtained were compared with recorded datasets for calibration purposes and for evaluating the model’s performance. The results of these applications are reported herein.

4.2 Application to the Case Study

The “Sinistra Ofanto” irrigation system is located in southern Italy, in the north-eastern part of the Apulia region (Province of Foggia) and covers an area of 22,500 ha. It was designed and constructed during 1980’s for pressurized on-demand delivery schedule and is currently managed and operated by a local water users’ organization (WUO), namely the “Consorzio per la bonifica della Capitanata” (CBC 1984; Altieri 1995). The area serviced by the system is subdivided into a “Low zone”, where water is supplied to farms by gravity, and a “High zone” where cropped fields are at higher elevations relative to the water source and irrigation water is conveyed and supplied by means of a lifting plant. The Low zone is composed by seven command areas called “districts”, each of them being sub-divided into smaller operational units called irrigation “sectors” that are composed by several grouped farms.

The study area corresponds to the District 10, which belongs to the Low zone, and thus receives water by gravity from the source. It covers an overall topographic area of about 2,000 ha, out of which the total irrigable area is 1,679 ha and the area currently
irrigated is 1,423 ha. The current cropping pattern of the district under study was obtained from WUO records and is reported in Table 4.1.

The District 10 is supplied with irrigation water from a storage and compensation reservoir named as “Reservoir 9-10”, having a total capacity of 47,000 m$^3$. This reservoir receives water from the main source, namely the Capacciotti dam, by means of a conveyance pipeline, and supplies water to both Districts 9 and 10. The hydraulic scheme of the low zone is presented in Fig. 4.1. The distribution network of District 10 is open-branched and is composed of buried pipelines, equipped with 394 delivery hydrants having nominal discharge of 10 l s$^{-1}$, each of them supplying water to several cropped fields.

The system is operated by a restricted-demand delivery schedule, all farmers taking water at their convenience with a maximum allowed flow rate of 10 l s$^{-1}$ and within the maximum seasonal allocated shares out of the total water supply available from the Capacciotti Dam. The service-oriented operation of the distribution network being conducted by the WUO ensures a minimum pressure head of at least 2 bars at each hydrant, which is suitable for trickle and micro-irrigation methods commonly used by farmers in the area. The layout of distribution network and location of delivery hydrants are reported in Fig. 4.2.

<table>
<thead>
<tr>
<th>Crops</th>
<th>Irrigated area (ha)</th>
<th>Irrigable area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vineyards</td>
<td>1073.6</td>
<td>1073.6</td>
</tr>
<tr>
<td>Olive</td>
<td>106.5</td>
<td>106.5</td>
</tr>
<tr>
<td>Orchards</td>
<td>131.4</td>
<td>131.4</td>
</tr>
<tr>
<td>Vegetables</td>
<td>111.3</td>
<td>111.3</td>
</tr>
<tr>
<td>Wheat</td>
<td>--</td>
<td>256.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1422.8</strong></td>
<td><strong>1679.0</strong></td>
</tr>
</tbody>
</table>

Table 4.1 Cropping pattern in the irrigation District No. 10
The average farm size ranges from 1.5 to 2.5 ha, thus the study area is characterized by a very high number of small land-holdings. On the other hand, due to the favorable agro-climatic conditions, agriculture in the area is intensive and highly market-oriented. Climate is semi-arid to sub-humid and reported as “Maritime-Mediterranean”, which is typical of the coastal areas of the Mediterranean region, with an average yearly precipitation of about 550 mm which is poorly distributed throughout the year. Therefore, profitable farming in the area is strongly dependant on irrigation.

The water billing procedure is performed by the WUO according to volumetric tariffs that increase along with the seasonal volumes withdrawn by farmers. The collection of water fees in the study area is reported as occurring from nearly 90% of the served users and is tightly linked to the quality of irrigation services provided by the WUO.
In other words, the annual fee collection is related to the adequacy and timely distribution of irrigation water to all farmers, i.e. to the delivery schedule performance (Sanaee-Jahromi et al. 2001), which in District 10 is found to be satisfactory, as the distribution network is operated on-demand and adequate flow rates and pressure heads are ensured throughout most of the district.

All hydrants are equipped with both a mechanical and an electronic flow meter, with a flow recorder, as well as with rubber-ring flow limiters restricting the discharge to a maximum of 10 l s$^{-1}$. Moreover, hydrants are provided with an electro-mechanical device capable of allowing the supply of water only to authorized users. The device keeps track of the water withdrawals by users and stores all the information about irrigation events in a fixed electronic memory. This information includes the timing and duration of
irrigations, hydrant opening and shut-off times, and delivered volumes to any of the authorized users, thus enabling the retrieval of operational datasets by operators at any time by means of a connection to portable computers. The use of this technology allows for accurate monitoring of irrigation system operation and for achieving better understanding of the irrigation management strategies followed by farmers, through the retrieval and analysis of historical data.

4.2.1 Model application at the district level

For testing the proposed model in district command areas, the operation of the delivery network of District 10 was monitored during the 2008 and 2009 irrigation seasons (March through November). The discharges flowing in the network, as well as the overall daily volumes withdrawn by farmers, were measured and recorded continuously by a Venturi-meter located just downstream from “Reservoir 9-10” along the main pipeline that conveys water to the cropped areas in District 10. The Venturi-meter allows flows ranging between 0 and 1000 l s\(^{-1}\) and is equipped with a transducer of the differential pressure occurring between the inlet and outlet of the pipe contraction (1000 mm – 450 mm), having nominal precision of 0.025 % as certified by the manufacturer (Endress-Hauser) for flow rates within 30 and 1000 l s\(^{-1}\).

Based on the recorded flow rates and the average hourly discharges, the probability distribution functions and the cumulative distribution functions of frequencies of hourly average flow rates (\(\mu_h\)) were derived for the 2008 and 2009 seasons following the methodology described by Khadra and Lamaddalena (2006), as shown in Figs. 4.3 and 4.4. These probability distribution functions were afterwards utilized as inputs by the HydroGEN model to simulate the opening and shut-off times for each delivery hydrants,
thus allowing the generation of hydrographs of hourly flow rates by the “Long” stochastic procedure (L). The same recorded flow rates were also used and processed to obtain the hourly flow hydrograph through the “Short” stochastic procedure (S). Both the “Long” and the “Short” stochastic procedures are described in section 3.2.8 of the Chapter 3.

The simulated flow hydrographs obtained from the model through the two stochastic approaches were compared to the water deliveries recorded during both irrigation seasons (2008 and 2009). The comparisons were carried out with the aim of evaluating the consistency of the proposed methodology and for better investigating any discrepancies.

In order to accurately map the cropped areas in the study site and to define the necessary crop and hydrant files, a high-resolution multispectral image was purchased from the Digital Globe Quickbird Satellite for a single overpass date. The image acquisition occurred under clear-sky conditions on May 22nd, 2006. The nominal spatial resolution of the image is 2.8 meters, which allowed accounting of reflectance from soil background for most of the crops grown in the area and especially for orchards, given their typical tree-spacings (5 x 5 m or 6 x 6 m) and the local farming practice of frequent soil tillage for weeds control. The image shown in Fig. 4.5 is an ortho-ready mosaic of the study area, projected in the UTM system, reference zone 33 North, with WGS 1984 as Ellipsoid and Datum. Several thematic layers representing cadastral maps, boundaries of irrigation districts, soil hydraulic and physical properties and layout of the water distribution network, were overlaid on the satellite image. A preliminary unsupervised classification was then conducted on the multi-spectral image using the Isodata clustering
method, using 20 maximum iterations and 80 initial categories. The generated unsupervised clusters were then regrouped into 10 classes representing different known crops and surfaces. Once recoding and editing was finalized, an error analysis was also conducted based on a pixel-by-pixel basis by means of the “Accuracy Assessment” utility in ERDAS Imagine software.

Fig. 4.3 Average hourly flow rates $\mu_h$ withdrawn during the 10-day peak demand period in District 10 during the 2008 and 2009 seasons.

Fig. 4.4 Probability distribution functions of hourly discharges withdrawn during the 10-day peak demand period for District 10 in the 2008 and 2009 seasons
This procedure aimed at evaluating how well the results from the classification process matched the actual ground data. The mis-classified pixels data were eventually corrected and assigned to the proper classes prior to the generation of the final map product, which is shown in Fig. 4.6.

During the ground-truthing campaign, additional information on the spatial variability of crop parameters was collected through field observation and by interviewing several local farmers and extension officers of the WUO, as related to crop spacing, age, cultivars, farming practices and irrigation methods. This data set is considered very relevant for accurate estimation of crop water requirements.

Fig. 4.5 Overview of the District 10 of the Sinistra Ofanto scheme as acquired by the Quickbird satellite on May 22nd, 2006
The use of multi-spectral satellite imagery allowed accurate mapping of cropped areas, and accounting for the spatial variability of parameters related to crop water use over large irrigated areas. In doing so, following the suggestion given by Droogers and Bastiaanssen (2002), it was possible to offset the limited spatial coverage of field-scale simulation model.

The first set of simulations were performed for the entire cropped area of District 10 to generate the daily irrigation volumes and hourly flow rates demanded at the upstream end of the delivery network during the 2008 and 2009 seasons. These simulations were based on information about management practices followed by growers that carry out deficit irrigations during specific time periods of the crop growth cycle.

![Fig. 4.6 Cropped areas for District 10 of the Sinistra Ofanto scheme resulting from the classification and re-coding of the multi-spectral image](image)
The application HydroGEN to the command area of District 10 accounted for these practices through the proper definition of crop and irrigation parameters included in the management menu of the crop input files.

The definition of the hydrant file entailed quantifying the application efficiency at the level of hydrants to allow computing the gross irrigation volumes to be delivered by the hydrants to fulfill the crop irrigation requirements of each serviced cropped fields. Data on application efficiency were provided by the technical staff of the WUA and by extension service specialists on the basis of the averaged delivered volumes and of the estimated irrigation requirements for the different crops grown in the command area. In other words, in the applications of HydroGEN to the case study, estimated averaged values of the application efficiency at hydrant level were used, as no measurements of irrigation requirements were conducted within the present research work and no other information were available from previous researches carried out in the study area.

The evolution of simulated daily irrigation volumes demanded at the upper end of the delivery network during 2008 and 2009 are shown in Fig. 4.7. The simulated and recorded seasonal volumes at the inlet of District 10 were compared only for 2009, as in 2008 the delivery network was shut off from July 11th to July 23rd, and from August 31st to October 1st, due to maintenance work. The comparison for 2009 shows a good match between simulated and recorded seasonal volumes (2,699,934 m³ vs. 2,540,074 m³, respectively), with a slight over-estimation (~ 6 %) by the model.

Applying the method of moving averages to the recorded daily irrigation volumes withdrawn by farmers revealed that the 10-day peak-demand period occurred from day-
of-year (DOY) 181 to 190 (i.e. June 30th to July 9th) in 2008, and from DOY 162 to 171 (i.e. June 11th to June 20th) in 2009.

As for the simulations, the peak-demand periods identified by the model on the basis of the forecasted daily volumes yielded similar results, as they ranged from DOY 179-188 (June 28th - July 7th) to DOY 189-198 (July 8th – July 17th) for the year 2008, and between DOY 156 - 165 (June 5th - June 14th) to DOY 159-168 (June 8th – June 17th) for year 2009. Therefore, the simulated peak-demand periods are in close agreement with the actual peak periods as computed on recorded data for years 2008 and 2009.

The difference in the simulated peak demand dates resulting from the different simulation runs is due to the stochastic components of the model that account for variability of crop emergence or green-up date, and of soil water content at the beginning of crop growth cycle. As mentioned above, HydroGEN determines the values of these parameters by means of random generation within specific user-defined ranges, thus each simulation run may result in slightly different daily irrigation volumes and therefore in different peak-demand dates.

Table 4.2 and Fig. 4.8 show good agreement between simulated and recorded volumes at the inlet of District 10 during the peak demand periods for both the 2008 (339,726 m³ vs. 337,468 m³, respectively) and 2009 seasons (397,093 m³ vs. 395,777 m³, respectively), with slight differences in the day-to-day distribution of aggregated volumes, which are very similar.
For both 2008 and 2009, the sum of the aggregated values over the peak demand period are slightly higher than the recorded values (+0.7% for 2008 and +0.3% for 2009), thus showing that, when applied to large command areas, the HydroGEN model performs quite well in simulating both the peak-demand periods, as well as the aggregated irrigation volumes withdrawn by farmers during these peak periods. The differences between simulated and observed data is most likely related to discrepancies in
the time duration of irrigations, or to the actual discharges withdrawn at hydrants that might be different than the nominal value assumed by the model, or to a different number of hydrants being in simultaneous operation on the different days of the peak period with respect to the simulated hydrants.

**Table 4.2** Comparison between simulated and recorded daily irrigation volumes for the 10-day peak period in the 2008 and 2009 irrigation seasons for the District 10 delivery network

<table>
<thead>
<tr>
<th>Days</th>
<th>Simulated Daily Volumes (m³) - 2008</th>
<th>Recorded Daily Volumes (m³) - 2008</th>
<th>Δ (%) 2008</th>
<th>Simulated Daily Volumes (m³) - 2009</th>
<th>Recorded Daily Volumes (m³) - 2009</th>
<th>Δ (%) 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.53E+04</td>
<td>2.97E+04</td>
<td>-14.8</td>
<td>2.77E+04</td>
<td>3.67E+04</td>
<td>-24.5</td>
</tr>
<tr>
<td>2</td>
<td>2.42E+04</td>
<td>3.22E+04</td>
<td>-24.8</td>
<td>3.84E+04</td>
<td>4.01E+04</td>
<td>-4.2</td>
</tr>
<tr>
<td>3</td>
<td>1.79E+04</td>
<td>2.65E+04</td>
<td>-32.4</td>
<td>3.98E+04</td>
<td>4.23E+04</td>
<td>-5.9</td>
</tr>
<tr>
<td>4</td>
<td>4.49E+04</td>
<td>3.39E+04</td>
<td>32.7</td>
<td>4.24E+04</td>
<td>4.11E+04</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>4.56E+04</td>
<td>3.94E+04</td>
<td>15.6</td>
<td>5.92E+04</td>
<td>3.60E+04</td>
<td>64.5</td>
</tr>
<tr>
<td>6</td>
<td>5.86E+04</td>
<td>4.00E+04</td>
<td>46.4</td>
<td>3.81E+04</td>
<td>4.07E+04</td>
<td>-6.3</td>
</tr>
<tr>
<td>7</td>
<td>3.10E+04</td>
<td>3.62E+04</td>
<td>-14.4</td>
<td>4.53E+04</td>
<td>4.34E+04</td>
<td>4.4</td>
</tr>
<tr>
<td>8</td>
<td>2.54E+04</td>
<td>2.98E+04</td>
<td>-14.7</td>
<td>4.51E+04</td>
<td>4.16E+04</td>
<td>8.6</td>
</tr>
<tr>
<td>9</td>
<td>3.30E+04</td>
<td>3.70E+04</td>
<td>-11.0</td>
<td>3.07E+04</td>
<td>4.28E+04</td>
<td>-28.3</td>
</tr>
<tr>
<td>10</td>
<td>3.39E+04</td>
<td>3.28E+04</td>
<td>3.3</td>
<td>3.04E+04</td>
<td>3.12E+04</td>
<td>-2.6</td>
</tr>
<tr>
<td>Total</td>
<td>3.40E+05</td>
<td>3.37E+05</td>
<td>+0.7</td>
<td>3.97E+05</td>
<td>3.96E+05</td>
<td>+0.3</td>
</tr>
</tbody>
</table>

**Fig. 4.8** Comparison between simulated vs. recorded daily irrigation volumes at the inlet of District 10 during the recorded 10-day peak demand period of 2008 and 2009
The evolution of hourly flows simulated by the model through the two stochastic approaches referred to as “Long” (L) and “Short” (S), as well as the comparison with the recorded values for each of the 10 days of the peak demand periods during the 2008 and 2009 seasons are reported in Figs. 4.9 and 4.11.

Both figures show that the typical irrigation demand pattern is not uniform during the daytime. It increases sharply early in the morning, peaks for few hours and then usually decreases in the evening. No low-peaks are observed during noon or around lunch time, as farmers can pre-set hydrants’ openings, irrigation durations and hydrants’ shut-off timings by programming deliveries through the electronic cards at their disposal, thus being able to leave the fields without terminating the on-going irrigations.

The zero flows recorded for a few hours on days 2 and 10 and shown in Fig. 4.9 were reported by the technical staff of the WUO as being related to network shut-offs due to emergency maintenance interventions carried out on July 1st and July 9th, 2008.

From Figs. 4.9 and 4.11 it can be also inferred that the simulated and recorded hydrographs follow similar patterns and that the model simulates hourly discharges that are in good agreement with the recorded data. This capability of the model is very relevant either when analyzing the operation of existing systems with the aim of performance assessment, or when designing and sizing new networks, as well as when evaluating modernization measures to be implemented in existing low performing ones.

The differences may result from a combination of several factors that, as in the case of daily volumes, include: (1) the actual discharges withdrawn from hydrants might be different than the hydrants’ nominal discharges assumed in the model for the simulations; (2) a different number of hydrants being actually in simultaneous operation
at specific hours than the simulated one; (3) to actual values of the application efficiency being different from the estimated ones that were utilized as inputs in the hydrant file, or (4) to different irrigation management strategies being followed by some farmers with respect to the simulated behavior. The actual volumes withdrawn by the farmers are related to the size of cropped area irrigated by each hydrant, as well as to the on-farm irrigation system utilized and to farmers’ decisions, whereas the number of hydrants in simultaneous operation is linked to farmers’ behavior or to the crop irrigation management strategy adopted at the field level for specific crop yield and quality targets.

A statistical analysis was performed on the simulated data series versus the recorded ones to evaluate the performance of HydroGEN in predicting the hourly flow rates during peak-demand periods. Linear regressions, root square mean errors (RSME) and coefficients of determination ($R^2$) were computed for the data series simulated through the “Long” (L) and “Short” (S) stochastic procedures versus the recorded data for the 2008 and 2009 seasons. The results from the statistical analyses are presented in the Table 4.3 and Figs. 4.10 and 4.12.

From Figs. 4.9 and 4.11 it can be observed that on some days the “Long” (L) stochastic approach yields hourly flow rates with a different distribution throughout the day, compared to the recorded values, but in general with peaks of similar magnitude as the recorded peak values occurring at different hours of the day.

From the results of the statistical analysis (Table 4.3 and Figs. 4.10 and 4.12) it can be seen that the “Short” (S) stochastic approach performs much better than the “Long” approach in terms of simulation of hourly flow rates. For both 2008 and 2009, the “Short” stochastic approach yields values of the RSME (70 and 50, respectively) lower
than those obtained through the “Long” approach (115 and 70, respectively). Also, the values of $R^2$ obtained through the “Short” approach for 2008 and 2009 (0.52 and 0.43, respectively) are higher than those obtained by means of the “Long approach (0.17 and 0.36, respectively). In other words, the hourly discharges simulated through the “Short” stochastic procedure more closely followed the pattern and the magnitudes of the recorded flow rates collectively demanded by the growers both in 2008 and 2009 for the irrigation system under study.

Table 4.3 Outputs from the statistical analysis of simulated versus recorded hourly flow rates during peak-demand periods of the 2008 and 2009 irrigation seasons for the District 10 delivery network

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SIMULATED - L</th>
<th>SIMULATED - S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RSME</td>
<td>$R^2$</td>
</tr>
<tr>
<td>2008</td>
<td>115</td>
<td>0.17</td>
</tr>
<tr>
<td>2009</td>
<td>70</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Fig. 4.9 Simulated and recorded hourly flow rates (l s$^{-1}$) for the 10-day peak period during the 2008 irrigation season for the District 10 delivery network of the Sinistra Ofanto system
Fig. 4.10 Regression between recorded and simulated hourly flow rates (l s⁻¹) through the “Long” and “Short” stochastic approaches for the 10-day peak period during the 2008 irrigation season for the delivery network of District 10 of the Sinistra Ofanto system.

Fig. 4.11 Simulated and recorded hourly flow rates (l s⁻¹) for the 10-day peak period during the 2009 irrigation season for the delivery network of District 10 of the Sinistra Ofanto system.
The model also enables the computation of relative frequencies and cumulative frequency of simulated flows. Figures 4.13, 4.14, and 4.15 show examples of the relative and cumulative frequencies of recorded and of simulated flows by using the L and S approaches for the 2008 irrigation season in District 10.

These outputs can be utilized by HydroGEN as inputs of probability distribution function for further simulations on the same delivery network, as well as on other systems with similar operation conditions, when recorded datasets on demand discharges are unavailable.

The results from the statistical analysis conducted on the frequencies of hourly discharges confirm that, for the irrigation system studied, the “Short” (S) stochastic approach performs better than the “Long” approach in simulating hourly flow rates, when HydroGEN is applied to the district command area.

**Fig. 4.12** Regression between recorded and simulated hourly flow rates (l s⁻¹) through the “Long” and “Short” stochastic approaches for the 10-day peak period during the 2009 irrigation season for the delivery network of District 10 of the Sinistra Ofanto system.
Fig. 4.13 Relative and cumulative frequencies of flows recorded during the 10-day peak period of the 2008 irrigation season for the delivery network of District 10

Fig. 4.14 Relative and cumulative frequencies of flows simulated through the Long stochastic approach for the 10-day peak period during the 2008 irrigation season for the delivery network of District 10
**Fig. 4.15** Relative and cumulative frequencies of flows simulated through the Short stochastic approach for the 10-day peak period during the 2008 irrigation season for the delivery network of District 10

**Table 4.4** Outputs from the statistical analysis on the frequencies of simulated versus recorded flow rates during peak-demand periods of the 2008 and 2009 irrigation seasons for the District 10 delivery network

<table>
<thead>
<tr>
<th></th>
<th>SIMULATED - L</th>
<th></th>
<th>SIMULATED - S</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.010</td>
<td>0.340</td>
<td>0.076</td>
<td>0.960</td>
<td>0.012</td>
<td>0.520</td>
<td>0.030</td>
</tr>
<tr>
<td>2009</td>
<td>0.014</td>
<td>0.47</td>
<td>0.085</td>
<td>0.963</td>
<td>0.016</td>
<td>0.511</td>
<td>0.042</td>
</tr>
</tbody>
</table>

For the 2008 irrigation season, the RSME of cumulative frequency of hourly discharges simulated through the “Short” approach yields a value of 0.030, whereas the RSME value related to the simulations through the “Long” approach results 0.076. As for the R² of the cumulative frequency, the value related to simulations through the “Short” approach is 0.99 and higher than 0.96, the value resulting from the “Long” approach.
Fig. 4.16 Regression between Cumulative Frequencies of simulated (L and S approaches) and recorded hourly discharges for the 10-day peak period during the 2008 irrigation season for the delivery network of District 10.

Fig. 4.17 Regression between Cumulative Frequencies of simulated (L and S approaches) and recorded hourly discharges for the 10-day peak period during the 2009 irrigation season for the delivery network of District 10.

As for the 2009 irrigation season, the RSME of cumulative frequency of the “Short” and “Long” approaches yields 0.042 and 0.085, respectively, whereas the R² of the “Short” and “Long” approaches results in 0.99 and 0.96, respectively. In other words, from the statistical analysis it can be inferred that the “Short” stochastic approach allows
the simulation of hourly discharges that follow closer the recorded discharges collectively
demanded by growers in the irrigation system under study during the peak periods of the
2008 and 2009 irrigation seasons.

4.2.2 Model applications at sector and hydrant levels

Given the availability of recorded volumes and discharges at some sectors for the
2007 season and of recorded volumes at the hydrant level for 2005, two further analyses
were conducted for model validation. The first analysis aimed at assessing the
applicability and reliability of the HydroGEN model at the level of small command areas
or irrigation sectors. Peak-demand volumes and discharges were simulated based on the
2007 climatic data for the entire cropped area included within Sector 2 of District 10. The
distribution network of Sector 2 supplies water to 19 delivery hydrants and covers a total
cropped area of 76.9 ha, out of which 17.4 ha are cultivated with table grapes, 24.8 ha
with wine grapes, 12.0 ha with peaches, 15.2 ha with olives and 7.5 ha with vegetables
(artichokes).

From records provided by the WUO and collected through field surveying it was
inferred that each hydrant serves an average area of 4.0 ha, with no more than 6 cropped
fields. Also in Sector 2 all hydrants are equipped with rubber-ringed flow limiters
allowing for a maximum delivery of 10 l s⁻¹ and this discharge value was used by the
model as nominal flow rate for the simulations.

Similarly as in District 10, the simulations were run by using both the “Long” and
the “Short” algorithms for calculating hourly discharges. Results from these simulation
sets were then compared against values recorded during the same year by an electronic
flow meter, calibrated on a regular basis and installed on the main pipeline of Sector 2, a few meters downstream from the inlet of its distribution network.

In details, the flow meter is model RPPxxx/16 manufactured by Nicotra Sistemi and consists of an electronic data logger that enables recording flow and pressure measurements. The flow measurements are carried out by measuring the differential pressure between the two sections (inlet and outlet) of a Venturi pipe installed in-line on the main conduit. The device is capable of measuring differential pressures within the range 0-400 mBar and pressures within the range 0-16 Bar. The precision obtainable in measuring the differential pressure and the absolute pressure are of ± 0.1% and ±1%, respectively.

The comparison shows a fairly good agreement between simulated and recorded volumes (193,472 m³ vs. 165,889 m³, respectively) even though the model slightly over-estimates (~ 16%) the seasonal irrigation demand.

The application of the 10-day moving average to the recorded daily volumes showed that in 2007 the peak irrigation demand period occurred between DOY 204 and 213 (July 23rd to August 1st), whereas HydroGEN simulated the peak-demand period as occurring in a range of decades from DOY 199 - 208 (July 19th – July 28th) to DOY 234-243 (August 22nd – August 31st), with several simulations identifying DOY 203-212 (July 22nd – July 31st) as the peak 10-day period. This last interval from DOY 203 to 212 was taken into consideration for the comparisons among simulated and recorded volumes and discharges. The results from simulations are presented in Table 4.5 and Fig. 4.18.
Table 4.5 Comparison between simulated and recorded daily irrigation volumes during the 10-day peak period of the 2007 irrigation season for the delivery network of Sector 2

<table>
<thead>
<tr>
<th>Days</th>
<th>Simulated Daily Volumes (m³)</th>
<th>Recorded Daily Volumes (m³)</th>
<th>∆ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.94E+03</td>
<td>2.72E+03</td>
<td>+ 8.1</td>
</tr>
<tr>
<td>2</td>
<td>3.43E+03</td>
<td>4.21E+03</td>
<td>- 18.4</td>
</tr>
<tr>
<td>3</td>
<td>2.52E+03</td>
<td>2.80E+03</td>
<td>- 10.3</td>
</tr>
<tr>
<td>4</td>
<td>8.87E+02</td>
<td>1.97E+03</td>
<td>- 55.1</td>
</tr>
<tr>
<td>5</td>
<td>1.92E+03</td>
<td>1.09E+03</td>
<td>+ 75.8</td>
</tr>
<tr>
<td>6</td>
<td>1.95E+03</td>
<td>1.58E+03</td>
<td>+ 23.2</td>
</tr>
<tr>
<td>7</td>
<td>4.91E+03</td>
<td>2.84E+03</td>
<td>+ 72.9</td>
</tr>
<tr>
<td>8</td>
<td>5.73E+02</td>
<td>2.25E+03</td>
<td>- 74.5</td>
</tr>
<tr>
<td>9</td>
<td>2.44E+03</td>
<td>2.84E+03</td>
<td>- 14.3</td>
</tr>
<tr>
<td>10</td>
<td>2.21E+03</td>
<td>1.51E+03</td>
<td>+ 46.6</td>
</tr>
<tr>
<td>Total</td>
<td>2.38E+04</td>
<td>2.38E+04</td>
<td>- 0.2</td>
</tr>
</tbody>
</table>

From Table 4.5 it can be seen that differences between simulated and recorded volumes exist in the daily values, whereas the total aggregated demanded volumes during the 10-day peak period are instead quite similar. This can be likely referred to the fact that the day-to-day irrigation volumes are more linked to stochastic issues (such as farmers’ habits or the type of crop irrigation management followed by them) that cannot be easily predicted and do not average out in small command areas. The overall volume demanded in the peak period is instead more related to the aggregated crop irrigation needs. Anyhow, from the comparisons it can be inferred that, when applied to small irrigation command areas or to a small group of hydrants, the HydroGEN model performs better (for this case study) in forecasting aggregated volumes rather than their daily distribution during the peak-demand periods. This consideration further stresses the outcomes from similar research works (see Walker et al. 1995; Texeira et al. 1996; Khadra and Lamaddalena 2006), i.e. that the use of soil-water balances for forecasting irrigations is appropriate when the final objective is estimating the aggregated demand from several cropped fields, otherwise this approach may lead to errors, since exact
irrigation timings and amounts are difficult to predict because farmers usually follow empirical methods or rules of thumb to apply water.

As for the daily flow hydrographs, Fig. 4.18 presents the comparison among two sets of hourly discharges simulated through the “Long” and “Short” approaches and the values recorded during the 10-day peak period at the inlet of the Sector 2 distribution network. From the comparison it can be inferred that both the “Long” and “Short” stochastic approaches utilized for calculating the hourly flow rates perform reasonably well in forecasting peaks in the demand, and that these peaks are of the same magnitude as the recorded ones. The values of RSME that result from comparing the hourly discharges simulated through the “Long” and “Short” approaches and the actual discharges recorded at the inlet of Sector 2 are of 11 and 7, respectively. Several discrepancies are noted in the hourly values and in the daily distribution of the simulated hourly discharges with respect to the recorded ones, revealing that, as expected, the model achieves better performance in forecasting hourly flow rates when applied to fairly large multi-cropped areas.

The second analysis was performed with a focus on seasonal irrigation volumes per crop, by running simulations only for the main crops grown in the study area, and comparing the resulting values with datasets on water withdrawals recorded during the 2005 season at 87 selected hydrants supplying water only to single-cropped farms or fields. These selected hydrants are scattered throughout the command area serviced by the distribution network of District 10 and belong to the areas of irrigation Sectors 1, 2, 5, 13, and 16. The seasonal volumes actually withdrawn during 2005 by growers from these hydrants were averaged out on a crop-wise basis prior to make the comparison, in order
to obtain the average irrigation volumes delivered to each selected crop and thus reduce the existing large variability within the recorded sets of values. This variability can be related to different crop varieties and crop ages, as well as to different strategies followed by farmers in crop irrigation management for specific yield and quality targets.

Table 4.6 presents the results of the analysis conducted at hydrant level, which reveal that the HydroGEN model performs well also in predicting the seasonal irrigation demand of the different crops. The small discrepancies (~ ±3-6%) noted for several crops, such as young table grapes, mature wine grapes, mature olive, young early peaches, mature early peaches, and mature late peaches, are most likely related to small errors in estimating crop and soil parameters (such as root depth, crop height, fractional canopy cover, water holding capacity) during the definition of the crop and soil input files with respect to the actual field growing conditions.

![Simulated and recorded hourly flow rates (l s⁻¹) for the 10 days of the peak period during the 2007 irrigation season for the delivery network of Sector 2](image)

**Fig. 4.18** Simulated and recorded hourly flow rates (l s⁻¹) for the 10 days of the peak period during the 2007 irrigation season for the delivery network of Sector 2
Table 4.6 Comparison between simulated and recorded seasonal irrigation volumes for the main crops grown in the study area during the 2005 irrigation season

<table>
<thead>
<tr>
<th>Crops</th>
<th>Simulated volumes (m³/ha)</th>
<th>Averaged recorded volumes (m³/ha)</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature Table grapes</td>
<td>2232</td>
<td>2240</td>
<td>-0.3</td>
</tr>
<tr>
<td>Young Table grapes</td>
<td>1885</td>
<td>1814</td>
<td>+3.9</td>
</tr>
<tr>
<td>Mature Wine grapes</td>
<td>2039</td>
<td>1979</td>
<td>+3.0</td>
</tr>
<tr>
<td>Young Wine grapes</td>
<td>1760</td>
<td>1770</td>
<td>-0.6</td>
</tr>
<tr>
<td>Mature Olive</td>
<td>1965</td>
<td>2033</td>
<td>-3.3</td>
</tr>
<tr>
<td>Mature Early Peaches</td>
<td>3001</td>
<td>2904</td>
<td>+3.3</td>
</tr>
<tr>
<td>Young Early Peaches</td>
<td>1905</td>
<td>2025</td>
<td>-5.9</td>
</tr>
<tr>
<td>Mature Late Peaches</td>
<td>3331</td>
<td>3455</td>
<td>-3.6</td>
</tr>
<tr>
<td>Young Late Peaches</td>
<td>2127</td>
<td>2158</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

4.3 Conclusions

A stochastic simulation model named HydroGEN was applied to a large-scale pressurized irrigation delivery system located in southern Italy with the aim of forecasting demand flows during peak periods. The model was tested at different management levels, from district to sector and hydrants, and the model’s applications entailed the use of high-resolution remote-sensing imagery acquired on a single date in 2006 and then processed following a ground-truthing campaign conducted during the same year.

Results from the different simulations were compared with historical datasets of irrigation volumes and discharges recorded by electronic flow meters installed at the upstream ends of district, sector and at hydrants. Some discrepancies between simulated and recorded data were noted, that can be related to small errors in estimating crop and soil parameters, to mis-estimation of application efficiency with respect to the actual values, as well as to large variability in irrigation management practices followed by local
farmers. Further research should be conducted through the use of high-resolution multispectral remote sensing imagery acquired on multiple dates, so as to determine the evolution of crop parameters (canopy cover and basal crop coefficients) with higher accuracy throughout the year. Also, the actual average values of the irrigation efficiency at hydrant level should be investigated with the aim of improving the accuracy of demand flow forecasts. This could be accomplished by measuring the necessary parameters for computing the irrigation requirements for the different crops grown in the study area and by comparing the required volumes with the delivered volumes as recorded by the electronic flow meters integrated within the hydrants.

Overall, the validation results showed that the model is capable of forecasting with good accuracy the timing of peak-demand periods, the irrigation volumes demanded by farmers during the season, as well as the hydrographs of daily volumes and hourly flow rates withdrawn by farmers during these peak-demand periods, especially when it is applied to large multi-cropped command areas.

The model can be utilized for simulating the demanded flows in existing irrigation delivery networks, which can then be further processed by some hydraulic simulation models for evaluating the networks’ behavior and to assess the network’s performance under different operating conditions. In this perspective, the HydroGEN model can be utilized as a tool for designing and sizing new delivery systems, as well as for modernizing low performing existing ones.
References


CHAPTER 5

A METHODOLOGY TO CONDUCT DIAGNOSTIC PERFORMANCE ASSESSMENT AND SIMULATION OF ALTERNATIVE DELIVERIES IN LARGE-SCALE PRESSURIZED IRRIGATION SYSTEMS

Abstract This chapter describes a methodology to conduct diagnostic performance assessment and simulate delivery scenarios in pressurized irrigation delivery networks. The rationale of the proposed methodology entails the combined use of an agro-hydrological model, a hydraulic simulation model, and of some specific performance indicators. The agro-hydrological model uses climatic data and spatially-distributed inputs that are derived from field information, and simulates the daily soil-water balance in all the cropped fields downstream from the delivery hydrants. In this way the model generates disaggregated information on soil water deficits and on required irrigation deliveries for the entire area serviced by the distribution network. After aggregating all the hydrant hydrographs, the agro-hydrological model then generates the overall demand flow hydrographs and the resulting flow configurations at the upstream end of the network. Subsequently, the hydraulic model reads the flow configurations generated by the agro-hydrological model and performs the simulation of delivery and the evaluation of hydraulic performance based on the physical characteristics and behaviour of the distribution network by using hydraulic performance indicators, and on the conditions of water delivery required for the proper operation of the on-farm irrigation systems. Additional performance indicators, which were specifically adapted to pressurized irrigation systems, are then utilized to refine the evaluation of performance achievements.
and to identify areas for improvement. These performance indicators were previously tested for validation on two irrigation sectors of a large-scale pressurized system located in southern Italy, in which water withdrawals by farmers from the delivery network are recorded on a continuous basis at hydrants during the entire irrigation season. Finally, the proposed methodology was tested on two irrigation districts at another large-scale pressurized irrigation system in southern Italy that is in need of modernization and whose current operation, besides heavily constraining farmers in managing irrigation of their crops, does not allow for an efficient use of the available water supply. The overall objective of the study presented in this chapter is to validate the proposed methodology for modernization of large-scale pressurized irrigation systems.

5.1 Background

In many areas of the world irrigation projects perform far below their potential (Small and Svendsen 1992) and this evidence was documented by several authors and institutions. In several cases, unrealistic or out-dated designs, rigid water delivery schedules and operational problems are among the principal reasons for the poor performance of irrigation systems (Plusquellec et al. 1994). In others, system management often fails to respond to the needs of users, in particular to smallholders carrying low social and political weight (UNESCO 2003). Studies at international level documented that in several cases the real limitations to achieve adequate performance can be found in the management component rather than in the physical and design characteristic of the networks.

The assessment of actual performance and potential improvement of conveyance and distribution systems have received greater attention in recent years, and this trend
will most likely extend to the near future, as public and private investments will be more addressed to modernization of ageing or poor-performing irrigation schemes rather than to further expansion of existing irrigation schemes. In this perspective, existing irrigation systems should be periodically evaluated for their performance achievements relative to current and future objectives. This requires detailed diagnostic methodologies to analyze system behavior, assess current performance, identify critical aspects and weaknesses, and to investigate potential improvements.

Several authors (Small and Svendsen 1992; Murray-Rust and Snellen 1993; Burt and Styles 2004) reported a remarkable lack of analytical frameworks within which irrigation managers or professional auditors can assess current achievements and diagnose feasible ways to enhance performance in the future. On the other hand, as pointed out by Prajamwong et al. (1997) it is difficult to successfully identify and implement improvement changes without field measurements and analytical tools for developing feasible alternative scenarios and for selecting the most effective measures with the greatest impact on system performance.

Bos et al. (2005) indicated that diagnostic assessments are made to gain an understanding on how irrigation functions, to diagnose causes of problems and to identify opportunities for enhancing performance in order that action can be taken to improve irrigation water management. The same authors reported that diagnostic assessments are to be carried out when difficult problems are identified through routine monitoring, or when stakeholders are not satisfied with the existing levels of performance achieved and desire changes in system operation. The central component of diagnostic assessment is represented by performance indicators, as their selection and application aim at understanding
relationships and at developing performance statements about irrigations. Overall, irrigation managers or auditors need first to acquire a good understanding of system behavior under different operating conditions prior to using management-support tools (simulation) to take or recommend appropriate decisions.

In this view, a sound methodology for analysis of the existing irrigation schemes under current and future management needs is strongly required. Monitoring a set of variables, which determine the behavior of a complex system (diagnosis), and evaluating the system response after alternative correcting measures (prognosis and simulation) represent the basic capabilities required for accurately addressing modernization processes. The diagnostic component should be used to conduct analyses on different aspects of system management, such as water demand, management of water supply, identification of current system management needs, system design, capability and performance. The simulation component should be capable of facilitating the appraisal of improvement options by evaluating the system response following modifications. Both the diagnosis and simulation phases should be based upon a set of properly chosen performance indicators able to account for the main variables effecting operation and for synthetically representing the state of the system with respect to defined management objectives.

There is a large set of indicators available in literature, but the majority were conceived and utilized to evaluate performance of canal (non-pressurized) irrigation systems and often consider only the irrigation volume as a main measurable variable.

In this perspective, the methodology proposed in this chapter enables to conduct diagnostic assessment, simulate alternative operational scenarios and evaluate
performance achievements in large-scale pressurized irrigation systems, thus constituting an analytical basis to address modernization processes in such systems with greater accuracy than was done in the past.

5.2 Rationale of the Proposed Methodology

The approach and components utilized within the proposed methodology are outlined in Fig. 5.1.

Fig. 5.1 Process and components utilized by the proposed methodology for conducting operational and performance analysis in pressurized irrigation systems
The first part of the methodology entails the generation of the flow demand hydrographs during peak-demand periods through the use of an agro-hydrological model named Hydro-GEN that performs the daily soil-water balance and the simulation of irrigation deliveries for all the cropped fields served by the distribution network. By aggregating the simulated hydrant flow hydrographs, the model generates the flow demand configurations for the entire distribution network. The Hydro-GEN model and its applications to a pressurized irrigation delivery system at different management levels were described in detail in Chapter 3 and 4.

The generated water demand scenarios are spatially and time distributed estimates that may be then used to define the expected levels of irrigation delivery service (objectives setting) from the distribution network over the different serviced areas. The flow configurations in the distribution network are then passed as inputs to a hydraulic model named COPAM (Lamaddalena and Sagardoy 2000) to simulate different operational modes, analyze the network’s hydraulic behaviour and evaluate hydraulic performance achievements with regard to the target delivery objectives. In this way, the COPAM simulation model allows identifying the potential failures of the irrigation network and the structural limitations under the different flow configurations.

The hydraulic simulations are based upon user-specified irrigation delivery conditions (or agreed-upon delivery service between the water management body and users) and utilize selected indicators and reference values to evaluate hydraulic parameters and identify the state of the system with respect to the specified management objectives. Moreover, the combined use of the Hydro-GEN and COPAM models verifies that the aggregated water demand and the adopted operational modes do not exceed the
daily available water supply and the maximum physical capacity of the distribution network.

As final step, additional indicators are used to evaluate water delivery variables, other than hydraulic parameters, and to refine the performance analysis. The outputs resulting from the COPAM model, along with the evaluation of irrigation delivery through the additional indicators, can be interpreted in terms of performance achievements based on the comparison with the farm requirements. Applying the above-described tools in the proposed sequence and analyzing the resulting outputs will guide the system’s managers and/or auditors in evaluating the irrigation delivery scenarios as satisfactory or unsatisfactory, and adjust the operations accordingly or identify the necessary physical changes.

5.3 Performance Indicators

Performance indicators are parameters resulting from the mathematical combination of measurable state variables and are conceived to synthetically assess how the irrigation system behaves with respect to the achievement of planned or targeted objectives. There is a large set of performance indicators available in literature, as many authors and institutions have proposed specific ways to measure performance of irrigation and drainage systems, as summarized by Rao (1993) and by Bos et al. (2005).

In the environmental and agro-economic context of the Mediterranean region, the main objectives of a water delivery system are as follows:

1. supplying water to farms according to farmers’ water demand, not only in terms of amounts but also in terms of adequate flow rate, pressure head and timing;
2. allowing cropping diversification;
3. contributing to increase or stabilize crop yields and farm net benefits;
4. supporting farmers investments and allowing improved farming practices;
5. achieving long-term sustainability of irrigated agriculture in the command areas.

The proposed methodology for diagnostic assessment entails the use of some performance indicators that were specifically adapted to pressurized delivery systems to describe the achievements by the irrigation distribution network with respect to the targeted water delivery objectives. Among these indicators, the Relative Pressure Deficit and Reliability at each hydrants were taken from previous works conducted by Lamaddalena (1997) and by Lamaddalena and Sagardoy (2000) and, together with the hydrant’s Sensitivity, which was instead defined within the present research, are used to measure and describe the hydraulic performance of the irrigation delivery networks in terms of pressure heads at the delivery points.

Three more indicators, namely the Relative Volume, the Relative Frequency, and the Relative Delay, were instead developed by modifying the indicator of Adequacy as it was originally conceived by Molden and Gates (1990) to conduct performance assessment in open channel networks. The modifications to the Adequacy indicator aimed at tailoring this criterion to pressurized irrigation distribution systems and thus at describing the adequacy of water delivery in terms of supplied volumes and of timeliness of irrigation.

Finally, also the indicators of Dependability and of Equity were modified with respect to those defined by Molden and Gates (1990), and then used to assess the degree
of spatial and temporal variability of irrigation delivery conditions over the command areas and during the periods of interest.

The Relative Pressure Deficit (Lamaddalena 1997) at each hydrant, $RPD$, is computed by:

$$RPD_{j,r} = \frac{(H_{j,r} - H_{REQ})}{H_{REQ}}$$  \hspace{1cm} (5.1)

where $H_{j,r}$ is the hydraulic head at the hydrant $j$ within the configuration $r$ of hydrants in simultaneous operation, and $H_{REQ}$ is the minimum pressure head necessary for proper operation of on-farm irrigation systems.

The representation of $RPD_{j,r}$ in a plane where the abscissas correspond to hydrants number and the ordinates to $RPD_{j,r}$ clearly identifies the hydrants having insufficient pressure for enabling proper on-farm irrigation.

As for the second indicator, in general terms the Reliability of a system describes how often the system fails or, in different terms, the frequency or probability that the system is in a satisfactory state. Following earlier works by Hashimoto (1980) and by Hashimoto et al. (1982), the mathematical definition of reliability at hydrant level was carried out by Lamaddalena (1997) as reported hereafter.

$$\alpha = \text{Prob} \left[ X_t \in S \right]$$  \hspace{1cm} (5.2)

where $\alpha$ is the hydrant’s reliability, and $X_t$ is the random variable denoting the state of the system at time $t$. The possible values of $X_t$ may fall in two sets: $S$, the set of all satisfactory outputs and $F$, the set of all unsatisfactory outputs denoting failure. Following this approach, at each instant $t$ the system may fall in one of these alternative
sets. Therefore the reliability of a system can be described by the probability \( \alpha \) that the system is in a satisfactory set.

The state of satisfaction at hydrant level is measured on the basis of the value of the available hydraulic head at the hydrant under the different flow configurations. Specifically, within each generated configuration \( r \) of hydrants in simultaneous operation, a hydrant \( j \) is considered satisfied when the following relationship holds true:

\[
H_{j,r} \geq H_{\text{REQ}} \tag{5.3}
\]

In the specific case of pressurized irrigation systems, the reliability of each hydrant expresses the variability over time of the available pressure head of irrigation water deliveries at hydrants during the period of interest. From the Eq. 5.2, the reliability of each hydrant can be computed on the basis of the following equation:

\[
\alpha_j = \frac{\sum_{r=1}^{C} I_{h_{j,r}} I_{p_{j,r}}}{\sum_{r=1}^{C} I_{h_{j,r}}} \tag{5.4}
\]

where

- \( \alpha_j \) = reliability of the hydrant \( j \)
- \( I_{h_{j,r}} = 1 \), if the hydrant, \( j \), is open in the configuration \( r \)
- \( I_{h_{j,r}} = 0 \), if the hydrant, \( j \), is closed in the configuration \( r \)
- \( I_{p_{j,r}} = 1 \), if the pressure head at the hydrant, \( j \), open in the configuration \( r \), is higher than the minimum required pressure head
- \( I_{p_{j,r}} = 0 \), if the pressure head at the hydrant, \( j \), open in the configuration \( r \), is lower than the minimum required pressure head
- \( C \) = total number of generated configurations.
The COPAM simulation model estimates the available pressure head (m) at each hydrant in operation under each flow configuration within the network and then calculates the values of the parameters \( I_{hj, r} \) and \( I_{pj, r} \), thus computing the corresponding value of the hydrant reliability, \( a_j \).

The sensitivity of hydrants, also named as Relative Pressure Deficit Sensitivity, \( RPDS \), refers to the range of fluctuations of the relative pressure deficit at hydrants, and how this range stretches across the zero-value line of \( RPD \), which in turn identifies the adequacy in the available pressure head with respect to the minimum required one, \( H_{REQ} \), for having the on-farm irrigation systems working properly. In detail, the minimum boundary of the range of \( RPD \) fluctuations is relevant for identifying both the potential failures and their severity. The sensitivity of hydrants is calculated through the Eq. 5.5:

\[
RPDS = RPD_{AVE} - 0.5 * RPD_{RANGE} = \left( \frac{H_{AVE} - H_{REQ}}{H_{REQ}} \right) - 0.5 \left( RPD_{MAX} - RPD_{MIN} \right)
\]

\[
=> RPDS = \left( \frac{H_{AVE} - H_{REQ}}{H_{REQ}} \right) - 0.5 \left[ \left( \frac{H_{MAX} - H_{REQ}}{H_{REQ}} \right) - \left( \frac{H_{MIN} - H_{REQ}}{H_{REQ}} \right) \right]
\]  (5.5)

where the limits of \( H_{MIN} \) and \( H_{MAX} \) are set as follows:

\( H_{MIN} \geq 0 \)

\( H_{MAX} \leq \text{Max operating pressure head bearable by pipes} \)

The Relative Volume, \( RV \), is a measure of the objective of the distribution network of delivering adequate irrigation volumes to each serviced cropped field with respect to the required ones. The \( RV \) is therefore a measure of Adequacy expressed in terms of delivered volumes and is defined by the following relationships:

at a given location
averaged over the region, \( R \), and the time of interest, \( T \)

\[
P_{av} = \frac{1}{T} \sum_T \left( \frac{1}{R} \sum_R RV \right)
\]  

(5.7)

where \( V_{DELI} \) and \( V_{REQ} \) are the irrigation volume delivered by the distribution network and the irrigation volume required for adequate crop irrigation management and target yield, respectively.

As for the objective of Adequacy in terms of timeliness of irrigation delivery, the Relative Frequency, \( RF \), and the Relative Delay, \( RDe \), were defined by the equations reported hereafter.

**RF**

at a delivery location:

\[
RF = \frac{F_{REQ} - F_{DELI}}{F_{REQ}}
\]  

(5.8)

and the average over the region, \( R \), and during the time of interest, \( T \):

\[
P_{AF} = \frac{1}{T} \sum_T \left( \frac{1}{R} \sum_R RF \right)
\]  

(5.9)

where \( F_{REQ} \) is the frequency of irrigation required by any combinations crop/soil/climate for not incurring in any soil water deficit, and \( F_{DELI} \) is the frequency of actual irrigation water delivery by the distribution network.

**RDe**

At a delivery location:
\[
RDe = \frac{DEL_{ALL} - DEL_{DELI}}{DEL_{ALL}}
\] (5.10)

and averaged over the region, R, and time of interest, T:

\[
P_{AD} = \frac{1}{T} \sum_{T} \left( \frac{1}{R} \sum_{R} RDe \right)
\] (5.11)

where \textit{DEL}_\textit{ALL} is the maximum allowed delay (days) of irrigation that would cause a yield reduction within 10% of the maximum obtainable yield due to soil water deficit, for any given combinations crop/soil/climate, and \textit{DEL}_\textit{DELI} is the actual delay of irrigation delivery (days) by the distribution network with respect to the required timing for achieving the maximum yield (no water deficit).

The \textit{RV}, \textit{RF} and \textit{RDe} are particularly meaningful when the distribution network is operated by rotation or by arranged delivery schedules, whereas when irrigations are under the control of farmers (demand delivery schedules) the timing of irrigations and the volumes withdrawn from the network and applied to cropped fields by farmers are more affected by the available water supply, by the network delivery capacity as well as by farmers’ habits and behavior rather than by the network operations. Indirectly, the irrigation events and the volumes withdrawn by farmers are also affected by the pressure head available at hydrants under the different flow configurations. At the same time, hydrants’ operation, flow rates and volumes withdrawn by farmers strongly affect the flow configurations in the different sections of the network and thus the conditions of water delivery to other hydrants. As a matter of fact, in pressurized delivery systems operated on-demand, when farmers open the hydrants and don’t find adequate pressure head for proper on-farm irrigation, they usually shut-off the hydrant and come back sometime later for irrigating their fields. In other words, water withdrawals by farmers at
given hydrants might be biased by the operation of other hydrants and by the behavior of
other farmers and, at the same time, they might effect the operation of other hydrants too,
especially when the distribution network has low delivery capacity or low flexibility.
Thus, the $RV$, together with $RPD$, $RF$ and $RDe$ indicate indirectly the network
performance or, in other words, the capability of the distribution network to
accommodate the farmers’ behavior and the farming practices followed in the entire
command area and to still deliver water with the required conditions.

As for the Dependability, this indicator expresses the temporal uniformity in the
conditions of irrigation delivery. When the concerned delivery parameter is the irrigation
volume, then the dependability refers to the degree of temporal variability of the $RV$ that
occurs over the region of interest, $R$, and is expressed by the Eq. 5.12:

$$P_D = \frac{1}{R} \sum_{r} CV_T(RV) = \frac{1}{R} \sum_{r} CV_T \left( \frac{V_{DELI} - V_{REQ}}{V_{REQ}} \right)$$

(5.12)

where $CV_T \left( \frac{V_{DELI} - V_{REQ}}{V_{REQ}} \right) = temporal coefficient of variation (ratio of standard deviation
to mean) of the RV over the time period of interest $T$ (variability from time to time over
the period $T$).

When the concerned delivery parameter is the timeliness of irrigation, the
dependability is then expressed in terms of temporal variability of $RF$ and/or of $RDe$ as
follows:

$RF$:

$$P_D = \frac{1}{R} \sum_{r} CV_T(RF) = \frac{1}{R} \sum_{r} CV_T \left( \frac{F_{REQ} - F_{DELI}}{F_{REQ}} \right)$$

(5.13)
where \( CV_T \left( \frac{F_{\text{REQ}} - F_{\text{DELI}}}{F_{\text{REQ}}} \right) = \) temporal coefficient of variation of \( RF \) over the time period of interest \( T \).

**RDe:**

\[
P_D = \frac{1}{R} \sum R \cdot CV_T (R\text{De}) = \frac{1}{R} \sum R \cdot CV_T \left( \frac{D_{\text{ALL}} - D_{\text{DELI}}}{D_{\text{ALL}}} \right)
\]

(5.14)

where \( CV_T \left( \frac{D_{\text{ALL}} - D_{\text{DELI}}}{D_{\text{ALL}}} \right) = \) temporal coefficient of variation (ratio of standard deviation to mean) of the RDe over the time period of interest \( T \) (variability from time to time over the period \( T \)).

When the concerned delivery parameter is the available pressure head at hydrant, the dependability corresponds to the hydraulic reliability at hydrants, as defined by the Eq. 5.4.

As for the Equity, this indicator refers to the spatial uniformity of the irrigation delivery conditions. When the concerned delivery parameter is the irrigation volume, the equity is expressed as the degree of spatial variability of the \( RV \) that occurs over the region of interest, \( R \), and is expressed by the following relationship:

\[
P_E = \frac{1}{T} \sum_T CV_{R} \left( RV \right) = \frac{1}{T} \sum_T CV_{R} \left( \frac{V_{\text{DELI}} - V_{\text{REQ}}}{V_{\text{REQ}}} \right)
\]

(5.15)

where \( CV_{R} \left( \frac{V_{\text{DELI}} - V_{\text{REQ}}}{V_{\text{REQ}}} \right) = \) spatial coefficient of variation of the \( RV \) over the region of interest \( R \) (variability from point to point over the region).
Likewise the dependability, when the concerned delivery parameter is the timeliness of irrigation, the equity may be expressed in terms of $RF$ or of $RDe$ by the following relationships:

$RF$:

$$P_E = \frac{1}{T} \sum_T CV_R \left( RF \right) = \frac{1}{T} \sum_T CV_R \left( \frac{F_{REQ} - F_{DELI}}{F_{REQ}} \right) \quad (5.16)$$

where $CV_R \left( \frac{F_{REQ} - F_{DELI}}{F_{REQ}} \right) = $ spatial coefficient of variation of the $RF$ over the region of interest $R$.

$RDe$:

$$P_E = \frac{1}{T} \sum_T CV_R \left( RDe \right) = \frac{1}{T} \sum_T CV_R \left( \frac{D_{ALL} - D_{DELI}}{D_{ALL}} \right) \quad (5.17)$$

where $CV_R \left( \frac{D_{ALL} - D_{DELI}}{D_{ALL}} \right) = $ spatial coefficient of variation of the $RDe$ over the region of interest $R$.

When the concerned delivery parameter is the available pressure head at hydrant, the equity corresponds to spatial variability of the $RPD$ or of $RPDS$ and thus is expressed either by the relationships 5.18 or 5.19.

$RPD$:

$$P_E = \frac{1}{T} \sum_T CV_R \left( RPD \right) = \frac{1}{T} \sum_T CV_R \left( \frac{H_{DELI} - H_{REQ}}{H_{REQ}} \right) \quad (5.18)$$
where \( CV_R \left( \frac{H_{DELI} - H_{REQ}}{H_{REQ}} \right) \) = spatial coefficient of variation of the \( RPD \) over the region of interest \( R \).

**RPDS:**

\[
P_E = \frac{1}{T} \sum T CV_R \left( RPDS \right) = \frac{1}{T} \sum T CV_R \left( RPD_{AVE} - 0.5 \times RPD_{RANGE} \right)
\]

where \( CV_R \left( RPD_{AVE} - 0.5 \times RPD_{RANGE} \right) \) = spatial coefficient of variation of the \( RPDS \) over the region of interest \( R \).

Once performance indicators are conceived and defined on the basis of measurable variables, ranking the state of a system requires the computed or estimated performance values being evaluated versus defined reference values. Setting minimum performance levels is therefore relevant to allow diagnostic analyses and to define states of the system as satisfactory or unsatisfactory.

As pointed out by Molden and Gates (1990), there are several means by which performance standards can be established in a formal systems-analysis context, but this aspect is out of the scope of this paper. Within the present work, a tentative set of reference standard values is proposed in the Table 5.1 for the main indicators. The values of performance indicators and the relative performance classes are based on prescription of experienced project personnel (expert opinions) and on the perceived implications of deviation of the performance measures from some reference values identified as satisfactory.
Table 5.1 Tentative reference standards for performance assessment

<table>
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<th>MEASURE</th>
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<tr>
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<td>≥ 0.0</td>
</tr>
<tr>
<td>RV</td>
<td>- 0.1 – 0.00</td>
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<tr>
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<tr>
<td>RDe</td>
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<tr>
<td>Reliability</td>
<td>≥ 0.8</td>
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<tr>
<td>Dependability</td>
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</tr>
<tr>
<td>Equity</td>
<td>0.0 – 0.4</td>
</tr>
</tbody>
</table>

5.4 Validation of Performance Indicators

The set of indicators presented in the previous section was applied for validation purposes to the distribution networks and command areas of Sectors n. 2 and n. 5 of the Sinistra Ofanto Irrigation system, which is a modern and fully pressurized system, located in southern Italy and is managed and operated by a local Water Users Organization (WUO). This irrigation system and its two irrigation sectors were selected based on the availability of recorded data on irrigation deliveries at hydrant level for the 2005 irrigation season. The main physical and operational features of the Sinistra Ofanto irrigation system were described in details in Chapter 4.

The distribution network of Sector 2 supplies water to 19 delivery hydrants and covers a total cropped area of 76.9 ha, out of which 17.4 ha are cultivated with table grapes, 24.8 ha with wine grapes, 12.0 ha with peaches, 15.2 ha with olives and 7.5 ha with vegetables (artichokes). In this sector each hydrant serves an average area of 4.0 ha, and delivers water up to 6 farmers, which are attributed by the WUO a specific code for accessing and operating the hydrants and thus withdraw irrigation water from the
distribution network at their convenience. Out of the total number of hydrants of the Sector 2, only 6 hydrants were considered for applying the set of performance indicators, and specifically those hydrants supplying irrigation water to 11 coded users who farmed single-cropped fields during the 2005 season.

The distribution network of Sector n. 5 serves 33 hydrants, supplying irrigation water to a total area 186.5 ha of which 166.5 ha were cropped in the 2005 irrigation season. Out of the total command area, 41 ha were cultivated with table grapes, 46.5 ha with wine grapes, 26.7 ha with peaches and 52.3 ha with olives. In this sector, only 23 hydrants supplying a total of 45 coded farmers were considered for the validation of performance indicators. Likewise for the Sector 2, the 45 codes taken into consideration are those supplying water to users who farmed single-cropped fields in the 2005 irrigation season. Data of irrigation withdrawals were retrieved from records provided by the WUO that operates the distribution networks, for the 11 coded users of Sector 2 and for the 45 coded users of Sector 5 for the 2005 season.

The entire distribution network of the Sinistra Bradano irrigation system is operated by a restricted-demand delivery schedule, with all farmers taking water at their convenience from the hydrants with a maximum allowed flow rate of 10 l s⁻¹ and within the maximum seasonal allocated volume shares out of the total available water supply. In both Sector 2 and Sector 5, all hydrants are equipped with rubber-ringed flow limiters allowing for a maximum delivery of 10 l s⁻¹ and this discharge value was used as nominal flow rate for simulating the irrigation demand and the resulting flow configurations in the networks.
Three different applications of the proposed performance indicators were conducted on the selected irrigation sectors, as described hereafter. The first application considered as time of interest the 10-day and the 30-day peak-demand periods during the 2005 irrigation season. The Hydro-GEN model was run for the distribution networks and cropped areas of Sector 2 and Sector 5 with climatic and crop data related to the 2005 irrigation season. This allowed identifying the 10-day and 30-day peak-demand periods, as occurring respectively between the day of the year (DOY) 176-185 (June 25th – July 4th) and between DOY 166-195 (June 15th – July 14th), and estimating the demand irrigation volumes for each crops, under the crop irrigation management scenarios of full replenishment of the depleted soil water in the root-zone.

The simulated demand irrigation volumes were then compared with the water deliveries recorded by the 11 hydrant codes of Sector 2 and the 45 hydrant codes of Sector 5, so as to compute the values of the Relative Volume, $RV$, for the identified 10-day and 30-day periods of the 2005 season. Also, simulations through the HydroGEN model and by means of a root-zone soil-water balance algorithm implemented in an Excel spreadsheet allowed estimating the required frequency of irrigation deliveries and the maximum allowed delay for each crop for avoiding yield reductions higher than 10%. These two variables were then used for computing the value of the Relative Frequency, $RF$, and of the Relative Delay, $RDe$, for the identified peak periods. Finally, the values of the spatial average (Sp. Avg.), standard deviation (STDV) and coefficient of spatial variation (CVr) were computed for the three considered performance indicators.

The results obtained from comparing the required and delivered irrigation volumes are presented in the following Tables 5.2 and 5.3. For the Sector 5, given the
large number of hydrant codes considered, only data referred to ten selected hydrants are shown.

As can be seen from Tables 5.2 and 5.3, large spatial variability exists in both sectors for what concerns the irrigation volumes withdrawn by farmers from the delivery networks (supplied deliveries) and thus for the estimated values of adequacy in terms of volumes, frequency and timing. Since in both sectors, farmers are in control of the irrigations, they withdraw and apply very different water volumes to their cropped fields, according to their perceptions of crop water needs and most likely according to different crop quality and yield targets. The large variability in farmers’ behavior with respect to estimated irrigation requirements can be inferred from the values of the coefficient of variation, \( CV_r \), of the different indicators of Adequacy expressed in terms of volumes and timing that were considered in this application. An even larger spatial variability occurs in Sector 5 than that of Sector 2, for all the indicators of adequacy except for the Relative Delay, \( RDe \), which is instead more variable in the Sector 2. In both sectors, the large variability in irrigation deliveries with respect to the required volumes and timings as estimated by HydroGEN may be related to the very small land-holdings and thus to a large variability in crops varieties and in farmers behavior over the command areas.

As long as the irrigation delivery network and the available water supply allows such a crop diversification and such a diversified farmers’ behavior in crop irrigation management and in irrigation withdrawals, the large variability revealed by the application of the proposed indicators may not represent necessarily a negative operational feature of the irrigation system, but instead can be taken as a measure of flexibility of irrigation delivery. On the other hand, this large variability may also
indicate the need for more careful monitoring of farm irrigations as well as for training and extension service activities to guide farmers in achieving better efficiency of water use. In case of limited system capacity or limited available water supply, a large variability in farmers’ behavior may reveal the occurrence of poor equity in water distribution and the need for enforcing specific constraints in water withdrawals.

The second application considered the period May to September and the irrigation volumes aggregated both on a monthly basis and for the entire 2005 irrigation season. Also in this application, the demand volumes for each crop grown were estimated by running simulations with the HydroGEN model, whereas the volumes withdrawn by each hydrant’s code were retrieved from the database of irrigation records made available by the WUO, and were afterwards aggregated on a monthly and seasonal basis.

The required and delivered irrigation volumes were then compared with the aim of estimating the Adequacy in terms of volumes through the values of the $RV$ under the management scenario of full replenishment of the depleted soil water from the crops’ root-zones. Also, the variability of $RV$ over space (hydrants) and over time (different months of the irrigation season) was computed. The variability over space is a measure of the equity of water distribution, whereas the variability over time accounts for its dependability.

The comparison between the required and delivered irrigation volumes for the two irrigation sectors is reported in Tables 5.4 and 5.5. Again, given the large number of fields serviced by the distribution network of Sector 5, Table 5.5 presents only data related to ten hydrant codes, but the values of spatial average, standard deviation and coefficient of variation are referred to computations carried out on all the hydrant codes.
The results presented in Tables 5.4 and 5.5 clearly show that very large spatial and temporal variability in farmers’ behavior exists in the two considered irrigation sectors also for what concerns the aggregated water deliveries, i.e. for periods larger than the 10-day peak demand one. In the specific case of Sectors 2 and 5, the application of the RV shows how the existing distribution networks and the restricted-demand schedule enforced by the WUO provide large flexibility in water delivery, thus not constraining farmers in crop irrigation management.

The third application concerned the objective of Adequacy in terms of available pressure head at hydrants with respect to the head requirements for proper operation of on-farm irrigation systems. Since data of pressure heads at hydrants were not available, the adequacy of deliveries was estimated for all the hydrants of the distribution networks of Sectors n. 2 and n. 5 upon simulated pressure head data. In details, the simulations through the HydroGEN model under the “full replenishment” management scenarios allowed generating the corresponding demand hydrographs and flow configurations in the distribution networks of both sectors during the peak-demand period. By assuming the volumes deliverable as being equal to the estimated required volumes ($V_{\text{deliverable}} = V_{\text{required}}$), then the performance evaluation in terms of pressure head was based on the fulfillment of demanded volumes and thus was conducted on the basis of the simulated demand flow configuration within the two distribution networks, vis-à-vis with their physical delivery capacities. The flow configurations generated by HydroGEN were then passed as inputs to the COPAM hydraulic model, which performed the simulations of the hydraulic behavior of the networks.
### Table 5.2: Required and supplied irrigation deliveries for the Sector No. 2 of the Sinistra Ofanto irrigation system during the 10-day and 30-day peak demand periods of the 2005 season

<table>
<thead>
<tr>
<th>HYDR. No.</th>
<th>COD No.</th>
<th>AREA (ha)</th>
<th>CROP</th>
<th>REQUIRED DELIVERIES</th>
<th>SUPPLIED DELIVERIES</th>
<th>ADEQUACY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>176-185 (m³/ha)</td>
<td>166-195 (m³/ha)</td>
<td>Max Freq. of Deliv.</td>
</tr>
<tr>
<td>9</td>
<td>46356</td>
<td>1.503</td>
<td>MTG</td>
<td>426</td>
<td>426</td>
<td>9</td>
</tr>
<tr>
<td>22/2</td>
<td>49192</td>
<td>1.577</td>
<td>MTG</td>
<td>426</td>
<td>426</td>
<td>9</td>
</tr>
<tr>
<td>22/2</td>
<td>49192</td>
<td>1.577</td>
<td>YTG</td>
<td>121</td>
<td>365</td>
<td>7</td>
</tr>
<tr>
<td>18</td>
<td>46232</td>
<td>1.017</td>
<td>MWG</td>
<td>279</td>
<td>562</td>
<td>12</td>
</tr>
<tr>
<td>17</td>
<td>47031</td>
<td>1.176</td>
<td>MWG</td>
<td>279</td>
<td>562</td>
<td>12</td>
</tr>
<tr>
<td>17</td>
<td>47032</td>
<td>1.20</td>
<td>MWG</td>
<td>279</td>
<td>562</td>
<td>12</td>
</tr>
<tr>
<td>22/1</td>
<td>49072</td>
<td>1.220</td>
<td>MWG</td>
<td>279</td>
<td>562</td>
<td>12</td>
</tr>
<tr>
<td>17</td>
<td>47031</td>
<td>1.176</td>
<td>YWG</td>
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<td>387</td>
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</tr>
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<td>20</td>
</tr>
<tr>
<td>9</td>
<td>46353</td>
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<td>MLP</td>
<td>510</td>
<td>510</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>46352</td>
<td>0.163</td>
<td>YLP</td>
<td>217</td>
<td>426</td>
<td>15</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Sp. Avg.</th>
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<th>CVr</th>
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</thead>
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<td></td>
<td>0.04</td>
<td>0.31</td>
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<td>0.94</td>
<td>0.97</td>
<td>0.38</td>
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</table>
Table 5.3 Required and supplied irrigation deliveries for the Sector No. 5 of the Sinistra Ofanto irrigation system during the 10-day and 30-day peak demand periods of the 2005 season

<table>
<thead>
<tr>
<th>HYDR. No.</th>
<th>COD No.</th>
<th>AREA (ha)</th>
<th>CROP</th>
<th>REQUIRED DELIVERIES</th>
<th>SUPPLIED DELIVERIES</th>
<th>ADEQUACY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>176-185 (m³/ha)</td>
<td>166-195 (m³/ha)</td>
<td>Max Freq. of Deliv.</td>
</tr>
<tr>
<td>2/1</td>
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<td>1.782</td>
<td>MTG</td>
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<td>9</td>
<td>316</td>
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<td>2/1</td>
<td>48351</td>
<td>1.375</td>
<td>MTG</td>
<td>211 654</td>
<td>9</td>
<td>465</td>
</tr>
<tr>
<td>2/2</td>
<td>49143</td>
<td>1.388</td>
<td>MTG</td>
<td>211 654</td>
<td>9</td>
<td>1205</td>
</tr>
<tr>
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<td>49145</td>
<td>0.979</td>
<td>MTG</td>
<td>211 654</td>
<td>9</td>
<td>721</td>
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<td>46483</td>
<td>1.102</td>
<td>MTG</td>
<td>211 654</td>
<td>9</td>
<td>1011</td>
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<td>46322</td>
<td>0.614</td>
<td>MTG</td>
<td>211 654</td>
<td>9</td>
<td>495</td>
</tr>
<tr>
<td>23</td>
<td>47084</td>
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<td>333</td>
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<td>46564</td>
<td>0.611</td>
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<td>414</td>
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<tr>
<td>20</td>
<td>46565</td>
<td>1.094</td>
<td>YLP</td>
<td>217 426</td>
<td>15</td>
<td>335</td>
</tr>
<tr>
<td>35/2</td>
<td>48952</td>
<td>1.125</td>
<td>YLP</td>
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<td>162</td>
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<tr>
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Sp. Avg. 0.76 0.65 0.58 3.11
STDV 1.22 0.68 0.41 1.91
CVR 1.60 1.05 0.70 0.61
Table 5.4 Required and supplied monthly and seasonal irrigation deliveries for the Sector No. 2 of the Sinistra Ofanto irrigation system during the 2005 season

<table>
<thead>
<tr>
<th>IDR. No.</th>
<th>COD No.</th>
<th>REQUIRED DELIVERIES (m³/ha)</th>
<th>SUPPLIED DELIVERIES (m³/ha)</th>
<th>ADEQUACY - RV</th>
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<tr>
<td>9</td>
<td>46356</td>
<td>0</td>
<td>617</td>
<td>660</td>
</tr>
<tr>
<td>22/2</td>
<td>49192</td>
<td>32</td>
<td>601</td>
<td>708</td>
</tr>
<tr>
<td>22/2</td>
<td>49192</td>
<td>32</td>
<td>601</td>
<td>708</td>
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<td>18</td>
<td>46232</td>
<td>85</td>
<td>626</td>
<td>458</td>
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<td>17</td>
<td>47031</td>
<td>4</td>
<td>690</td>
<td>904</td>
</tr>
<tr>
<td>17</td>
<td>47032</td>
<td>535</td>
<td>511</td>
<td>1003</td>
</tr>
<tr>
<td>22/1</td>
<td>49072</td>
<td>0</td>
<td>1101</td>
<td>742</td>
</tr>
<tr>
<td>17</td>
<td>47031</td>
<td>4</td>
<td>690</td>
<td>904</td>
</tr>
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<td>9</td>
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<td>0</td>
<td>690</td>
<td>1365</td>
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<tr>
<td>9</td>
<td>46353</td>
<td>1951</td>
<td>427</td>
<td>973</td>
</tr>
<tr>
<td>9</td>
<td>46352</td>
<td>0</td>
<td>0</td>
<td>162</td>
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</table>

Spat. Average

<table>
<thead>
<tr>
<th>Temp. Aver.</th>
<th>Val ass Ave</th>
<th>STDV.</th>
<th>CVr</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.71</td>
<td>0.72</td>
<td>0.27</td>
<td>-0.93</td>
</tr>
</tbody>
</table>

Val Ass Average

<table>
<thead>
<tr>
<th>STDV</th>
<th>CVr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.71</td>
<td>0.72</td>
</tr>
</tbody>
</table>

STDV

| 0.60 | 0.97 | 0.68 | 1.10 | 0.22 | 0.20 |

CVr

| 0.9 | 1.4 | 2.6 | 4.0 | 0.2 | 1.1 |

1.80
Table 5.5 Required and supplied monthly and seasonal irrigation deliveries for the Sector No. 5 of the Sinistra Ofanto irrigation system during the 2005 season

<table>
<thead>
<tr>
<th>IDR No.</th>
<th>COD No.</th>
<th>REQUIRED DELIVERIES (m³/ha)</th>
<th>SUPPLIED DELIVERIES (m³/ha)</th>
<th>ADEQUACY - RV</th>
<th>Temp. Aver.</th>
<th>Val ass Ave</th>
<th>STDV</th>
<th>CVr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M  J  J  A  S  TOT</td>
<td>M  J  J  A  S  TOT</td>
<td>M  J  J  A  S  TOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td>48354</td>
<td>281 273 914 295 287 2051</td>
<td>423 649 654 441 220 2387</td>
<td>-0.34 -0.58 -0.33 0.31 -0.14 -0.11</td>
<td>0.11</td>
<td>0.43</td>
<td>3.99</td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td>48351</td>
<td>0 1383 305 212 389 2288</td>
<td>423 649 654 441 220 2387</td>
<td>-1.00 1.13 -0.53 -0.52 0.77 -0.04</td>
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<td>0.92</td>
<td>29.79</td>
<td></td>
</tr>
<tr>
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<td>49143</td>
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<td>423 649 654 441 220 2387</td>
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<td>0.94</td>
<td>2.73</td>
<td></td>
</tr>
<tr>
<td>2/2</td>
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<td>0 371 995 389 362 2117</td>
<td>423 649 654 441 220 2387</td>
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<td>-0.08</td>
<td>0.08</td>
<td>8.94</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>46483</td>
<td>0 641 714 713 0 2068</td>
<td>423 649 654 441 220 2387</td>
<td>-1.00 -0.01 0.09 0.62 -1.00 -0.13</td>
<td>-0.26</td>
<td>0.26</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>46322</td>
<td>0 900 1104 213 0 2217</td>
<td>423 649 654 441 220 2387</td>
<td>-1.00 0.39 0.69 -0.52 -1.00 -0.07</td>
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<td>0.29</td>
<td>0.83</td>
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<td>47084</td>
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<td>522 1019 530 533 520 3124</td>
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<td>0.05</td>
<td>0.49</td>
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<tr>
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<td>46564</td>
<td>298 654 1025 748 114 2839</td>
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<td>0.70</td>
<td>1.11</td>
<td>1.58</td>
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<tr>
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<td>46565</td>
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<td>425 209 426 427 218 1705</td>
<td>0.49 2.33 0.47 0.62 -1.00 0.24</td>
<td>0.33</td>
<td>0.33</td>
<td>1.29</td>
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</tr>
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<td>0.08</td>
<td>0.08</td>
<td>0.97</td>
<td>12.28</td>
</tr>
<tr>
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<td>1.09</td>
<td>4.88</td>
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<tr>
<td></td>
<td></td>
<td>Spat. Average</td>
<td>-0.01 0.71 0.16 6.07 0.71 0.05</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Val Ass Average</td>
<td>0.01 0.71 0.16 6.07 0.71 0.05</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>STDV</td>
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<tr>
<td></td>
<td></td>
<td>CVr</td>
<td>83.60 1.64 3.74 0.11 0.52 4.20</td>
<td></td>
<td></td>
<td></td>
<td>17.92</td>
<td></td>
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</tbody>
</table>
The use of COPAM hydraulic model allowed generating a set of pressure head data at delivery points, thus allowing the computation of the Relative Pressure Deficit, \( RPD \), and the Relative Pressure Deficit Sensitivity, \( RPDS \), for all hydrants.

Following, the results of the above-described application are presented in the Tables 5.6 and 5.7 and Figs. 5.2 and 5.3.

Table 5.6 and Fig. 5.2 clearly show that the simulated performance of the distribution network of Sector 2 is acceptable in terms of available pressure heads at hydrants.

**Table 5.6** Assessment of performance achievable by the network of Sector No. 2 on simulated pressure heads at hydrants during the peak demand period of the 2005 season

<table>
<thead>
<tr>
<th>Hydr. N.</th>
<th>( RPD_{\text{MIN}} )</th>
<th>( RPD_{\text{MAX}} )</th>
<th>( RPD_{\text{RANGE}} )</th>
<th>( RPD_{\text{AVE}} )</th>
<th>( H_{\text{REQ}} )</th>
<th>( H_{\text{MIN}} )</th>
<th>( H_{\text{MAX}} )</th>
<th>( H_{\text{AVE}} )</th>
<th>( RPD_{\text{S}} )</th>
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<td>0.30</td>
<td>0</td>
<td>0.30</td>
<td>20</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>0.30</td>
<td>0</td>
<td>0.30</td>
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<td>26</td>
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<td>0.30</td>
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<tr>
<td>3</td>
<td>0.39</td>
<td>0.40</td>
<td>0.01</td>
<td>0.40</td>
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<td>27.8</td>
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\[
\text{Spat. Aver.} = 0.55 \\
\text{STDV.} = 0.74 \\
\text{CVr} = 1.35
\]
The majority of hydrants would have pressure heads higher than the minimum required ($H_{REQ} = 20$ m) for adequate operation of the farm irrigation systems, and relatively small fluctuations of the RPD will occur during the peak-demand period, but for most of hydrants these fluctuations would fall entirely in the positive range. Only hydrant 4, 9 and 13 may on some occasions suffer from slight relative pressure deficits, respectively, of -0.32 for hydrant 4, of -0.09 for hydrant 9 and of -0.28 for hydrant 13.

From Fig. 5.2 it can also be observed that both hydrants 4 and 13 have similar values of the hydrant sensitivity, but also that hydrant 13 is performing lower that hydrant 4 as its range of fluctuation is very small but all falling in the negative field, while hydrant 4 has a wider fluctuation of RPD but its range falls across the zero line and thus partly in the positive and partly in the negative ranges. This means that hydrant 13 has higher probability of low performance than hydrant 4, and that the severity of low performance for hydrant 13 is higher than that occurring to hydrant 9.
Table 5.6 shows also the estimated value of Equity expressed as the spatial variability (CVr) of the \textit{RPDS} over the sector during the peak-demand period and calculated through Eq. 5.19. By comparing the value of CVr with the reference standard values proposed in the Table 5.1 the equity of pressure head in the distribution network of Sector 2 can be ranked as “poor” as there is a large variability of pressure head conditions and of \textit{RPDS} among hydrants.

From Table 5.7 and Fig. 5.3 it can be inferred that the performance of the distribution network of Sector 5 would also be good in terms of pressure head for almost all hydrants. Only the hydrants 21, 32 and 33 may perform unsatisfactorily on some occasions, with the hydrant 21 having similar sensitivity than the hydrants 32 and 33 (values of \textit{RPDS} of 0.39, 0.27 and 0.32 respectively) and thus similar severity but higher probability of low performance (smaller \textit{RPD} fluctuations but all included in the negative range).

![Fig. 5.3 Performance achievable by the distribution network of Sector No. 5 in terms of pressure head based on simulated flow configurations](image)
Table 5.7 Assessment of performance achievable by the distribution network of Sector No. 5 on simulated pressure head data at hydrants during the peak demand period of the 2005 season

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<th>Hydr. N.</th>
<th>$\text{RPD}_{\text{MIN}}$</th>
<th>$\text{RPD}_{\text{MAX}}$</th>
<th>$\text{RPD}_{\text{RANGE}}$</th>
<th>$\text{RPD}_{\text{AVE}}$</th>
<th>$\text{H}_{\text{REG}}$</th>
<th>$\text{H}_{\text{MIN}}$</th>
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<th>CVr</th>
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Table 5.7 also presents the estimated value of Equity expressed as the coefficient of variation (CVr) of the \textit{RPDS} over the sector during the peak-demand period. Also in this case, the value of CVr is higher than 1.0 and thus, according to the proposed reference standard value of Table 5.1, the equity in terms of pressure head in the distribution network of Sector 5 can be considered as “poor” due to the large variability of pressure head conditions and of \textit{RPDS} among all hydrants.

5.5 The Study Area

The methodology for analyzing operation and performance of pressurized delivery networks was applied to two district delivery networks of an existing irrigation scheme located in southern Italy that is in urgent need of modernization due to its poor performance in terms of water delivery to farmers.

The actual operation of the distribution system under study, the resulting effects of the operational procedures on crop irrigation management, the low performance in water delivery and the need for system modernization, were all described in details in Chapter 2.

The Sinistra Bradano irrigation scheme (Fig. 5.4) is located in the western part of the province of Taranto and covers a total topographic area of 9,651 ha. The system is divided into 10 operational districts, ranging in size from a minimum of 353 ha to a maximum 1,675 ha. Each district is in turn subdivided into sectors that consist of a grouped number of farms. The water source is a storage reservoir located on the Bradano River in the nearby region of Basilicata, with a total capacity of 70 Mm$^3$, out of which 35 Mm$^3$ are usually available for irrigation of the Sinistra Bradano system.
Important conveyance and distribution losses are reported for the study area (INEA 1999), as only 16.4 Mm$^3$ are finally delivered to the cropped fields out of the total volume of 23 Mm$^3$ that is diverted from the reservoir. Water is conveyed to the area through a main conveyance canal, from which it is then distributed to farms by means of 10 open-branched district distribution networks. The entire irrigation system is subdivided into three operational portions that are commanded by progressive sections of the main canal. The water diversions from the main canal to the district distribution networks are controlled by cross-regulators and orifice-type undershot-gate offtakes that are manually operated by the WUO staff. The branched delivery networks consist of gravity-fed buried pipelines delivering water to farms with low pressure head.

![Overview of the Sinistra Bradano irrigation system](image-url)

**Fig. 5.4** Overview of the Sinistra Bradano irrigation system
The pressure at farm hydrants thus originates from the difference in elevation between the offtakes along the conveyance canal and the lower-elevation irrigated areas. The Sinistra Bradano irrigation system covers an overall cropped and irrigable command area of 8,636 ha. A large reduction in the area served by surface water from the WUO and a corresponding strong increase in the area irrigated by groundwater pumping was documented for the system in Chapter 2 based on records provided by the WUO. These changes in the serviced areas are most likely a consequence of poor conditions of water delivery with respect to farmers’ needs. The poor performance in water delivery, as well as the need for system modernization, was documented by previous research works conducted on the study area. As a result, at present many farmers rely mainly on groundwater pumping for irrigating their crops. Those farmers who still withdraw water from the delivery network need to use pumps downstream of the hydrants to adequately feed their irrigation systems, given the fact that the available pressure head at hydrants is not sufficient for proper operation of the on-farm trickle and sprinkler irrigation systems.

The delivery of water by the WUO usually starts by late April and ends by late October and the distribution networks are operated on a rotation delivery schedule. The rotation is fixed for the entire irrigation season with a flow rate of 20 l s\(^{-1}\) ha\(^{-1}\), with 5 hours of delivery to each user and a fixed interval of 10 days.

For the purposes of the present study, the inconsistency between the water delivery schedule currently enforced by the WUO and the crops’ requirements in terms of irrigation volumes can be inferred from the data presented in Table 5.8 where comparisons are made between required and delivered volumes and timings of irrigations during the 10-day peak demand period of the 2009 season, for the main crops grown in
the study area. Again, the required volumes and timings, as well as the maximum allowed delay (days) for avoiding yield reductions higher than 10% of the maximum achievable yield, were estimated through simulations run by the HydroGEN model and by the soil-water balance algorithm implemented in Excel worksheet, whereas actual deliveries were retrieved from records provided by the WUO. Based on the values reported in Table 5.8 it can be inferred that the current water deliveries are not matching crop needs. The values of Relative Volume, RV, show that in most of the cases the volumes delivered are excessive with respect to the estimated requirements.

**Table 5.8** Estimation of the adequacy of water deliveries in terms of volumes and timings of irrigation for the peak demand period of the 2009 season for the main crops grown in the study area

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<th>Crop</th>
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<th>Y TG</th>
<th>M WG</th>
<th>Y WG</th>
<th>M O</th>
<th>Y O</th>
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<th>Y C</th>
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**Legend:** MTG, YTG = mature and young table grapes; MWG, YWG = mature and young wine grapes; MO, YO = mature and young olives; MFO, YFO = mature and young fruit orchards; M TGc = mature covered table grapes; MC, YC = mature and young citrus; Veg = vegetables; M Alm = mature almonds
Only for mature wine grapes and vegetables the delivered volumes are not sufficient to fulfil the irrigation requirements during the peak period. The values of the Relative Frequency, RF, reveal that the current delivery schedule is inadequate for all the considered crops, except for the mature olive orchards. The crops suffering most for inadequate frequency of deliveries are the vegetables, table grapes and wine grapes. Also, the estimated values of the Relative Delay, RDe, show that several crops under the current delivery schedule receive water with delays with respect to the required irrigation timing that goes way beyond the maximum allowed delay for avoiding yield reduction higher than 10%. In other words, olive and fruit orchards as well as citrus and vegetable may face yield reduction way higher than 10% due to inadequate timing of irrigation deliveries.

Within the Sinistra Bradano irrigation system, two district distribution networks, namely Districts 7 and 10, were considered in the present study for the application of the proposed methodology, in view of their physical and operational features. Both the districts are located within the third and last operational portion in which the Sinistra Bradano system is subdivided, with the District 7 being at the initial part of this portion and the District 10 located at the last part, and thus being supplied by the tail-end section of the main canal.

The distribution network of District 7 (Fig. 5.5) serves 326 hydrants, supplying irrigation water to a total irrigable area of 586.6 ha of which 119.8 ha are cultivated with table grapes, 54.3 ha with olives, 162.3 with citrus, 58.9 with summer vegetables and 2 ha with almonds. At the design stage the total command area was subdivided into 20 irrigation sectors, whose size ranged from 20 ha to 36 ha.
The District 10 (Fig. 5.6) is composed by three sub-areas that are supplied by three distribution sub-networks originating from three different diversions along the last section of the main canal, namely the Division 7 (D7), 8-North (D8N) and 8-South (D8S). The sub-network D7 supplies 129 hydrants, serving a total irrigable area of 252.6 ha, out of which 198.5 ha are cultivated with citrus, 20.3 with table grapes, 19.6 ha with vegetables, 10.5 ha of olives, and 3 ha with orchards. The sub-network D8-N supplies water to 161 hydrants and serves an overall irrigable area of 661.2 ha, out of which 69.8 ha are cultivated with table grapes, 236.8 ha with citrus, 347.6 with vegetables and 4.9 with olives. The total irrigable area served by the sub-network D8-S is 445 ha, out of
which 81.3 ha are cultivated with table-grapes, 230.5 ha with citrus, 42.6 ha with olives and 75.5 ha with vegetables, with a total of 133 hydrants.

All hydrants in both districts are equipped with flow meters and with rubber-ringed flow limiters allowing for a maximum delivery of 10 l s\(^{-1}\) or 20 l s\(^{-1}\), according to the cropped area supplied downstream. These discharge values were used as nominal flow rates for simulations related to the current state and operation of the distribution networks. In simulating improved operational scenarios the flow rates at hydrants were instead set according to the estimated discharges required by the downstream cropped and irrigated fields.
5.6 Application of the Proposed Methodology to the Selected Irrigation Districts

A more flexible delivery was considered and simulated as alternative schedule to the fix rotation currently enforced in both the irrigation Districts 7 and 10 of the Sinistra Bradano irrigation system. Specifically, the simulations focused on a restricted-demand delivery to be implemented in both districts to allow more flexibility to farmers for better managing irrigation to their crops. The feasibility and performance achievable under this alternative delivery schedule were analyzed vis-à-vis to the physical features and constraints of the existing distribution networks.

For both the districts, applying the Hydro-GEN model to the existing distribution networks and to the cropped command areas allowed simulating the irrigation demand hydrographs and the resulting flow configurations during the 10-day peak demand period. The simulations were conducted by using climatic and crop data referred to the 2009 irrigation season and under the irrigation management scenario of full replenishment of the soil water depleted in the root zone, yielding the 10-day peak demand period as occurring in the interval DOY 197-206 (July 16th – 25th). Figure 5.7 shows the simulated demand hydrographs for both districts during the 10-day peak period.

Under the improved delivery scenarios the simulated demand hydrographs and flow configurations result from assuming the fulfilment of the required deliveries at farm level, which means that irrigation deliveries were simulated to occur according to the required volumes and timing as estimated by the HydroGEN model. In this way, the simulated deliveries in terms of volumes and frequency would occur in such a way to be adequate to the ones required for proper farm irrigation. In other words, the adequacy of
the simulated deliveries in terms of volumes and timing was set as pre-requisite for evaluating the network performance under the required flow configurations.

**Fig. 5.7** Simulated hydrographs of hourly flow rates (l s$^{-1}$) for the 10-day peak period during the 2009 irrigation season for the delivery networks of District 7 and District 10 of the Sinistra Bradano system
The flow hydrographs and the resulting flow configurations generated by the HydroGEN model were then inputted in the COPAM model for simulating the hydraulic behaviour and performance of the networks with respect to the target deliveries. The hydraulic performance was analyzed by using three main indicators, namely the Relative Pressure Deficit, $R_{PD}$, the Hydrant Sensitivity, $R_{PDs}$, and the Hydrant Reliability, $R$. Also for these applications, the Equity of the deliveries in terms of available pressure heads was estimated by using the Eq. 19.

As far as the network of District 7 is concerned, simulations of the restricted demand schedule on the existing delivery network show that poor performance would be achieved in terms of available pressure heads at hydrants and this would be most likely due to physical constraints and limitations. As can be seen from Figs. 5.8 and 5.9 showing $R_{PD}$, $R$ and $R_{PDs}$ obtained under this scenario, nearly all hydrants would fall in unsatisfactory state with respect to the pressure head necessary ($H_{REQ} = 20$ m) for proper operation of the farm irrigation systems.

For nearly all the hydrants the $R_{PD}$ would be way lower than zero, reaching for several hydrants very negative low peaks (up to values of −4.4). Only for very few hydrants, located in the initial and terminal portions of the network, the minimum required pressure conditions could be satisfied. At the same time, the reliability would yield value of zero for most of the hydrants, revealing unsatisfactory states, and thus insufficient pressure heads on most of the times that the hydrants would be accessed and operated by farmers.

As for the hydrant sensitivity, from the Fig. 5.9 it can be easily inferred that most of the hydrants have very negative value of the $R_{PDs}$. 
Fig. 5.8 RPD and $R$ values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 of the Sinistra Bradano system for the 10-day peak period during the 2009 irrigation season.

Fig. 5.9 RPDS values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 for the 10-day peak period during the 2009 irrigation season.
Figure 5.9 reveals either large fluctuations of the pressure head at hydrants occurring or the relative position of the minimum values of RPD being below the zero-line that represents the adequacy of delivery expressed in terms of pressure head.

Several physical improvements, and their effects on the hydraulic behavior of the distribution network, were simulated by using the available modeling tools in the sequence indicated in Fig. 5.1. In this set of simulations, a satisfactory performance was found to be achieved based on the following physical measures:

1. replacement of the flow limiters on all the hydrants, so as to reduce the maximum flow rate that can be withdrawn by users to 10 l s⁻¹ and thus reduce the occurrence of peak flows in the distribution network;
2. installation of a flow limiter at the upstream end of the district network, in order to limit the peak flow in the network to a maximum of 500 l s⁻¹ so as to ensure adequate delivery conditions at hydrant level;
3. increase in the total piezometric elevation at the upstream end of the network from the current value of 42 m to 82 m a. s. l. so as to ensure enough pressure head at all hydrants under the different configurations of hydrants in simultaneous operation.

Figures 5.10 and 5.11 show that, after implementing this set of physical improvements, the distribution network of District 7 would be capable of satisfying the necessary delivery conditions for proper operation of farm irrigation and allow adequate and flexible crop irrigation management to farmers.
Under the flexible delivery scenario and with the improved network, the RPD for most of the hydrants would be greater than zero, meaning that the available pressure head would be higher than the minimum required.

**Fig. 5.10** RPD and $R$ values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 after implementing the physical improvements

**Fig. 5.11** RPDS values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 after the implementation of the physical improvements
Only a few hydrants, corresponding to the numbers from 98 to 107, would have $RPD$ values lower than -0.4 with low peaks up to -1.32, denoting serious pressure deficits. These hydrants would thus not be capable of satisfying the required pressure head conditions, even if the piezometric head at the upstream end of the network is further increased up to 106 m. This is most likely due to the disadvantageous location of these hydrants in combination with the network layout and pipe size configurations that would cause high friction losses and make these few hydrants perform unsatisfactorily under most of the flow configurations. This aspect can also be noticed from the simulated reliability of hydrants under the simulated operation of the modernized network. For the majority of hydrants the reliability would reach values of 1.0, apart from a very limited number of hydrants having reliability lower than 0.7. In four cases, corresponding to the hydrants numbered 94, 104, 106, and 107, the reliability would approach values of zero, denoting the occurrence of unsatisfactory states every time these hydrants are operated.

As far as the hydrant sensitivity is concerned, by observing Fig. 5.11 the improved network seems to work pretty well, as the values of $RPDS$ for nearly all the hydrants, apart from the very few previously identified, would be very close to or higher than zero, revealing that the ranges of fluctuation of the $RPD$ would be small and/or that the minimum $RPD$ values would be mostly above zero.

Under this scenario, the Equity in terms of pressure head was estimated through Eq. 5.19 and expressed as the spatial variability, $CV_r$, of the $RPDS$ over the district during the peak-demand period. The value of Equity resulted of 1.03, thus revealing that under this improved scenario a large variability of pressure head conditions and of $RPDS$ among hydrants would still exist.
Comparing the computed value with the reference standards proposed in Table 5.1 allowed classifying the equity in terms of pressure head in District 7 with the upstream piezometric elevation of 82 m as “poor.”

From the analysis of hydraulic behavior of the network after the physical improvements it can be inferred that the few hydrants characterized by low performance should be operated separately from the rest of hydrants with the aim of ensuring adequate performance to the entire distribution network. In other words, these hydrants should be operated during low-peak demand hours in order to avoid excessive peak flows in the pipe network and thus the high friction losses resulting from limited pipe sizes or limited section capacity.

From Fig. 5.7 showing the demand flow hydrograph simulated for District 7 it can be seen that low-peak demand flows occur daily before 6 AM and after 6 PM and, so restrictions in the operation could be set to allow farmers accessing these hydrants within this specific time slots.

Further simulation runs show that a complete satisfactory state for all the hydrants under the peak flow configurations would require an upstream piezometric head of 106 m, as can be noticed from the Figs. 5.12 and 5.13 presenting the simulated \( RPD \), \( R \) and \( RPDS \) achievable under this improvement scenario. After this further increase to 106 m a.s.l. the estimation of Equity yielded a value of 0.49 that enables to classify the Equity under this improvement scenario as “fair,” as there is still variability of pressure head conditions and of \( RPDS \) among hydrants, but this variability decreased from the scenario with the piezometric elevation of 82 m a.s.l.
Fig. 5.12 *RPD* and *R* values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 after increasing the total piezometric head to H = 106 m a.s.l.

Fig. 5.13 *RPDS* values obtained simulating the restricted demand delivery scenario on the distribution network of District 7 after increasing the total piezometric head to H = 106 m a.s.l.

As for the District 10, simulations were run separately for each of the three distribution sub-networks (Diversion 7, \(D_7\), Diversion 8 North, \(D_8-N\), and Diversion 8 South, \(D_8-S\)) to evaluate the feasibility of the flexible water delivery schedule and to
assess the performance achievable with the existing network and under the improved scenarios. Nevertheless, only results related to the sub-networks D8-N and D8-S of District 10, which represent the very tail-ends of the entire irrigation system, are presented in this section.

Simulating the implementation of the restricted demand delivery schedule, the sub-network D8-N, as it is in the present state, would perform very poorly in terms of pressure head at hydrants. Figures 5.14 and 5.15 present the $\text{RPD}$, $\text{R}$ and $\text{RPDS}$ by the distribution network D8-N under restricted demand schedule. The values of these parameters in the figures clearly show that the network in its current state would not be capable of supplying water by restricted demand schedule with adequate performance, as all the hydrants except one would fall in unsatisfactory state. The pressure heads for all hydrants of the network would be much lower than the required ones.

![Hydrants Analysis](image1)

![Hydrants Analysis (reliability)](image2)

**Fig. 5.14** $\text{RPD}$ and $\text{R}$ values obtained simulating the restricted demand delivery scenario on the existing distribution network D8-N of District 10 of the Sinistra Bradano system
The value of the reliability at all hydrants, except for one, would be falling along the zero line, meaning that hydrants would be in unsatisfactory state every time they are operated. Figure 5.15 shows the occurrence of limited to medium fluctuations of pressure heads at hydrants, but all falling within the negative range.

Further simulations were run also for this sub-network to figure out the effects of physical improvements on its hydraulic behavior, and satisfactory performance would be obtained after the implementation of the physical improvements indicated hereafter:

1. limitation of the flow rate that can be withdrawn by users to 10 l s\(^{-1}\) by the installation of adequate rubber-ringed flow limiters at all hydrants;
2. increase of the total piezometric elevation at the upstream end of the network from the current value of 36 m a.s.l. to 86 m a. s. l. to ensure enough pressure head under the different configurations of hydrants in simultaneous operation.

**Fig. 5.15** RPDS values obtained simulating the restricted demand delivery scenario on the distribution network D8-N of District 10
Figures 5.16 and 5.17 present the results of simulations and the performance achievable by the sub-network D8-N after the indicated modernization measures.

**Fig. 5.16** $R_{PD}$ and $R$ values obtained simulating the restricted demand delivery scenario on the distribution network D8-N after implementing physical improvements.

**Fig. 5.17** Values of $RPDS$ obtained simulating the restricted demand delivery scenario on the distribution network D8-N of District 10 after implementing the physical improvements.
After the implementation of physical improvements, only a few hydrants, namely those between the numbers 106 and 121 and between 138 and 160, would still fall in unsatisfactory states due either to their disadvantaged locations or to physical constraints in the upstream pipe sections.

In order to achieve adequate performance in terms of pressure head, it is recommended to allow the operation of these hydrants during low-peak demand hours (6 PM to 6 AM) to ensure also for them the adequacy of deliveries in terms of flow rates and pressure heads. After this set of physical improvements the estimation of Equity yielded a value of 2.37 that reveals a very large variability of pressure head conditions and thus a “poor” level of equity among hydrants.

Alternatively, rising up the performance of these groups of hydrants to a satisfactory level, and avoiding at the same time the restriction of their operation during peak hours requires increasing the upstream piezometric head up to 140 m. Figures 5.18 and 5.19 present the simulated values of $\text{RPD}$, $R$ and $\text{RPDS}$ after rising the piezometric elevation up to 140 m a.s.l.

From these figures it can be noticed that an upstream piezometric elevation of 140 m would allow all hydrants performing more than satisfactorily in terms of pressure heads and that the values of the reliability indicator would be equal to 1 for nearly all hydrants of the network, meaning that the pressure head of delivery would be equal or higher than the required one every time that the hydrants are operated.

Also, the value of $\text{RPDS}$ for all hydrants, except for three, would fall in the positive range and for most hydrants would be way higher than zero and also would show quite limited pressure fluctuations. Under this improved scenario, the estimated value of
Equity would be of 0.34, showing a much smaller variability of pressure head conditions among hydrants with respect to the situation with the upstream piezometric elevation of 86 m a.s.l.

**Fig. 5.18** Values of $RPD$ and $R$ obtained simulating the restricted demand delivery scenario on the distribution network D8-N after increasing the total piezometric heat up to 140 m a.s.l.

**Fig. 5.19** $RPDS$ values obtained simulating the restricted demand delivery scenario on the distribution network of D8-N after increasing the total piezometric head to $H = 140$ m a.s.l.
By increasing the upstream piezometric elevation from 82 to 140 m a.s.l., the equity in terms of pressure conditions at hydrants would change from ‘poor’ to ‘good.’

Similar results were obtained simulating the restricted demand delivery on the sub-network D8-S in its current state. Figures 5.20 and 5.21 clearly show that the performance achievable by the D8-S network in terms of pressure heads would be very poor, as the values of $RPD$ would be way below the zero line, the values of the reliability would be zero and the value of $RPDS$ would be way below zero for all hydrants.

Similar physical changes as those proposed for the sub-network D8-N are necessary to the sub-network D8-S to make it capable of performing satisfactorily under the restricted demand delivery schedule. Figures 5.22 and 5.23 present the simulated values of $RPD$, $R$ and $RPDS$ after up-grading the network D8-S by means of the following physical measures:

1. limitation of flow rate that can be withdrawn by farmers to 10 l s$^{-1}$ by installation of adequate rubber-ring ed flow limiters at all hydrants;
2. increase of the total piezometric elevation at the upstream end of the network from the current value of 36 m to 86 m a.s.l.

From these figures it can be noticed that under the improved scenario only a few hydrants out of the total number, namely the hydrants numbered from 53 to 66 and from 165 to 178, would not achieve satisfactory performance in terms of pressure heads. Also in this case, it is recommended the access and operation of these groups of hydrants by farmers separately from all the rest and only thus during low-peak demand hours.

The Equity in this case would result “poor,” as the calculated value of 1.74 would reveal large variability in pressure head conditions among hydrants.
Fig. 5.20 *RPD* and *R* values obtained simulating the restricted demand delivery scenario on the existing distribution network D8-S of District 10 of the Sinistra Bradano system.

Fig. 5.21 *RPDS* values obtained simulating the restricted demand delivery scenario on the distribution network D8-S of District 10.
Fig. 5.22 Values of $RPD$ and $R$ obtained by simulating the restricted demand delivery scenario on the distribution network D8-S after implementing physical improvements.

Fig. 5.23 $RPDS$ values obtained simulating the restricted demand delivery scenario on the distribution network D8-S of District 10 after implementing of the physical improvements.

Results from simulations show that a further increase of the upstream piezometric head to 126 m a.s.l. would allow all the hydrants of the D8-S network performing
satisfactorily with respect to the required pressure head conditions, at any time they are accessed and operated by farmers.

Fig. 5.24 RPD and $R$ values obtained simulating the restricted demand delivery scenario on the distribution network D8-S after increasing the total piezometric head to 126 m a.s.l.

Fig. 5.25 RPDS values obtained simulating the restricted demand delivery scenario on the distribution network of D8-S after increasing the total piezometric head to $H = 126$ m a.s.l.
Figures 5.24 and 5.25 show that, after this further improvement, all the hydrants would achieve adequate or more than adequate performances, and specifically $RPD$ values higher than zero, $R$ values equal or very close to 1 and $RPDS$ values very close or higher than zero.

The estimated value of 0.39 would rank the Equity as “good” in this scenario and would show a strong reduction in the spatial variability of pressure head conditions at hydrant by rising the upstream piezometric head from 86 m to 126 m a.s.l.

For both the districts that were analyzed, physical improvements of the distribution networks entail the increase of the piezometric heads at the upstream ends so as to allow the demand flow configurations and offset all the resulting friction losses, also ensuring adequate delivery conditions. To address this aspect, a pump system can be designed and sized to operate either at a fix set-point or to modulate the flow rate and pressure head based on their characteristic curves and according to the downstream requirements. Assuming the operation of both districts by restricted demand, flow regimes in the pipe networks would vary with time based on configurations of hydrants in simultaneous operation. As a result, also friction losses would vary with time and so will also do the total dynamic head (TDH) that is needed at the upstream end of the network to offset head losses and to fulfill the pressure requirements at the delivery points. Under these conditions, a sound technical solution could be represented by pumping plants capable of adjusting both the discharge and TDH based on downstream requirements, and thus on the basis of system curves resulting from the flow configurations and from the configurations of hydrants in simultaneous operation in the distribution network. These technical features can be accomplished by means of variable speed pumps, in which
pump units are equipped with inverters and devices for modulating the speed and operate on the basis of specific hydraulic algorithms.

5.7 Summary and Conclusions

In this chapter, an innovative methodology aiming at diagnostic assessment of existing pressurized irrigation delivery networks was presented. The methodology entails the use of an agro-hydrological model for generating the demand flow hydrograph and flow configurations in the network, of a hydraulic simulation model to analyze its behavior under the generated flow configurations, and of a set of performance indicators to evaluate the delivery achievements with respect to target delivery objectives.

Both the agro-hydrological and hydraulic simulation models were tested and validated in previous research works and in different applications, proving their capability to forecast flow scenarios and resulting hydraulic behaviors with adequate accuracy.

The performance indicators were conceived for application to pressurized networks and were tested for validation on two irrigation sectors of a large-scale system of southern Italy on which water deliveries to farmers are recorded and stored at hydrant level for monitoring and for water billing purposes.

Finally, the proposed methodology was applied to a large-scale irrigation system in need of modernization, and specifically to two tail-end irrigation districts, and enabled the analysis of networks performances under different flow configurations. This application showed the usefulness of the combined analysis and simulation tools for addressing physical and operational aspects of modernization of poor performing delivery networks.
In this perspective, the proposed methodology can be utilized as an analytical framework for designing and sizing new irrigation delivery systems as well as for modernizing and re-engineering low performing systems, but also for assisting the management of irrigation schemes in developing operational plans and in avoiding situation of poor performance in water delivery to farmers.

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CHAPTER 6
GENERAL SUMMARY AND CONCLUSIONS

General Summary

The present research provided the capability to address the modernization of pressurized irrigation delivery networks by developing, testing and integrating analytical tools for conducting diagnostic performance assessment, simulation of alternative delivery scenarios and appraisal of improvement options. These represent the three main methodological steps entailed by the modernization process. Diagnostic performance assessment requires that target delivery objectives be clearly defined (objective setting) between the service provider and the service users, and that performance achievements be evaluated with regard to the targeted or agreed-upon objectives. Simulation of alternative scenarios and appraisal of improvement options entail modeling the hydraulic behavior of the network under different flow configurations, and require the capability to evaluate the resulting performance achievements by means of measurable variables.

Overall, the methodology developed in this research enables to conduct the above-indicated methodological steps in analytical mode and in the appropriate sequence with the aim of identifying and simulating the effectiveness of feasible improvements in the physical infrastructure and in the operation of low-performing pressurized irrigation delivery networks.
Conclusions

Assessing and enhancing the performance of irrigation systems constitute major goals for improving water resources management in the arid and semi-arid agricultural areas of the Mediterranean basin. These tasks can be accomplished through the analysis of operation of irrigation networks with respect to current and future performance objectives. This requires evaluating the main physical processes governing the behavior of irrigation systems by monitoring a set of operational parameters, or alternatively, using properly calibrated simulation models able to reproduce the systems’ behavior under different operating and flow conditions.

The enhancement of the HydroGEN model and its validation at different management levels in a modern irrigation delivery network addressed the challenging task of forecasting peak water demand hydrographs and flow configurations in pressurized distribution systems with the necessary accuracy to make the subsequent performance analysis reliable. The use of the HydroGEN model allows up-scaling the soil water balance simulations from the field to the network level, and translating the irrigation volumes required by the crops into discharges demanded by farmers during the peak period and under different on-farm irrigation management strategies. Some discrepancies between simulated and recorded data were noted while validating the model, that might result from small errors in the estimation of crop and soil parameters, and from the large variability of crops varieties and of irrigation management practices followed by farmers throughout the system under study. Further research should be conducted through the use of high-resolution multi-spectral remote sensing imagery acquired on multiple dates, so as to determine the evolution of crop parameters (canopy
cover and basal crop coefficient) and the crop variability with higher accuracy throughout the irrigation season. Monitoring the irrigation deliveries to farmers at hydrants is crucial to account for the variability in farmers’ irrigation practices and habits.

The integration between HydroGEN and COPAM models makes the results from the agro-hydrological simulations functional to the analysis of the hydraulic behavior of the network under different flow configurations.

The modification of performance indicators conceived for canal systems, their validation on modern pressurized delivery networks, and the proposed set of reference standard values enable managers, technical staff and auditors to evaluate the adequacy and consistency of actual deliveries relative to scheduled or targeted objectives. Further testing of the proposed indicators and reference standard values is recommended on systems operated with different delivery schedules in order to evaluate their reliability in operational analyses.

By applying the entire methodology to existing irrigation distribution systems, irrigation managers and auditors can easily identify the sensitive areas of the networks, where failures may likely occur or where water deliveries may be inadequate. The simulation and performance assessment components constitute valuable support in identifying the improvement options, in verifying their effectiveness, and in selecting the most promising measures for improving the overall delivery performance.

Overall, the proposed methodology can be utilized as a useful tool for designing and sizing new irrigation delivery systems as well as for modernizing and re-engineering low performing systems, but also for assisting the management of irrigation schemes in developing operational plans and in avoiding situation of poor performance in water
delivery. In either case, this methodology enables managers, auditors or designers to accomplish the required tasks on the basis of analytical assumptions.
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