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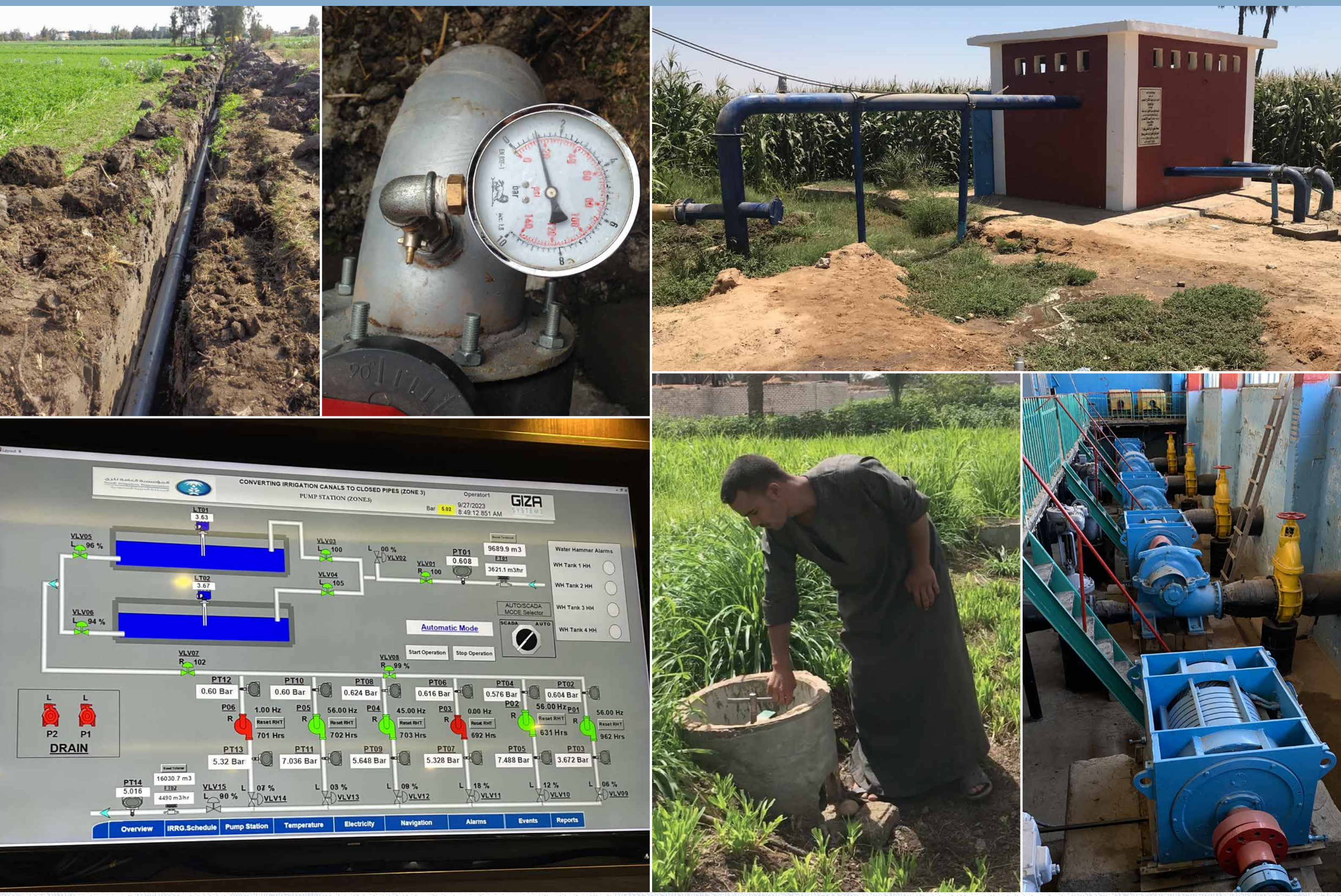
# Mapping System and Services for Pressurized irrigation systems – MASSPRES

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# Mapping System and Services for Pressurized irrigation systems – MASSPRES

FAO
IRRIGATION
AND DRAINAGE
PAPER
68

by
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# Table of Contents

# Boxes

# Figures

# Tables

# Acronyms

| | |
|---|---|
| **COPAM** | Combine optimization and performance analysis model |
| **EH** | pressure equity |
| **EQ** | discharge equity |
| **GMIA** | Global Map of Irrigated area |
| **HDPE** | high density polyethylene |
| **ICC** | Indexed Characteristics Curve |
| **IMT** | irrigation management transfer |
| **ITRC** | irrigation training and research center |
| **MASSPRES** | Mapping System and Services for Pressurized irrigation systems |
| **MASSCOTE** | Mapping System and Services for Canal Operation Techniques |
| **NPSH** | Net positive suction head |
| **O&M** | operation and maintenance |
| **PE** | polyethylene |
| **PIM** | participatory irrigation management |
| **PUH** | percentage of unsatisfied hydrants |
| **PVC** | polyvinyl chloride |
| **RAP** | Rapid Appraisal Procedure |
| **Re** | hydrant reliability |
| **RPD** | relative pressure deficit |
| **RPE** | relative pressure exceedance |
| **SCADA** | Supervisory Control and Data Acquisition |
| **WAPOR** | Water Productivity through Open-access of Remotely sensed data |
| **WDS** | water delivery service |
| **WUA** | water user associations |

# Symbols

| | |
|---|---|
| **a** | celerity |
| **C** | number of configuration |
| **d** | nominal discharge |
| $dH_1$ | change in water level |
| **D** | pipe diameter |
| $DH_{j,r}$ | relative pressure deficit |
| $\varepsilon$ | accepted tolerance |
| **ECw** | average electrical conductivity |
| **ET** | net crop water demand |
| **ETo** | reference crop evapotranspiration |
| **f** | Darcy–Weisbach friction factor |
| $H_{min}$ | minimum required head for the appropriate operation of the on-farm systems |
| $H_{j,r}$ | pressure head of hydrant |
| **g** | gravitational acceleration |
| **K** | number of hydrants |
| **Kc** | crop growth coefficients |
| $K_r$ | number of hydrants simultaneously operating |
| **j** | hydrant |
| $l_{min}$ | minimum length |
| **p** | elementary probability |
| $P_q$ | cumulative probability |
| **P** | pressure |
| $P_0$ | "operating point" of the network |
| **Q** | discharge |
| $Q_0$ | upstream discharge |
| $Q_{up}$ | several discharges |
| **Qtir** | discharge corresponding to K hydrants drawn at random |
| **q** | fractional change of discharge |
| **r** | generated configuration |
| **R** | total number of hydrants |
| **S** | sensitivity |
| $S_{hyd}$ | hydrant sensitivity |
| **t** | time |
| **V** | mean flow velocity |
| $Z_0$ | piezometric elevation |
| **z** | pipe elevation |

# Units

| | |
|---|---|
| **bar** | Bar |
| **dS/m** | Decisiemens per metre |
| **GB** | Gigabyte |
| **GHz** | Gigahertz |
| **ha** | Hectare |
| **l s-1** | Litre/second |
| **m** | metre |
| **m a.s.l** | metres above mean sea level |
| **MB** | megabyte |
| **$Mm^3$** | million cubic metre |
| **$m^3$** | cubic metre |
| **$ms^{-2}$** | metre per square second |
| **$ms^{-1}$** | metre per s second |
| **$Nm^{-2}$** | Newton per Square Metre |
| **Pa** | Pascal |
| **s** | second |

# Foreword

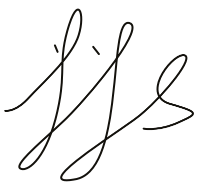
Water scarcity and intense competition for limited water resources are now driving private and public irrigation organizations to modernize their irrigation systems. During the 1960s and 1970s, pressurized irrigation systems were a focus of attention as they offered the potential for efficient water use, reduced disputes among farmers, and reduced the environmental problems that could arise from misuse of irrigation water. Thus, one option is to switch to pressurized systems.

Much of the work done in the past focused on designing and optimizing systems and FAO made substantial contributions to this effort producing several publications. In 1988, "Design and optimization of irrigation distributions networks" was published, followed by "Performance Analysis of On-Demand Pressurized Irrigation Systems" and a supporting computer software package (COPAM) in 2000, which enabled complex pipe networks to be optimized and system performance to be evaluated. In 2007, FAO developed Mapping System and Services for Canal Operation Techniques (MASSCOTE), a methodology for irrigation scheme performance and planning for modernization, which focused on large canal irrigation systems.

This publication builds on this work and adapts the MASSCOTE rationale to pressurized irrigation systems, known as MASSPRES: "*Mapping System and Services for Pressurized irrigation systems.*" This represents a significant output from the joint-collaborative program between FAO and CIHEAM-Bari.

Large pressurized irrigation systems serving many farmers is a complex area of planning and design. But the benefits in terms of simplifying system management and enabling farmers to irrigate on-demand to meet their crops water needs, rather than working to some rigid supply-oriented rotation, are immense. Every effort has been made in this publication to overcome the complexity with simple explanations and the use of practical examples, case studies, and user-friendly computer software, which together can facilitate understanding and application.

This publication will be of particular interest to irrigation planners and designers, and professionals involved in irrigation modernization and to those in universities and colleges who are involved in in-service training and preparing future generations of irrigation engineers and system managers.



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# Glossary

**Configuration**

A configuration is a group of hydrants operating at the same time across the irrigation system. The discharge required to satisfy all these hydrants at the same time is referred to as the discharge configuration.

**Equity** describes the spatial variability across an irrigation system and is a measure of the quality of service to farmers. In particular:

- **Discharge equity (DE)** measures the variation between actual discharge and nominal discharge among hydrants operating within a given configuration, or the variation taking account of all the generated hydrant configurations, or the variation among a pre-selected percentage of deficit occurrences.
- **Pressure equity (EH)** measures the variation in pressure among hydrants operating within a configuration, or the variation taking account of all the generated hydrant configurations, or the variation among a pre-selected percentage of deficit occurrences. The first case is relevant if pressure regulators are not installed at hydrants. The second and third are relevant when flow regulators are installed.

**Hydrant** is a hydraulic device specially designed to deliver water from a pressurized distribution system to an individual farmer or group of farmers. Hydrants should be equipped with a flow regulator to deliver the nominal discharge even when the pressure head changes. Ideally, a hydrant should also include a volumetric flow meter and a gate valve to open/close the discharge.

**Reliability** measures the probability that the pressure head at a hydrant at a given time is in a satisfactory state. It is a measure of the temporal variability of a system.

**Sensitivity** measures changes in hydrant reliability when changes occur in pressure and discharge at the head of a system.

**Steady flow (steady-state flow)** occurs when the flow remains the same over time at a given point in a system. Most pipelines are designed for steady-state flow. **Unsteady flow** (also called transient flow) refers to flows that vary over time at a given point in a system.

**System capacity** normally describes the volume of water that a system is capable of carrying in a given time. In the context of this paper, capacity refers to an integration of several concepts and indicators that show what the system is capable of, rather than just a "single indicator."

# Summary


In 2007, FAO produced Irrigation and Drainage Paper 63: *Modernizing irrigation management – the MASSCOTE approach* (Renault, Facon and Wahaj, 2007). This is a methodology specifically designed to assist technical experts, irrigation professionals, and managers, engaged in the difficult task of modernizing medium and large-scale canal irrigation systems.

MASCOTTE was developed to tackle the problems and deficiencies experienced in managing complex canal distribution systems. Although globally, most large-scale schemes use canals, there is a significant and growing interest, particularly in water-scarce regions, in medium and large-scale pressurized pipe systems. These received much attention in the 1960s and 1970s when many systems were installed, mainly in countries in the water-scarce Mediterranean basin and other regions. They offered many advantages over canal systems such as on-demand irrigation, which gave farmers greater flexibility in managing water on-farms, reduced water wastage and disputes among farmers, and less environmental impact from misuse of irrigation water. Today, many of these early systems are in need of modernization as cropping patterns and technologies changed and socioeconomic conditions improved. Water scarcity is increasing, and governments, faced with ever-increasing demands for water and food production, are also looking to switch technologies from canals to pressurized systems to reap the advantages that such systems offer.

Pressurized systems bring simplicity to irrigating farmers, but they are inherently complex both in terms of their design and operation in meeting the changing water demands associated with on-demand irrigation. To support both improving the performance of existing systems and the design of future systems, pressurized irrigation needs the equivalent of MASSCOTE methodology to provide a step-by-step process to diagnose deficiencies and establish plans for modernization.

This publication builds on the holistic approach of MASSCOTE to provide a framework for assessing and improving the overall performance of medium and large-scale pressurized irrigation schemes. Known as *Mapping System and Services for Pressurized irrigation systems* (MASSPRES), it introduces the MASSPRES approach and the step-by-step diagnosis of system performance. An important first step is the Rapid Appraisal Procedure (RAP), which is central to mapping the system performance. The complexities of managing demand under unsteady flow conditions are described together with innovative methods for assessing acceptable pressures and discharges at farm hydrants under a wide range of operating configurations rather than relying on the earlier methods of statistical analysis. Various indicators are developed to assess capacity, reliability, equity of distribution, sensitivity to change, and the risks of perturbation and incorporated into user-friendly software. Practical examples and case studies in Egypt, Italy, Spain, and Tunisia demonstrate the effectiveness of this approach and offer evidence-based solutions to improving performance.

# 1. Introduction

## 1.1 THE CHALLENGES FACING MEDIUM AND LARGE-SCALE IRRIGATION

This is a timely publication as the world is facing increasing water scarcity, and governments are demanding more efficient systems of water use, particularly in agriculture, which not only accounts for 70 percent of all freshwater withdrawals globally but has an unenviable reputation for poor water use efficiency. The average overall efficiency of irrigation systems, based on crop water use (evapotranspiration) divided by water withdrawals into the system, is estimated to be 55 percent, with figures ranging from 40-65 percent (Hoogeveen *et al.*, 2015)[1].

Over the past century, medium and large-scale irrigation schemes have made a major contribution to increasing global food production, reducing hunger and poverty, and securing the rural livelihoods of many millions of smallholder farmers. However, there have been significant discrepancies between design assumptions based mainly on bio-physical criteria, such as agronomy, hydraulics, and engineering, and the operational reality that falls short in terms of water use efficiency, productivity, and socioeconomic and institutional aspirations (Plusquellec, 2019)

Much investment has gone into improving infrastructure, building, rehabilitating, and modernizing schemes during the latter part of the 20th century, but with limited success. As well as the structural transformation of schemes, extensive changes in irrigation management are also taking place to support performance improvements. Participatory irrigation management (PIM) was introduced at different levels to improve the management and water delivery service to farmers. Irrigation management transfer (IMT) was also initiated in some countries. This involves transferring tertiary level water management from government control to groups of farmers or water user associations (WUA) to instil a sense of water stewardship among farmers and for system managers to focus on providing irrigation services for which farmer groups are expected to pay. This is a complex and site-specific issue, and so far, interventions have had mixed success.

Much of this criticism is aimed at large-scale canal systems, and although the above interventions were designed to achieve specific targets, they lacked the integrity of an absolute and coordinated modernization approach, which could transform a system into a well-engineered, well-managed, and efficiently operated scheme.

## 1.2 A METHODOLOGY FOR IMPROVING PERFORMANCE

In 2007, FAO produced Irrigation and Drainage Paper 63: Modernizing irrigation management – the MASSCOTE approach (Renault, Facon and Wahaj, 2007).

[1] The terms 'water use efficiency' and 'irrigation efficiency' have been, and continue to be, a subject of much misunderstanding and debate with many different definitions emerging as a result. In this paper, both terms are used in the general sense of making the best use of available water for producing crops and, from a farmer's point of view, ensuring that water they abstract for irrigation is consumed by the crop and is not wasted unnecessarily.

This is a methodology specifically designed to assist technical experts, irrigation professionals, and managers, engaged in the difficult task of modernizing medium and large-scale irrigation canal systems to use identified targets to establish effectiveness in terms of financial resources, water use efficiency, productivity, and the environment. Although mainly based on FAO's work in Asia, where many large-scale irrigation schemes exist and are underperforming for a variety of reasons, this approach is generic and is thus applicable to large surface irrigation schemes elsewhere. Its application has also been extended to countries in the Near East and North Africa region.

MASSCOTE seeks to stimulate a critical sense among engineers to diagnose and evaluate obstacles, constraints, and opportunities and develop a consistent modernization strategy. The methodology takes a step-by-step approach to convert complexity into simple and straightforward elements that can be tackled. These are explored in a recursive process leading progressively to a new approach to irrigation system management and improvements in canal operation and water delivery service.

## 1.3 APPLY THESE PRINCIPLES TO PRESSURIZED IRRIGATION SYSTEMS

MASSCOTE is an important asset for improving medium and large-scale canal systems, and, with some modifications, it can also be applied to medium and large-scale pressurized irrigation systems, which received much attention in the 1960s and 1970s. These systems offered greater flexibility in adopting on-demand irrigation, gave farmers greater flexibility in managing water on farms, reduced water wastage and disputes among farmers, and resulted in less environmental impact from misuse of irrigation water. Such systems were the focus of FAO Irrigation and Drainage Paper 44: *Design and optimization of irrigation distribution networks* (Labye, 1988) and FAO Irrigation and Drainage Paper 59: *Performance analysis of on-demand pressurized irrigation systems* (Lamaddalena and Sagardoy, 2000). These publications provided the foundations for designing and analyzing the performance of medium and large-scale (and complex) pressurized on-demand irrigation systems. Although pressurized systems have much to offer, many earlier schemes need modernization as cropping patterns change, technologies improve, energy prices increase and socioeconomic conditions change. Pressurized systems need the equivalent of MASSCOTE to provide a step-by-step diagnosis of system performance as a means of determining what needs to be done to improve system performance.

This publication now brings together this earlier work, mostly focused on the design and hydraulic analysis, with the more holistic approach of MASSCOTE to provide a framework for assessing and improving the overall performance of medium and large-scale pressurized irrigation schemes. Like MASSCOTE, MASSPRES is based on a step-by-step diagnosis of system performance as a means of determining what needs to be done to improve system performance.

**In summary**

**Chapter 1** Briefly introduces the challenges facing medium and large-scale irrigation systems along with methodologies to improve the performance of pressurized irrigation systems.

**Chapter 2** Introduces the MASSPRES approach and the step-by-step diagnosis of system performance. It describes the tools for identifying efficient and workable management strategies for operating pressurized irrigation systems to provide better service delivery. MASSPRES analysis comprises two phases. Phase 1 is an initial diagnostic phase to establish status and system operation, and phase 2 focuses on the development of a plan for modernization.

**Chapter 3** describes the Rapid Appraisal Procedure (RAP), which is central to mapping the system performance in phase 1. This is an approach developed by FAO and the Irrigation Training and Research Center (ITRC) at the California Polytechnic State University to enable irrigation scheme managers and farmer groups to work together during this initial phase. FAO recommends RAP because it focuses on key information that can be gathered quickly, it is systematic, and comprehensive and includes physical, management, and institutional aspects of system operation.

**Chapter 4** describes how to appraise the hydraulic performance of pressurized systems. It introduces the challenges of managing pressures and discharges in complex pipe networks under steady and unsteady flows, and when all hydrants are unable to operate on-demand at the same time. The chapter introduces COPAM v4.0 software, which is used to appraise system performance based on how systems perform in practice rather than the earlier design approach, which relied on statistical analysis. The software is developed around a set of innovative indicators that enable designers and managers to assess the acceptability of pressure and discharges at farm hydrants under a wide range of operating configurations. The chapter also introduces the concept of system capacity, which is developed in chapter 5.

**Chapter 5** develops the capacity concept and seeks answers to the question: does the pipe system have sufficient capacity to achieve the desired pressure and discharge requirements at each hydrant in the network? The indicators provide the information on which to answer this question. Models within the COPAM v4.0 software are described that enable the indicators to be calculated, and information is provided on how to interpret the results. Case studies show how the indicators are used in practice.

**Chapter 6** focuses on the concept of equity and the development of two indicators: pressure equity, which indicates how capable the system is at maintaining acceptable pressures at the farm hydrants, and discharge equity, which performs the same function for discharges at the farm hydrants. As the publication is restricted to systems that use flow regulators, only pressure equity is described. A case study is used to demonstrate the practical use of this indicator.

**Chapter 7** focuses on the concept of sensitivity. Although the pressure at hydrants is key to good performance on the farm, there are many changes that occur in a network, such as farmers opening and closing hydrants that cause upstream system pressure and discharge to fluctuate. Just how such fluctuations affect the pressure at the hydrants is described as sensitivity. A case study is used to demonstrate the practical use of this indicator.

**Chapter 8** describes the phenomenon of perturbation and the development of an indicator to measure it. Perturbations are sudden pressure changes in the system, also called 'water hammer,' which can seriously damage and, in severe cases, burst pipes. A perturbation indicator, called Relative Pressure Exceedance (RPE), provides information on the pressure head that may occur in the system when hydrants are suddenly closed or when pumps start and stop. Two different boundary conditions are considered, supply from a reservoir and from a pumping station, as this has influence over the pressure changes that may be experienced in a system.

**Chapters 9 and 10** offer case studies where modernization has taken place. The authors use MASSPRES to show how this approach can identify problem areas and offer evidenced-based solutions to improve performance.

# 2. Mapping System and Services for Pressurized irrigation systems

MASSPRES is based on a step-by-step diagnosis of system performance. It is a set of tools to identify efficient and workable management strategies for operating pressurized irrigation systems to provide better service delivery. The analysis is in two main phases:

1. An initial diagnosis phase to establish the current status and system operation. This provides ground-truth evidence about how the system functions, how it is managed and organized, and the quality of service it delivers to farmers.
2. The next step involves developing a modernization plan based on the diagnosis, which focuses on operating the system. Both users and operators play important roles in operating the system, its management, and service delivery, and so MASSPRES uses a participative approach to developing the plan.

## 2.1 A STEP-BY-STEP FRAMEWORK

MASSPRES uses a step-by-step process to:

- map the salient features of the system;
- identify and delineate the institutionally and spatially manageable building blocks of system operations and management; and
- identify the best strategies for the operation and service delivery of each building block.

### 2.1.1 Mapping - Phase 1. Initial diagnosis

Steps 1-5 are about collecting baseline information.

1. ***Mapping the system performance through RAP***
   A rapid appraisal of the system is performed using the RAP tool (see chapter 3). The appraiser adopts a systematic approach to assess the scheme water balance, status of the irrigation and associated infrastructure, cost of operation and maintenance, management and operational strategies, and water delivery service. This assessment identifies and scores system indicators that can be targeted in the modernization plan. These indicators are benchmarks that can also measure progress during any intervention. As MASSPRES encourages users' participation, this enables all stakeholders to engage in prioritizing plans.
2. ***Mapping the system capacity***
   System capacity is mapped to get an insight into the system's ability to serve demand. More specifically, this mapping assesses the dimensions of system components against the requirement of conveyance and distribution of water at a given level of discharge and pressure at the farm hydrant. The overall analysis of the hydraulic performance of the pressurized distribution system is described in chapter 4, while the in-depth description of analyzing the system capacity is described in chapter 5.
3. ***Mapping system equity***
   Equity is mapped to evaluate how uniformly the system pressure and discharge

are distributed among the hydrants. For this purpose, two equity parameters i.e., pressure equity (EH) and discharge equity (EQ) are elaborated in chapter 6.

4. *Mapping system sensitivity*

   The sensitivity of the hydraulic network is mapped to evaluate the change in hydrants' discharge due to changes in discharge and/or pressure at the head of the system. Sensitivity mapping is described in chapter 7.

5. *Mapping system perturbation*

   In this step, the magnitude and frequency of perturbation in the distribution network are mapped. Perturbation is usually caused by sudden changes in the system, such as the closure of gate valves, changes in the configuration of operating hydrants, or stopping/starting pumps. The causes of perturbation and remedial measures are discussed in chapter 8.

### 2.1.2 Mapping - Phase 2. Service-oriented management and system operation

Steps 6 to 11 are about mapping a vision for service-oriented management (SOM) and modernization.

6. *Mapping services*

   This involves assessing all the different services provided to different users and their related costs. This is needed to analyse modernization options and to establish a preliminary vision for the scheme. Options include different service categories, the level of flexibility, and the allocation and scheduling of water deliveries.

7. *Mapping management*

   Large schemes are often divided into sub-units for operation and maintenance (O&M) purposes, including defined levels of service, which may differ from one sub-unit to another. Within each sub-unit, a workable compromise is required among a mix of criteria, including the physical and hydraulic system, the institutional and managerial resources in each sub-unit, and the costs involved.

8. *Mapping system operation and its improvement*

   This is about assessing the resources, opportunity, and demand for improved system operation. This is largely determined by the anticipated level of service to farmers, but the analysis will need to include the constraints imposed by the operating characteristics of the pipe system, including the extent of perturbations and the sensitivity of structures to changes in supply and demand.

9. *Options for improving system performance and management*

   This is about specifying how existing water resources and inputs will be allocated in a more cost-effective and responsive way, changing the operational strategy, and investing in improved techniques and infrastructure. Modernizing a system should make full use of advanced concepts in irrigation and hydraulic engineering, agronomic science, economics, and social science to identify the simplest components and a workable solution.

   Extensive farmer participation will form an important part of selecting the most appropriate option to pursue. There is a wide variety of design concepts, structures, methods of control, and schedules, and it is essential that farmers at the downstream end of the system are fully satisfied with the proposed quality of service.

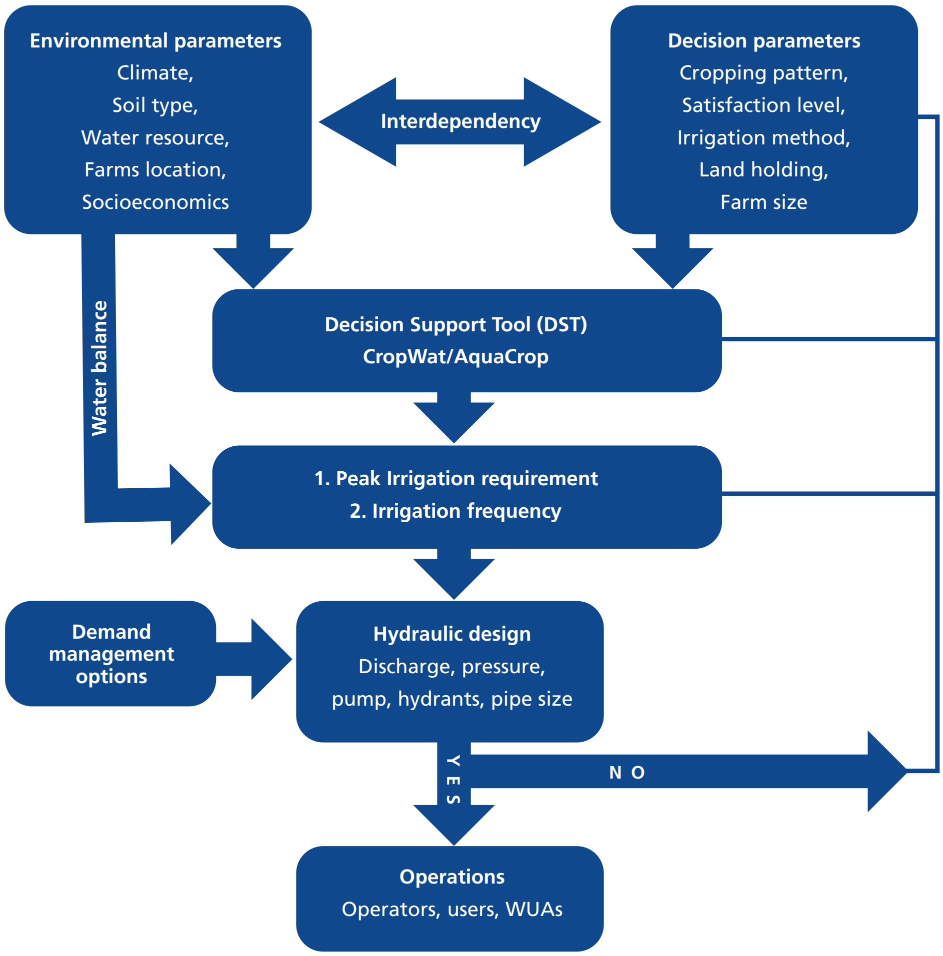
10-11. *Integration of service-oriented management options, and developing a modernization plan*

Based on the mapping in steps 1-9, it should be possible to develop a vision for irrigation and a plan for implementation. The performance will only improve if designers and operators have a common and well-defined vision of operation procedures and maintenance requirements, if performance standards are precisely defined at each management level, and if there is an appropriate incentive structure. Monitoring and evaluation will also be part of the process of modernization to ensure that objectives are achieved and maintained.

## 2.2 DESIGN CRITERIA AND IMPACTS ON IRRIGATION SYSTEMS PERFORMANCE

Pressurized irrigation systems are designed to improve system performance and enhance farm profits (Kurtulmus *et al.*, 2018). The first objective is achieved by improving irrigation reliability and reducing the system's conveyance losses, while the net profit is increased by controlling unnecessary irrigation water fees and increasing crop productivity. The optimum designed capacity of a pressurized irrigation system depends on several parameters, which can be classified into the following two groups, environmental parameters and decision parameters (Lamaddalena and Sagardoy, 2000) (Figure 2.1).

FIGURE 2.1
**Design outline of a pressurized irrigation system**




*Source: Authors' own elaboration.*

### 2.2.1 Environmental parameters

Designers have little control over environmental parameters that are largely responsible for the irrigation system's overall water demand. These include:

- climate conditions
- physical properties of soil
- water resources infrastructure
- location of water resource
- socioeconomic condition

Climate data are used to calculate crop evapotranspiration, which is the primary environmental demand. This combines with crop characteristics, such as growth stage coefficients; and soil characteristics such as infiltration rate, field capacity, wilting point, and management allowable depletion to establish the amount and frequency of irrigation using decision support a tool such as FAO's CropWat (Smith, 1992), or crop-water productivity models, such as FAO's AquaCrop (Steduto *et al*, 2012).

Data on water resources and infrastructure, such as storage reservoir(s), is required to compare water demand with water availability during periods of peak demand. The location of the water resource is also important as this determines the design of the conveyance system.

Account must also be taken of the socioeconomic circumstances of the farmers as they determine the size, location, and layout of individual land-holdings and the method of irrigation used on the farm.

### 2.2.2 Decision parameters

Designers have more control over:

- cropping pattern
- demand satisfaction
- irrigation application method and land holding
- density and location of hydrants
- design discharge of hydrants
- operation and maintenance (calibration, validation)

Cropping patterns are mostly driven by climatic conditions, particularly temperature, and by market demand for agricultural products. The system must be capable of meeting the peak crop water demand based on the cropping pattern, and the climatic conditions as these determine the capacity of the conveyance network. For this purpose, a thorough investigation of the water balance should be undertaken to cover multiple decades. The system should be capable of meeting the peak demand for at least 80 percent of the time (Lamaddalena and Sagardoy, 2000). The water balance should be corrected for the overall efficiency of the irrigation system, taking into account the reservoir storage, the conveyance through different modes or structures, and the on-farm water application efficiency. In locations where there are water shortages, alternative management solutions should be recommended, such as partial cultivation of the command area, border strip/furrow irrigation, or deficit irrigation in order to achieve the optimum yield. Designers must also have access to the cadastral maps or satellite imagery of the project area at an appropriate scale. It is advisable that the spatial information of agricultural land and residential plots be integrated with the ownership and demographic data of the area to identify the exact area (ha), number, location, and type of the landholdings of an individual farmer. This will facilitate locating the most appropriate position and capacity of hydrants for efficient operation. The maps should always be kept updated by describing the layout of the irrigation and drainage networks. Additional features such as the location of pumping stations, regulation, protection, and control equipment, surface reservoir(s), and access routes should be clearly marked on the maps or identified on satellite images.

## 2.3 OPERATION, MAINTENANCE, AND MANAGEMENT

Although operation, maintenance, and management are usually grouped together, they are fundamentally different in terms of required skills, budgetary allocations, and institutional responsibilities.

Operation is related to the day-to-day adjustment of pressure and discharge of the irrigation system to ensure service delivery according to the farmers' (users') requirements. The fundamental skill required for this activity is to identify the issues and constraints expressed by farmers who require water service delivery, reading the pressure and flow gages, opening and closing flow control components, and operating the pumping units.

Maintenance deals with diagnosing and rectifying malfunctions to ensure that the system continues to perform to its designed capacity. This requires moderate to high skill levels. Preventive maintenance is carried out on a seasonal or periodic basis, and curative maintenance covers urgent circumstances and failures.

The system management deals with long-term strategic modifications and changes to operating procedures to achieve the objectives in the areas of system automation, efficiency enhancement, safety practices, and environmental sustainability. Operating the system often provides the data and information to execute the maintenance and management inputs.

## 2.4 OPERATIONAL OBJECTIVES

The essential purpose of an irrigation system is to efficiently provide irrigation water to farmers at the point and time of their desire to get optimum crop yields. Besides this broad objective, the following are the specific modes of irrigation system operation (Renault, Facon and Wahaj, 2007).

- The pre-scheduled operation plans under generalized field and environmental conditions are subject to change to accommodate changes that occurred due to updated crop water requirements, changes in water availability at the source, and modification to the system hydraulic parameters. This is called predictive operation; it also involves seasonal tasks such as filling the pressurized irrigation network at the start of the season.
- Smooth operation requires minimizing perturbation (changes in operating pressure or discharge) caused by sudden changes in water requirements, such as in the event of a heatwave or rainfall. Perturbation can be minimized by adjusting the settings of control devices either manually or electromechanically to ensure

system safety and to stabilize operations. This operation mode can be termed as the reactive operation.

- The irrigation system must go under a rigorous monitoring and evaluation process at predefined intervals. Monitoring and evaluation are intended to help system managers and operators in decision-making and to ensure proper service delivery to farmers. Monitoring and evaluation involve comparing actual vs intended physical status of the irrigation infrastructure and its various components (pumps, control devices, discharge regulators, pressure gages, etc.), comparing actual vs design system variables, such as discharge and pressure at the critical points, and the quality of service delivery (reliability) to farmers.

## 2.5 FUNCTIONS OF PRESSURIZED SYSTEMS STRUCTURES

Irrigation system operation is defined as executing a set of specific procedures and rules to perform a function. The network of pressurized irrigation infrastructure is a set of interconnected hydraulic structures or components to ensure several functions. The structures or components of a network and their specified functions are as following:

### 2.5.1 The storage function

The purpose of the storage function in a watershed is to collect and store runoff from rivers and streams by excess rainfall to deliver it more conveniently and at a critical time according to the user's requirement. Depending on its size, operating rules, and storage location, the lag time between reaching a specific storage level and its distribution through the network may have different time steps varying from a few hours to years. A surface reservoir behind an embankment is always required to ensure the storage function. It is important to distinguish between the surface storage reservoir upstream of the service area and the inline or intermediary storage reservoirs. The coordinated releases of water from these reservoirs according to the crop water requirement of the service area, system lag time, and carrying capacity of the pressurized irrigation system ensures the proper use of the storage function.

Moreover, a comprehensive storage function should also account for the potential contribution of groundwater aquifers. Groundwater storage can significantly reduce the lag time and conveyance losses when incorporated correctly in a storage function. However, it is also important to ensure that the groundwater withdrawal is sustainable. The sustainability of groundwater aquifers can be increased by incorporating conjunctive surface and groundwater management to ensure aquifer recharge.

### 2.5.2 The conveyance function

The conveyance function in a modern pressurized irrigation system comprises surface or buried conduits of concrete, steel, polyvinyl chloride (PVC), polyethylene (PE), or high density polyethylene (HDPE) with a protective coating to withstand environmental degradation. In relatively larger irrigation systems, this function comprises a combination of pipe conduits and open channels to optimize cost and conveyance efficiency. The pipe system used for the conveyance function can either be fully pressurized and capable of conveying water against the topographic gradient or open to the atmosphere in which the water is conveyed under gravity.

### 2.5.3 The diversion function

The diversion function is a procedure to divert water towards the conveyance system, which carries it to the service area. Water is diverted to the conveyance system in several ways, the most common being a diversion weir or cross regulator constructed across rivers, streams, and main canals. This structure can be gated or ungated, and it raises the water level in the upstream vicinity of the main stream to the desired level, which is enough to feed the low pressure off taking pipes. Diversion through pressurized pipes can also be accomplished by installing submerged outlets under the live storage level of storage dams or with high capacity pumping into the pressurized conveyance system. Each arrangement depends on the topographic condition of the area and the distance from the service area to water sources.

### 2.5.4 The distribution function

Distribution is a function to divert water and distribute it among the key points of the service area (hydrants). In most cases, a network of surface or buried pressurized pipes is used to perform this function. These pipes are classified as main lines, sub mains, branches, and distributors based on their diameter, nominal pressure, and length and make up the on-farm distribution network. Water is distributed across the network according to a design criterion.

### 2.5.5 The delivery function

In a modern pressurized and fully demand-based irrigation system, water is delivered to the users according to the crop water requirement on their cultivated land. In this case, the water source is usually not constrained. However, for a restricted water source, a rationing delivery function is recommended to ensure equitable water availability for all users on the network. This type of distribution is accomplished by a rotational plan. A properly conceived distribution function is intended to enhance the equity and reliability of water availability at the service points in terms of flow and pressure.

### 2.5.6 The control function

For the proper operation of a conveyance and distribution network, an appropriate control function must be in place. For pressurized irrigation systems, the control function regulates and maintains a live operating pressure, ensuring that all outlets or hydrants operate normally. Pressure valves and flow regulators are used for the control function.

### 2.5.7 The safety function

The safety function safeguards the physical integrity of the pipe network. A pressurized irrigation system branches from source to sinks. Therefore, the carrying capacity, or discharge, and the operating pressure vary gradually along this system. Excessive pressure in the pipe system can also build due to unsteady flow conditions caused by hydrants' sudden opening and closing. A safety function with the help of pressure release or overflow valves can dispose of excessive pressure and/or discharge to safeguard the physical infrastructure.

### 2.5.8 The measurement function

The irrigation system management involves regular decision-making to maintain the system in running condition and assess the water delivery charges. Therefore, such information must be obtained at the system level, which can help organize an appropriate response at a proper time. For this purpose, monitoring discharge and pressure through a measurement function using suitable devices, such as inline flow meters, venturi meters, and ultrasonic pipe flow meters at key junctions and points in the network is important for the system managers and operators.

### 2.5.9 The information transmission function

The purpose of a proper information transmission function is to ensure that the data collected in the field are available in real or near real-time in the decision-making centres so that quick and accurate decisions are made to respond to the system dynamics. Nowadays, the information transmission function is performed by wireless equipment coupled with the sensory instrument installed on the irrigation network and is widely termed as Supervisory Control And Data Acquisition (SCADA) system. SCADA can play a crucial role in the water management of large-scale pressurized irrigation systems; it can monitor soil moisture in near-real time and allow irrigation start/stop messages to be sent to the control system.

### 2.5.10 The information management function

The information management function is not an integral part of the physical irrigation network. It is a sequence of corresponding data processes such as compiling, analyzing, extracting information and archiving. It also supports the organization's plans for improvements, expansions, and modernization.

## 2.6 TYPES OF DELIVERY SCHEDULES

In any irrigation scheme, irrigation water is delivered to each branch of the distribution system (open or pressurized) from its parent branch and ultimately to the farmer's turnout or hydrant under different arrangements called delivery schedules. The selection of a specific delivery schedule for an irrigation scheme depends upon several factors, i.e., the type of irrigation system, availability of water at the source, the capacity of the conveyance and distribution system, cropping pattern, and peak demand. Different types of water delivery schedules are defined by specific delivery characteristics, i.e., frequency of delivery, delivery rate, delivery duration, and delivery timeliness. There are four main types of irrigation delivery schedules widely reported in the literature (Clemmens, 1987) and described below.

### 2.6.1 Rotation schedule

Rotation is a rigid delivery schedule that provides no flexibility in irrigation delivery frequency, rate, and duration. In this arrangement, a delivery schedule is made in the central project office. A fixed flow rate is sanctioned for each branch of the distribution network with a fixed frequency of rotation, typically a week or ten days. The duration of a fixed flow rate is then computed proportionally to the size of the landholding of each farmer so that all the farmers have an equal volume of water per unit of irrigated land during one rotation. There are also some variants of the rotation schedule in which the frequency or duration is varied a few times during a growing season to compensate for varying evapotranspiration needs.

In a rotation schedule, every farmer knows the exact time and duration for which (s)he would receive irrigation water and is aware of under irrigation. Therefore, the rotation delivery schedule is widely suited for cereal and deep-rooted crops. Farmers in semi-arid regions, where groundwater abstraction is economically feasible, enjoy some level of flexibility in the frequency and duration of irrigation by utilizing groundwater conjunctively. In some cases, there is also an informal exchange of irrigation turns among farmers with mutual agreement. Another modification to the rotation schedule in small community-based irrigation schemes is the sharing of irrigated land, whose size is determined by water availability at the source. In exceptional cases, a rotation delivery schedule can be used with a pressurized irrigation system during the period of peak water requirement. In this case, the delivery is directed to a fixed proportion of irrigators for the first half of the rotation cycle, while the remaining irrigators receive water in the second half of the rotation cycle.

### 2.6.2 Centralized schedule

Centralized scheduling is a “top-down” approach with the possible assumption of unsteady flow conditions and knowledge of cropping patterns and crop water requirements. The centralized command executes the schedule to determine water deliveries at all service points within an irrigation scheme. This schedule is not responsive to the farmers’ demand because its foundation assumes that it is impractical to get feedback from many farmers or groups of farmers. The centralized command has an in-depth understanding and knowledge of water demand in the service area. That is why centralized scheduling is not a flexible schedule in a real sense, and its flexibility only works in the top-down direction. It does not account for the variation in demand at the farmers’ end. In a few circumstances, the centralized scheduling can be justified, i.e., when water is scarce and the objective is to distribute the scarce resource among as many irrigators as possible, or delivery sans fee, i.e., when there is no institution to fix the market value of water.

### 2.6.3 Arranged schedule

The most convenient schedule for delivering irrigation water to farms equipped with on-farm irrigation technologies is the arranged schedule. Irrigation water demands are calculated and requested automatically or semi-automatically using electronic devices with or without human guidance for a particular day, flow rate, and duration. The information is then forwarded to the irrigation project authority. Occasionally, limitations may be applied on maximum flows during peak water demand periods, which can be managed accordingly at the farm level by adjusting the duration of irrigation. This type of delivery schedule requires close coordination between the user and project authority, and demands can be made in advance to provide enough time for sanctioning the delivery. The flow rate and duration of irrigation are prearranged when the requests are made at short notice. However, the farmer may have the option to request a desired flow rate and/or duration if the request is put forward well in advance. The farmer has the freedom to self-operate the field hydrant at the prearranged time. During peak demand, water can be allocated to the users on a volumetric basis to respect the right of access to water of the larger group of users. In the arranged schedule, water is charged based on per unit volume consumed. That is why the field turnouts must be metered individually or at the WUA level to avoid conflicts. The arranged schedule is well suited for modern irrigation schemes, including pressurized irrigation systems. It has been successfully adopted in California, Mexico, Columbia, and North Africa in irrigation districts with various field sizes ranging from 5 to 50 hectares.

### 2.6.4 Demand based schedule

In a limited rate demand schedule, there is no need to make a request because water is always available on demand. Such a delivery schedule can also be called “on-demand”.

For on-demand systems, the hydrant discharge must be fixed with appropriate flow regulators. On a small scale, water delivery from a privately owned tube well is an option. On a larger scale, the limited rate demand delivery schedule requires a very flexible distribution system capable of responding automatically to the start and stop of the turnout (hydrant) flow. Good examples are the Canal de Provence in France and the Capitanata Consortium in Italy.

## 2.7 COMPONENTS OF A PRESSURIZED IRRIGATION SYSTEM

Pressurized irrigation systems are often demand-driven, and were developed to increase the flexibility and reliability of irrigation at the service point. The selection of appropriate components is an integral part of the pressurized irrigation system design, which aims to meet the crop water requirement of the service area. These major components of the irrigation system are the following:

### 2.7.1 Storage unit

When the water source for a pressurized irrigation system originates from a stream or canal that operates on a rotation delivery schedule, water from the source is diverted to a nearby or on-farm storage unit. The stored water is then distributed through the pressurized distribution system according to the design criteria. Large-volume storage tanks are ideal for storing enough water to meet the peak water demand, but there is a need to consider the opportunity cost of the land occupied with the storage. An optimal size can be determined based on the cost of increased depth or reduced service flexibility. If natural topographic depressions are available near the project site, converting them into a sump can be more economical. The site of the proposed storage unit should be appropriately secured to ensure the safety of the farmers and grazing livestock. Lining the storage unit with HDPE geomembrane or plastic mulching should be provided to avoid seepage. The construction of appropriate inlet and outlet structures is also essential to prevent damage to the banks during filling and pumping.

### 2.7.2 Pumping unit

The pumping unit is the most important component in pressurized irrigation systems. Pumps lift the water from the storage or source and inject it under the required pressure into the distribution system. The pump selection with an appropriate capacity is a critical design parameter. Before the pump selection, the maximum design discharge and required pressure at the highest point in the scheme must be known. With this information, several pump characteristic curves are then assessed to select one which can satisfy the required conditions with the highest possible efficiency. Following this, the Net Positive Suction Head versus Discharge (NPSH-Q) curve should be evaluated to ensure that the available NPSH is greater than the required NPSH. The pump should also be capable of operating at different impeller speeds to match the required discharge. This is particularly helpful when the irrigation system runs at partial capacity during the early crop growth stages. Several options are available on the market to power the pump, such as electric-powered pumps, pumps driven by diesel engines, and solar-powered pumps. The selection depends on the available power source and cost. Solar-powered pumps have minimal operating cost, but the duration of the operation is primarily governed by the irradiance and sunshine hours.

### 2.7.3 Conveyance and distribution network

Conveyance and distribution networks consisting of pipelines have several advantages. They are considered the most efficient means of distribution in terms of water-saving and their ability to transmit pressure facilitates the execution of flexible irrigation deliveries. When the conveyance and distribution network is buried, it does not interfere with the movement of farm machinery, the right of way is always clear, and the natural drainage channels are not intercepted, thus reducing the cost of additional cross drainage works. With the piped network, the irrigators have the flexibility to turn the flow on or off. This action generates a remote response conveyed through the pressurized network to start low-pressure flow under gravity from a source of water or turn on a pump to supply the need in terms of flow rate, duration, or frequency. Since it is difficult or costly to intervene with the alignment and size of the pipes once they are installed, the designer needs to take great care in choosing a durable pipe material and pipe size to optimize cost of current and future pumping requirements.

### 2.7.4 Delivery and application devices

To maximize the use of irrigation water at the field level, delivery devices are installed at the field hydrants to control water flow according to the desired criteria. These devices are gate valves, flow regulators, pressure regulators, hydroelectric flow controllers, and metered hydrants. Depending on the mode of irrigation application, delivery devices are coupled with the water application systems or devices to provide water to individual plants, i.e., via drip emitters, bubblers, pulsators, porous pipes, sprayers, and sprinklers. The delivery and application devices play an essential role in delivering the required amount of water to the desired location in a farmer’s field.

### 2.7.5 Measurement devices

The measurement devices in a pressurized irrigation system can monitor the system pressure and discharge at various network points. The most common measurement devices used in a pressurized pipe network are the inline flow meter, venturi meter, electromagnetic flow meter and ultrasonic pipe bands. These devices can be of recording type or can be read directly on a user-friendly gauge. For pressure measurement, Bourdon gauges are commonly used. They should be installed in an easily accessible location for convenient reading and maintenance on all hydrants and other critical points of the network.

# 3. The Rapid Appraisal Procedure

Analyzing the performance of an irrigation system identifies constraints and problem areas. Although there are many ways of assessing performance, FAO recommends using the Rapid Appraisal Procedure (RAP), developed by FAO and the ITRC at the California Polytechnic State University to enable irrigation scheme managers and farmer groups to work together during this initial phase. RAP is recommended because it is quick, systematic, and comprehensive and includes physical, management, and institutional aspects of system operation.

RAP, initially designed for mapping large-scale canal system performance (MASSCOTE approach), has been revamped for use with pressurized irrigation systems of different sizes. The methodology offers a systematic set of procedures for diagnosing bottlenecks in system performance and service delivery levels. It provides irrigation managers with a clear picture of problem areas and enables them to prioritize the steps needed for improvement. It also provides initial indicators to use as benchmarks to compare improvements in performance once modernization plans are implemented.

The following is an overview of RAP and highlights the issues that are particularly relevant to pressurized irrigation systems. The full RAP manual will be needed to undertake an appraisal, and this is available in the ANNEX of the document[2]. A desktop application and spreadsheet version are available to download to enable appraisers to collect and collate data digitally in a user-friendly manner that guides the user through the various steps. However, users who do not have access to a computer, particularly during fieldwork, can use downloadable forms to fill in manually.

BOX 3.1

**Development of RAP software**

RAP desktop application is developed to provide a well-structured and user-friendly interface that helps users to quickly produce the assessment. The application development started with the review of the RAP functions and the creation of a software architecture that reflects the three elements of RAP. The major benefits of the computerized version are the enhanced analysis, the immediate reporting function, the visualization and the possibility to share the analysis quickly. The software is designed to increase the user experience, as it integrates straightforward guidance for the assessment steps, definitions and result interpretation.

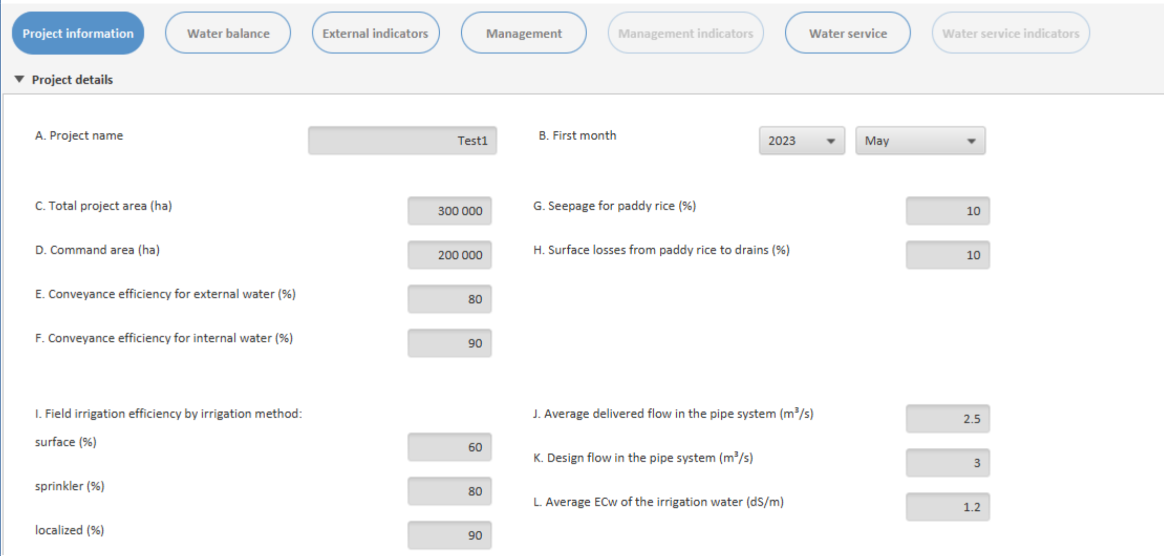
*Source: https://www.fao.org/land-water/databases-and-software/rap/en/*

[2] The software is hosted by the website of FAO Land and Water Division, https://www.fao.org/land-water/databases-and-software/rap/en/

## 3.1 DIAGNOSIS AND EVALUATION OBJECTIVES

Diagnosing actual system performance is a fundamental step to determine the pathways for improvement. RAP for pressurized irrigation systems provides user-friendly tools to critically assess three interrelated elements: water balance (water resources – supply and demand), system management (organizations and institutions), and water delivery service (physical water distribution system).

FIGURE 3.1
**Scoring of actual and stated water delivery service**




*Source: https://www.fao.org/land-water/databases-and-software/rap/en*

The appraisal includes:

- stocktaking of manageable assets: water resources, institutional resources, and irrigation infrastructure;
- evaluating system capacity and performance using indicators to identify the underlying causes of under-performance;
- detecting changes since the original system design and installation;
- looking forward to the desired physical condition and performance when the system is modernized.

The time needed to conduct the appraisal depends on the size and complexity of the system, as well as data availability, collaborative stakeholders, and timing of the assessment. For example, an appraisal in the off-season will require more time to fully understand how the scheme operates than when observing the scheme in full operating mode. A typical appraisal, from preparation to completion, can take up to 1 to 2 months for a small or medium-scale scheme with varying topographical conditions. A typical timeline includes data and information collection (2-3 weeks), field visits (2-3 weeks), and write-up (2 weeks).

It is important to manage and limit the time spent on RAP, but if this highlights the need for more in-depth analysis in specific areas, then time must be allocated for this.

## 3.2 APPRAISING DESIGN AND METHODOLOGY

Structured surveys are used to gather both qualitative information and quantitative data. From this, the two main outputs are a structured set of databases and performance indicators.

### 3.2.1 Irrigation system scale

Initially, RAP was designed for evaluating large-scale surface irrigation schemes. However, interest in small- and medium-scale system performance is growing, so RAP has been revamped to be sufficiently scale-neutral and is now applicable to appraise small-, medium-, and large-scale systems.

### 3.2.2 Framing the appraisal

RAP only applies at the distribution system level, from water intake to the farm hydrant. It does not include an appraisal of on-farm irrigation systems. However, it is important to have a broad understanding of how water is used on-farm, though full appraisal would be a separate task. If several irrigation systems are supplied from the same water source, separate RAPs will be needed for each scheme.

### 3.2.3 The time horizon for assessment

The RAP should provide information on a recent agricultural season. This is meant to be a snapshot rather than a trend analysis. A typical season is preferable, one that avoids extreme events, such as drought and abnormally poor performance, which may be beyond the immediate control of the scheme managers.

### 3.2.4 Target group and stakeholders

RAP must be conducted by experienced agricultural water management professionals to avoid misinterpretation and errors in data and results that may lead to inappropriate decision-making.

Although RAP is designed with experienced professionals in mind, it also addresses several questions aimed at stakeholders. Water delivery service to farmers is an essential element of the appraisal process and should involve as many farmers as possible. This '360-degree' evaluation can clarify any discords that often occur between system managers and farmers.

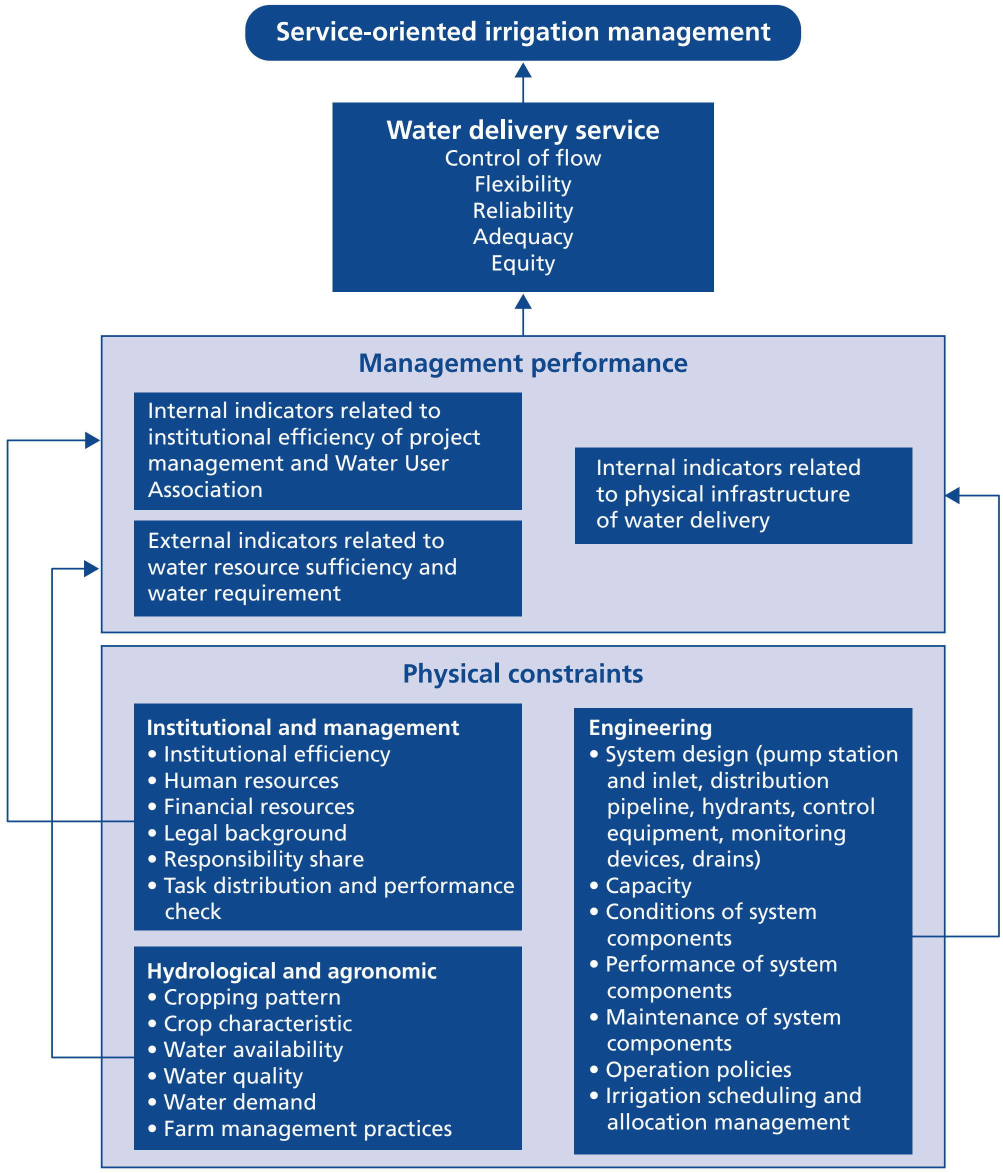
## 3.3 DATA REQUIREMENT

The RAP methodology is data-intense. It requires substantial ground-truth information to acquire accurate assessments. The data collection methodology is based on surveys, interviews, field observations, and document analysis. However, global datasets are helpful to obtain an overall view of the command area. It is recommended to start the assessment with a "virtual tour" to generate bulk information in advance. Information such as topography, climate, vegetation, soil, and characteristics of the agriculture sector can be obtained and analysed in support of the field observations. If field measurements or observations are not available at the time of appraisal, open-access sources can be used to construct bulk information. The RAP Manual includes several open-access platforms that can be used in such situations. These global platforms integrate and synthesize the validated data and allow unlimited data retrieval. Such datasets should also be used to properly frame the baseline assessment and understand the prevailing trends in the irrigation scheme. It is, however, important to note that the original scope and scale of RAP requires micro-analysis. Therefore, local data and information have absolute priority throughout the appraisal.

## 3.4 APPRAISING STRUCTURE AND SCOPE

The structure and scope of RAP for pressurized irrigation systems are described in a flow chart (Figure 3.2). This is based on the understanding that irrigation systems operate under a set of physical, institutional, and resource constraints. The process identifies and assesses these constraints and develops plans that can transform traditional management into service-oriented irrigation management.

FIGURE 3.2
**Scoring of actual and stated water delivery service**




*Source: Authors'own elaboration.*

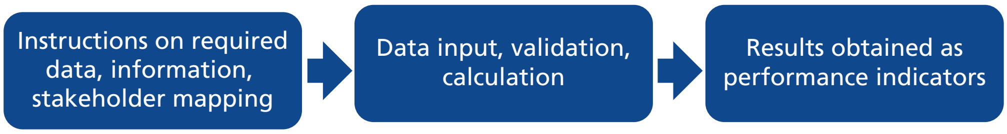
Three inter-related elements present different perspectives on water management, and as such, they are central features of RAP:

- Water balance (hydrology and agronomy) appraises water resources, supply, and agronomic demand
- Management (organizations and institutions) appraises current structures and mechanisms to identify constraints
- Water delivery service (engineering and infrastructure) appraises the physical water distribution system, its characteristics, performance, operating policy, condition, and maintenance.

Each element has dedicated sets of external and internal performance indicators (see section 3.5.3 and 3.6.4 for the definitions of external and internal indicators) to direct professionals and decision-makers in translating the defined bottlenecks and gaps into improvement, rehabilitation, or modernization strategies. The overall goal is to transform traditional management into service-oriented management.

The following is a guide to the appraisal of the three elements, which are developed in more detail in the RAP Manual and spreadsheet. Although each element is evaluated separately, they follow the same analytical process (Figure 3.3). When they are brought together, they provide a comprehensive assessment of the system as a whole.

FIGURE 3.3
**Flowchart of calculation mechanism**



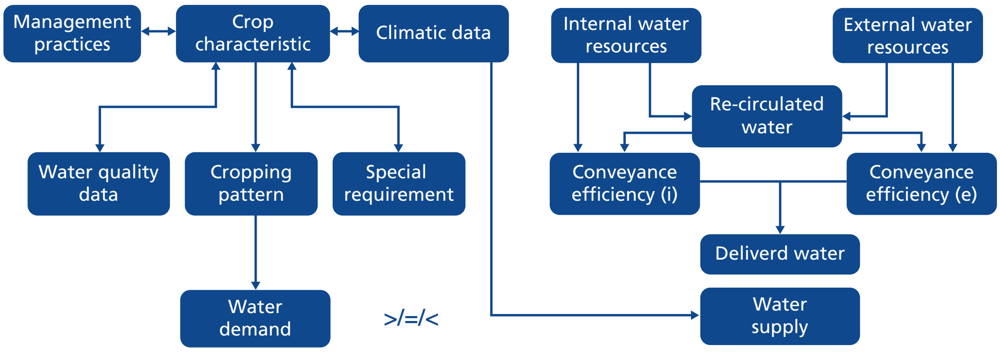

*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20 Manual.pdf.*

## 3.5 APPRAISING THE WATER BALANCE

The water balance requires sets of hydrological and agronomic data to determine the balance between water resources and the water requirement of the crops. It accounts for all inflows and outflows within defined boundaries and includes information about different water efficiencies (e.g., conveyance efficiency and application efficiency), and provides a good assessment of existing constraints and opportunities for improvement. It sets the stage for determining the level of water delivery service to be achieved and for designing appropriate allocation strategies. The RAP includes a water balance at the system/project level and assesses external indicators and potential for water conservation.

The water balance is described in a flow chart (Figure 3.4) and is a guide through the main factors that determine the balance. Water demand indicates the total net irrigation demand required at the system level, and water supply incorporates the total available water resources for irrigation.

FIGURE 3.4
**Calculating an irrigation scheme water balance**




*Source: Authors'own elaboration.*

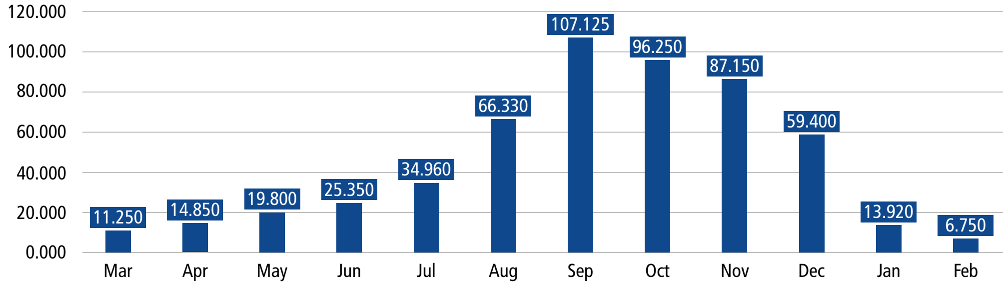
### 3.5.1 Water demand

Irrigation water demand is derived from disaggregated crop information and calculating net crop water requirements based on crop growth coefficients (Kc) and monthly reference crop evapotranspiration (ETo). Crop water requirement at the field level is determined by multiplying the net crop water requirement by the cropped area. This is adjusted to take account of special measures, such as the need for salinity control, crop pre-wetting, and regulated deficit irrigation practices.

Establishing gross irrigation requirements requires taking account of effective rainfall and on-farm water losses (irrigation efficiency), which is usually expressed as a function of the irrigation method (surface, sprinkler, localized), though much depends on the management abilities of the farmer.

Figure 3.5 illustrates typical monthly time steps in net crop water demand in an irrigated command area. Care is needed to avoid confusion between monthly data, average, and total water use data.

FIGURE 3.5
**Monthly net crop water demand (ET) in an irrigated command area (mm$^3$)**

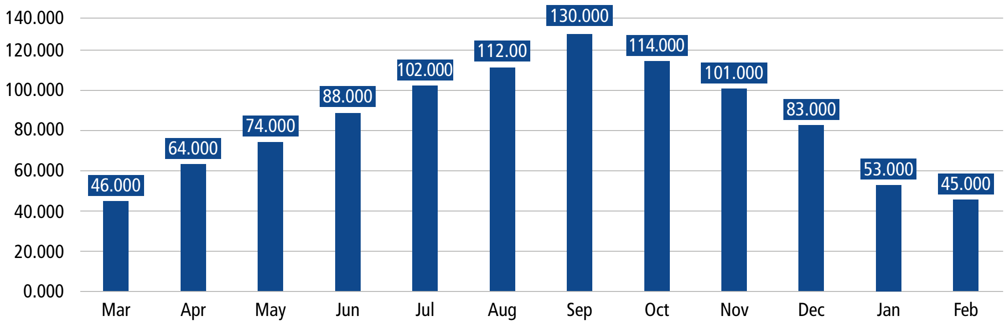



*Source: Authors' own elaboration with RAP v1 software.*

### 3.5.2 Water supply

Water supply, both surface and groundwater, can be sourced directly from the irrigated command area and outside the area. Water resources can be re-circulated, so re-used water accounts an additional water supply. Gross water supply is adjusted by the conveyance efficiency to calculate the net water supply delivered to farms. The 'losses' in the conveyance system may have strategic importance if there is insufficient water supply to meet demand. Figure 3.6 illustrates the typical variability of external water supply to a command area on a monthly basis.

FIGURE 3.6
**Monthly gross external water supply to an irrigation command area (mm3)**




*Source: Author's own elaboration with RAP v1 software.*

### 3.5.3 Water balance – external indicators

The main performance indicators measure the balance between available water supply and water demand in the command area (command area irrigation efficiency), and between delivered water supply and water demand in the command area (field irrigation efficiency). The greater the deviation from 100 percent, the larger the imbalance.

All the water balance related indicators are termed as external indicators as in most cases the sources of water is located outside of the scheme boundary. The indicators can vary monthly, and plus and minus signs express over-supply and water scarcity. The final indicators are obtained as averaged annual results and monthly sub-results.

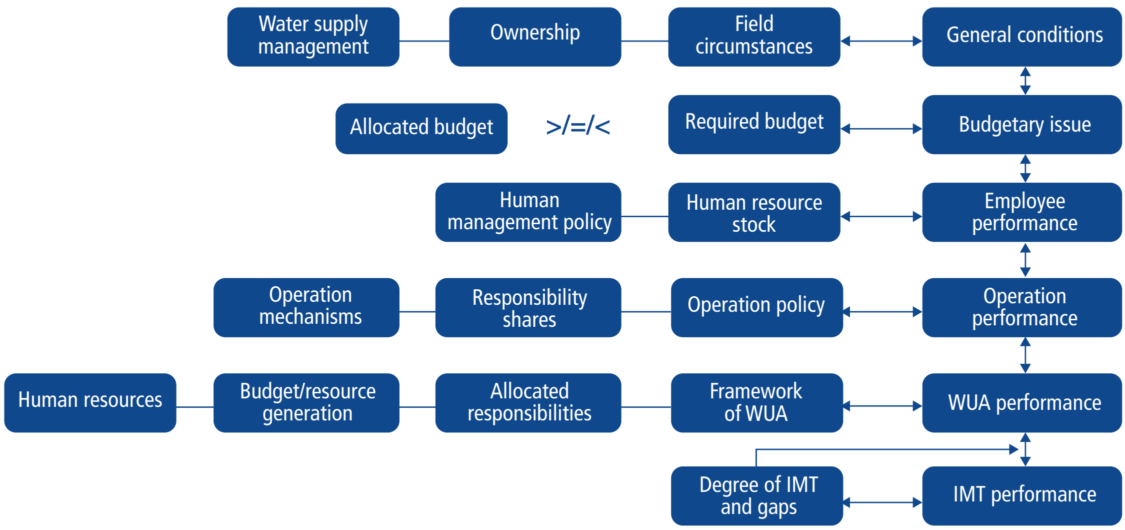
The rest of the external indicators are mostly related to the design capacity of the system and economic productivity. External indicators are expressed in quantitative terms. However, the results must be interpreted in context and require experienced professional judgment throughout the process.

## 3.6 APPRAISING MANAGEMENT: INSTITUTIONAL MECHANISMS

Institutional mechanisms are essential to make and enforce the rules that enable irrigation managers to provide irrigation services to farmers. Assessing the performance of management is particularly challenging as organizations and institutions are shaped by national policies, regulations, social and cultural backgrounds. Appraising performance requires gathering information about the overall institutional mechanisms and touches on several aspects, such as general conditions in the command area, budgetary issues, employee performance, operation performance, WUA performance, and the extent of IMT (Figure 3.7). Data are gathered through open-ended responses and scoring exercises. Although a step-by-step guide is part of the scoring plan to avoid arbitrary assessment, the appraisal requires expert judgment and continual dialogue with farmers and other stakeholders.

Management appraisal occurs at two levels: overall system management, which concerns the establishment, operation and maintenance, and development of a public irrigation scheme, and WUA management concerning the responsibilities allocated to farmers' organizations. Whatever the level, the appraisal must target those officially responsible for irrigation management, whether this is the state, farmer organizations, or individual farmers. In the case of a co-managed irrigation scheme, the appraisal requires the involvement of multiple levels.

FIGURE 3.7
**Appraising irrigation scheme management**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20Manual.pdf.*

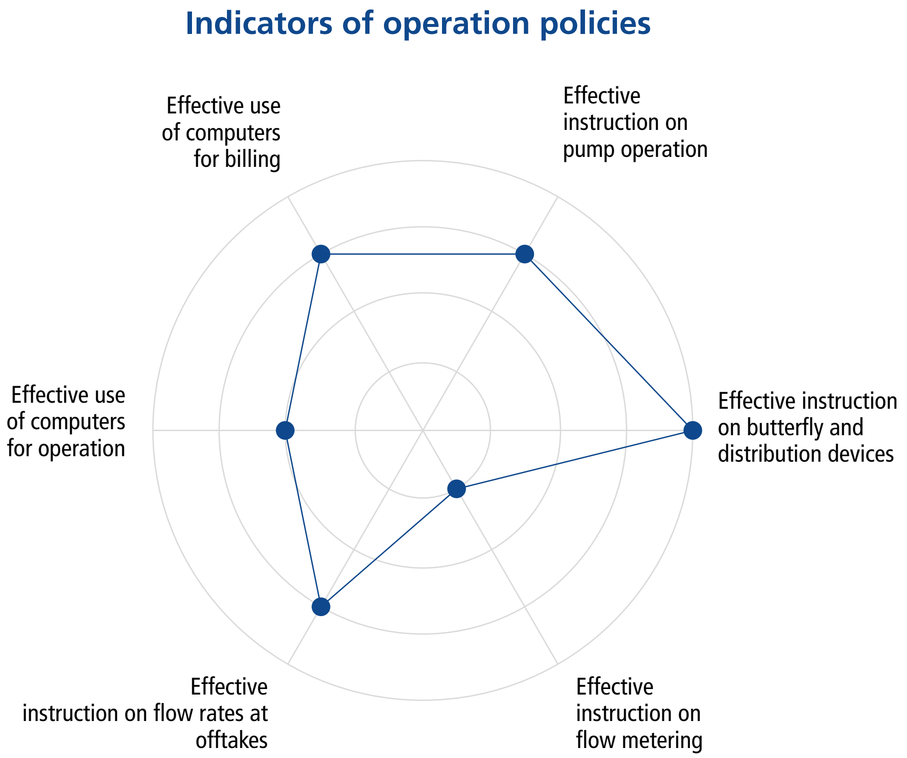
## 3.6.1 Management

Although RAP covers a one-year period, appraising management requires information of a longer time period, one reason being that investments are often uneven and spread over several financial years. A one-year view of finance may well give a false impression. Finance is central to appraising management and includes a comparison of the actual budget with the set budget for the year.

Management appraisal also includes human resources. Human resources are the backbone of efficient management; thus, stocktaking and metrics to assess performance are a significant part of the appraisal process.

The appraisal must also take account of operation policies that determine the efficiency of delivering and implementing management rules.

FIGURE 3.8
**Scoring of actual and stated water delivery service**




*Source: Authors' own elaboration with RAP v1 software.*

Note that high staff turnover might occur due to temporary labor requirements of specific works and may distort the management picture in a given year.

### 3.6.2 Water user associations

Extending appraisal to WUA is required on schemes where farmer organizations have taken over responsibility for managing parts of the irrigation system. This is happening as public authorities wish to reduce the financial burden of operating irrigation systems, but equally, farmers are able to adopt more agile management mechanisms that work to their advantage. However, legal background, liabilities, and responsibilities are mostly determined by national policies that can significantly differ from one country to another. For large-scale schemes, there may be several WUA operating within a command area that requires a separate appraisal.

The appraisal includes a review of basic institutional functions to clarify responsibilities. Budgetary issues are investigated, including the sources of finance. Most WUA are likely to be self-financing from water fees collected from farmers. Similar metrics to those applied to system management can also be applied to WUA staff.

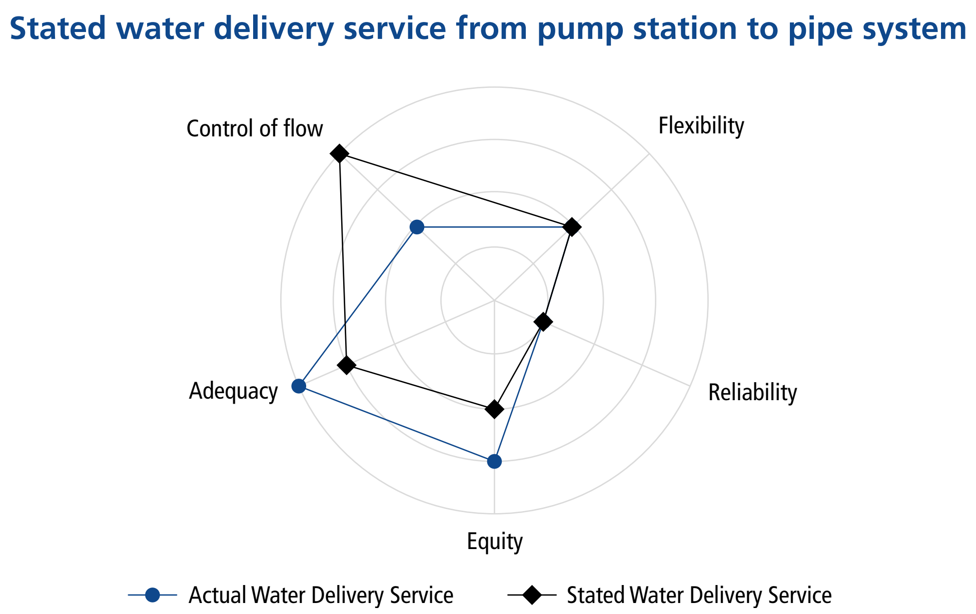
The revamped RAP introduces a new set of data related to IMT. Farmers not only contribute financially to system management, but they may also contribute in-kind. This, too, must be appraised so that farmer contributions to O&M can be fully valued.

### 3.6.3 Water delivery service: a management perspective

Service-oriented irrigation management performance is measured using five indicators: control of flow, flexibility, reliability, adequacy, and equity of water supply (Figure 3.9).

Indicators are designed to be scored based on the stakeholders' perception on the 5-point Likert scale.[3] Each score is described with guiding definitions to reduce subjectivity. The almost identical set of indicators is applied at three levels: system level, system-level operated by paid employees, and final distribution level. The indicators are scored by management (stated water delivery service) and also by farmers (actual water delivery service) to allow for comparison between the perceptions of management and farmers. What is important for management may be less significant for farmers. Opinions being diametrically opposed can be moved towards universally agreed on system management.

FIGURE 3.9
**Scoring of actual and stated water delivery service**




*Source: Authors' own elaboration with RAP v1 software.*

### 3.6.4 Management – internal indicators

All the appraisal indicators related to the management and water service of the irrigation scheme are termed as internal indicators. The management appraisal brings together clusters, six sets of internal indicators related to budget, employees, operation, WUA, IMT, and water delivery service. Together, they capture the prevailing institutional mechanisms in the irrigation system for multiple years.

These qualitative metrics are particularly useful in assessing the feasibility of further investments for modernization. For example, schemes already struggling with poor financing might be reluctant to manage assets with high operating costs. Also, investments implemented in a fragile institutional environment might fail to capitalize

[3] Responders specify their level of agreement to a statement typically in five points: (1) Strongly disagree; (2) Disagree; (3) Neither agree nor disagree; (4) Agree; (5) Strongly agree.

on the potential revenues. Therefore, the indicators related to budget and employees unfold essential information about the appropriate investment program such as fund uptake, time horizon, and resource endowment.

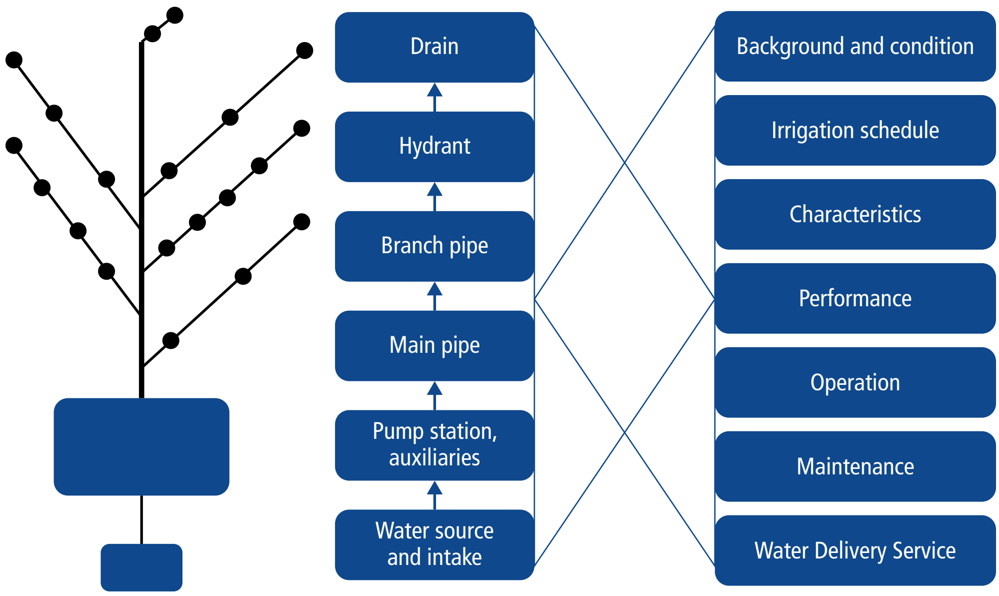
Clusters related to the operation, WUA, and water delivery service are appraised through composite indicators. Qualitative scoring plans are provided to each dimension per cluster to minimize the subjectivity of the appraisal.

Finally, IMT appraisal consists of comparing official and actual responsibilities amongst WUA and farmers. As in the case in many qualitative assessments, value-added roles can be significantly improved from the information gathered. While drawing conclusions, it is strongly recommended to support the appraisal with a thorough explanation in narrative form.

## 3.7 APPRAISING WATER DELIVERY SERVICE: PHYSICAL INFRASTRUCTURE

The water delivery service covers the engineering aspects, including the infrastructural constraints. The appraisal includes all the physical system components from the water source and intake to the drainage system (Figure 3.10).

FIGURE 3.10
**Appraising water delivery service**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20Manual.pdf.*

Evaluating pressurized irrigation systems can be more complex than open-canal systems in the sense that delivering an adequate supply depends on both pressure and flow parameters. Evaluating both is only possible from a theoretical perspective, and so any deviation from required flow and pressure is only a proxy for required changes.

The most significant performance indicators of irrigation conveyance systems are directly related to discharge. This is easily tracked in open canal systems but less so in closed pipe systems. Establishing cause and effect between system components is also not easy. For example, even small equipment malfunctions along the system can prevent efficient water delivery. RAP takes account of this and measures management performance through sets of potential physical constraints to reach service-oriented irrigation management.

Physical appraisal involves all the standard components of a pressurized irrigation system. It includes engineering design, operation, and timely maintenance as prerequisites of acceptable delivery service. However, not all components have the same impact on performance. For example, a sluice gate in poor condition may still be able to supply the design discharge. But the seemingly negligible dislocation of a flow measuring device might severely distort the discharge values. Thus, defining performance indicators that simply refer to the function of individual components, although important, is not nearly enough. RAP, therefore, must take account of both the performance of individual components and provide metrics that appraise their performance as part of the irrigation system.

### 3.7.1 Sequential appraisal of system components

The appraisal captures the system components from water intake to the drains and recognizes that components are connected in sequence. Thus, appraising a standard pressurized system must include both the component parts and the interaction with components downstream to ensure high performance.

The components to appraise include the water source and intake, pump station and auxiliary works, main pipeline, branch pipes, hydrants (at point of delivery), and drains (Figure 3.11). Open-ended responses aim to generate a rich pool of information about the engineering characteristics. But this type of questioning may not provide enough explanation and will require careful interpretation by experienced professionals with good local knowledge.

The appraisal emphasizes the basic design criteria for designing pressurized systems: capacity corresponding to the peak water demand and the required capacity of the pump station and the hydrants. The status of performance, operation, and maintenance of each component is measured separately through scoring systems complemented with guided definitions. If other significant appraisal criteria occur due to any particular aspect of the system, it must be indicated in the final assessment.

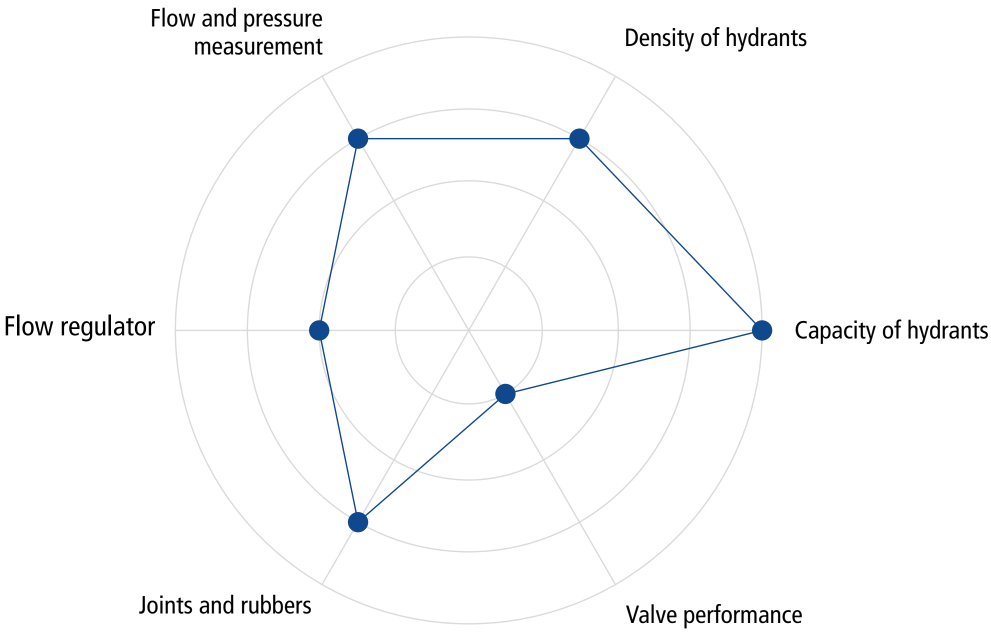
### 3.7.2 Irrigation schedule

The quality of the water delivery service depends on the irrigation schedule. Many of the indicators of flexibility, reliability, equity, and adequacy can be directly improved by a well-established irrigation schedule. However, multi-cropping systems further complicate the already difficult task of creating agreed schedules. Experiences among many public irrigation schemes suggest that the official irrigation schedule suggested by the state does not always match with the actual schedule on the ground. The appraisal must enable the two to be compared and appropriate action taken to bring them into alignment.

### 3.7.3 Water delivery service – farmers' perspective

Service-oriented irrigation management performance from a farmer perspective is measured using five indicators: control of flow, flexibility, reliability, adequacy, and equity of water supply. The aim is to align the results received from scheme managers with those of farmers and to use any difference to resolve possible conflicts.

FIGURE 3.11
**Scoring the performance of deliveries**




*Source: Authors' own elaboration with RAP v1 software.*

This appraisal can also identify the more vulnerable farmers who are not satisfied with the service. In pressurized systems, the most vulnerable are not necessarily those at the tail-end of the system as in canal irrigation. Care is needed to identify the hotspots in the system during the appraisal.

### 3.7.4 Water delivery service – internal indicators

The good condition and performance of system components are prerequisites for any hydraulic assessment. Systems evaluated only from a hydraulic and hydrological performance will not provide a complete picture. Even if the initial design allows sufficient pressure for reliable and equal distribution, the poor physical condition can hamper actual water delivery. The water service appraisal brings together five sets of internal indicators related to characteristics, performance, operation, maintenance, and water delivery service. It must be re-iterated that these dimensions may not all correlate with each other. Therefore, the clusters provide individual assessments about each dimension. Targeted interventions can be prioritized during the planning phase. For example, if the overall goal of modernization is to expand the useful life of the system, poorly maintained assets must be prioritized even if they still perform well.

BOX 3.2

**Piloting the concept of rapid appraisal procedure for pressurized systems in Egypt**

Revisiting the RAP methodology was prompted by the FAO assignment to assess a series of IRRIgation improvement programmes in Egypt between 2017 and 2020. This involved the reconstruction of the traditional water distribution systems and the introduction of improved irrigation systems. The RAP initially designed for open-canal systems had significant potential to carry out systematic performance benchmarking. Therefore, FAO piloted several options to extend the applicability of RAP to different system configurations, including pressure distribution systems. The Egypt case study paved the way for the revamped RAP.

The On-farm Irrigation Development Project in the Old Lands (OFIDO) was implemented on 31 916 feddan in Kafr el-Sheikh, Beheira, Minya, Beni-Sueif, Assuit, Sohag, Qena, and Luxor. The project replaced the traditional distribution systems with multiple water-lifting points and earthen canals with low-pressure networks. The RAP was used to assess the pressurized systems' performance and compare it with the traditional systems. Representative irrigation systems were sampled to conduct the assessment and draw lessons from the improvement programmes. However, RAP provides an option for a case-by-case evaluation.

Therefore, each sampled irrigation system was individually assessed, and the results of the case studies were synthesized. The data covering two agriculture seasons were collected through in-field measurements to calculate the water balance. The crop characteristics, management practices, climatic data, crop evapotranspiration, and flow were monitored in the sampled systems. The pressurized irrigation systems showed a remarkable performance in terms of field irrigation efficiency. The investigated pressurized networks reached 98 percent field irrigation efficiency, while severe water scarcity and oversupply were observed in traditional systems (Salman *et al.,* 2020a).

The RAP management chapter was only completed after the assessment and management turnover. The established WUA were surveyed, and key characteristics defined. The assessment showed that management turnover was initiated at a late stage of the project execution, and management roles were handed over without sufficient capacity-building and organizational arrangements.

The RAP results proved that the operation modes of WUA are arbitrary and not entirely consistent with the national legislation. As a result, the management tasks regarding the operation, maintenance, distribution, and organization are not explicitly assigned to the stakeholders. The fragile institutional environment is one of the significant drawbacks to exploiting the full potential of the pressurized irrigation systems. The water delivery service was assessed sequentially, scrutinizing the consecutive water distribution levels one by one.

The traditional water distribution setting involves the pumps (water withdrawal from branch canals), mesqa distribution canal (conveyance and distribution from the pumping station to lower level canals), and marwa distribution canal (conveyance and distribution from the mesqa canal to the field). The low-pressure irrigation systems followed the initial design levels but converted the respective distribution levels to a pumping station, mesqa pipeline, and marwa pipeline. The final distributaries are hydrants, supplying water directly to the field. The RAP is used only for physical and not for hydraulic assessment.

However, the water service chapter gives essential information on the condition and performance, without which the interpretation of hydraulic underperformance would be difficult. The assessment required data collection for the system, field observations, and several interviews with stakeholders. The assessment highlighted considerable performance heterogeneity amongst systems, which was influenced by the quality of the construction, the distribution arrangements, the organization of O&M works, and the capacity of the WUA.

The pressurized irrigation systems performed well in terms of creating equity amongst users and being reliable. However, the rotational irrigation schedule set back the potential increase in service flexibility. Furthermore, the system design did not involve flow control devices. The RAP identified the particular flaws in each investigated system, based on which corrective measures could be suggested. Also, common observations were defined, which referred to structural challenges in the project design and implementation.

The Egypt case study was the first attempt to pilot and validate the RAP for pressurized systems. The methodology has proven to be robust but data-intense. Despite the demanded efforts, the RAP implementation is recommended in data-scarce environments thanks to its ability to initiate systematic data collection. The results coming from the RAP were translated into technical recommendations to guide the future irrigation investment programmes in Egypt.

*Source: Salman, M., Pek, E., Giusti, S., Lebdi, F., Almerei, A., Shrestha, N., El-Desouky, I. et al. 2020a*

## 3.8 SYNTHESIS OF RESULTS

The RAP is built on the concept that all management elements (hydrological, organizational, and water service) must function properly to achieve consistently high performance. One without the other cannot provide a sufficient irrigation service. Moreover, the underperformance of one element can substantially undermine the performance of the others. Once the assessment is performed, the results of the elements must be collated and the bottlenecks defined. This can support the design of future rehabilitation and modernization programmes to address malfunctions.

# 4. Appraising hydraulic performance

## 4.1 INTRODUCTION

Branched pressurized irrigation systems offer a high degree of control over water supply to farmers and the potential for on-demand water delivery. This means that farmers can irrigate as and when they need to rather than to a fixed schedule, and they are able to stop and start water flow as and when needed. Many of these options are not readily available to farmers who are supplied from open canal systems.

Irrigation system capacity is normally designed for the maximum discharge assuming steady-state flow and is based on calculated maximum crop water requirements and the number of farms being irrigated at the same time. On-demand irrigation, however, is more complex as farmers can individually choose when they irrigate and how much water they will take. The worst case would occur when all the farmers on a system decide to irrigate at the same time and require the maximum flow at the design pressure. But designing a system to meet this extreme requirement is usually uneconomic, and so farmers and designers must reach a compromise between performance and cost and decide on a reasonable schedule that meets all the discharge and pressure requirements at the farm hydrant most of the time. In the past, Clément (1966) used a statistical approach, based on an agreed probability of occurrence, to determine the number of farmers that would be able to irrigate properly at the same time. In turn, this determines the design discharge and pressures for the pipe network. If more farmers then start irrigating, the system would fail to provide the right discharges and pressures for everyone.

This approach provides a 'maximum' discharge to enable engineers to design the system, but it does not take account of how it functions in practice. It takes no account of the many different configurations of farmers irrigating at the same time and the different discharge requirements needed to meet these demands.

## 4.2 DEVELOPING AND USING COMBINE OPTIMIZATION AND PERFORMANCE ANALYSIS MODEL SOFTWARE

In 2000, as computers were being increasingly used for routine design work, an improved approach to design pressurized irrigation systems was developed (Lamaddalena and Sagardoy, 2000) based on how the system might perform in practice rather than based on statistical analysis. This approach i) generated different discharge configurations flowing into each section of the network, ii) determined pipe-sizes taking into account such discharges, and iii) enabled the development of indicators to assess system performance, including reliability and relative pressure deficit. The computer software COPAM (Combine Optimization and Performance Analysis Model) was developed to undertake the calculations (Box 41). Although initially a design tool, this approach now enables managers to appraise the performance of existing systems by measuring the extent of system 'failure' under different operating configurations and the impact this has on service delivery.

BOX 4.1
**The development of Combine optimization and performance analysis model software**

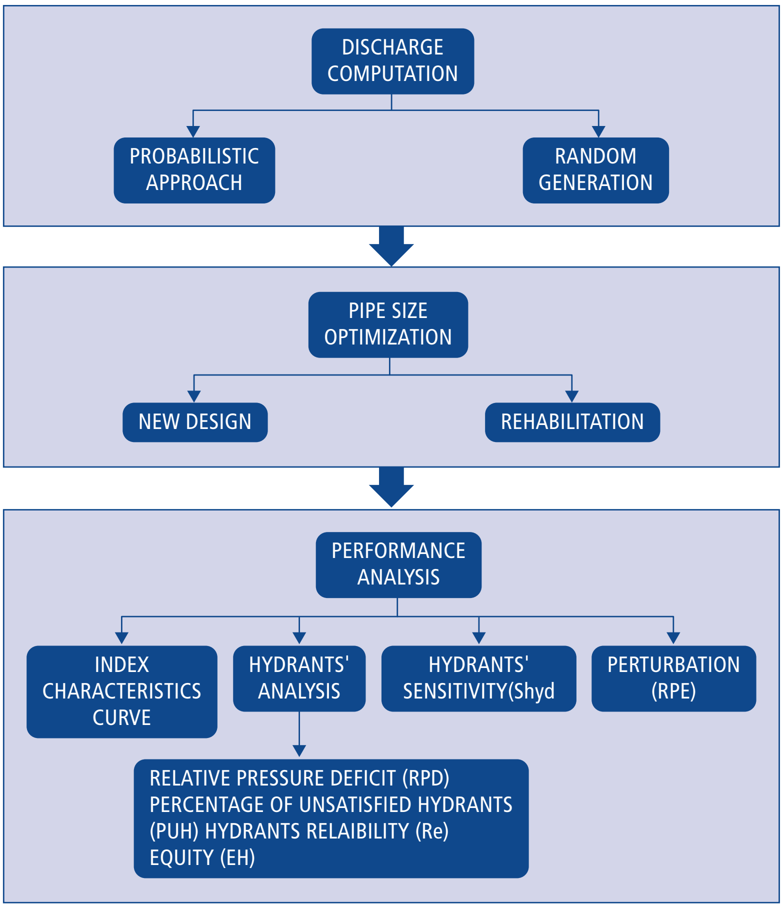
A software to support appraisal was based on a revamp of the version in the RAP (Burt and Facon, 2002) (Chapter 3). To appraise the performance of pressurized irrigation systems, an updated version of the software named "Combined Optimization and Performance Analysis Model - COPAM" (Lamaddalena and Sagardoy, 2000) was developed in the framework of this publication. The latest version, COPAM v4.0, now incorporates additional functions to analyse sensitivity (Lamaddalena and Fouial, 2019) and perturbation (Derardja, Lamaddalena and Fratino, 2019) and is used extensively in this paper to diagnose faults in the system.

*Source: Authors' own elaboration based on COPAM v4.0.*

COPAM v4.0 now accommodates new performance indicators developed in line with the MASSPRES approach. These include indicators for capacity, sensitivity, equity, and perturbation. These new indicators are described in detail in chapters 5, 6, and 7. A users' guide for COPAM v4.0 is provided in Annex 2.

Figure 4.1 illustrates the flow of actions in the COPAM v4.0 software supporting the MASSPRES approach.

FIGURE 4.1
**Flow chart of the Combine optimization and performance analysis model v4.0 modeling approach**

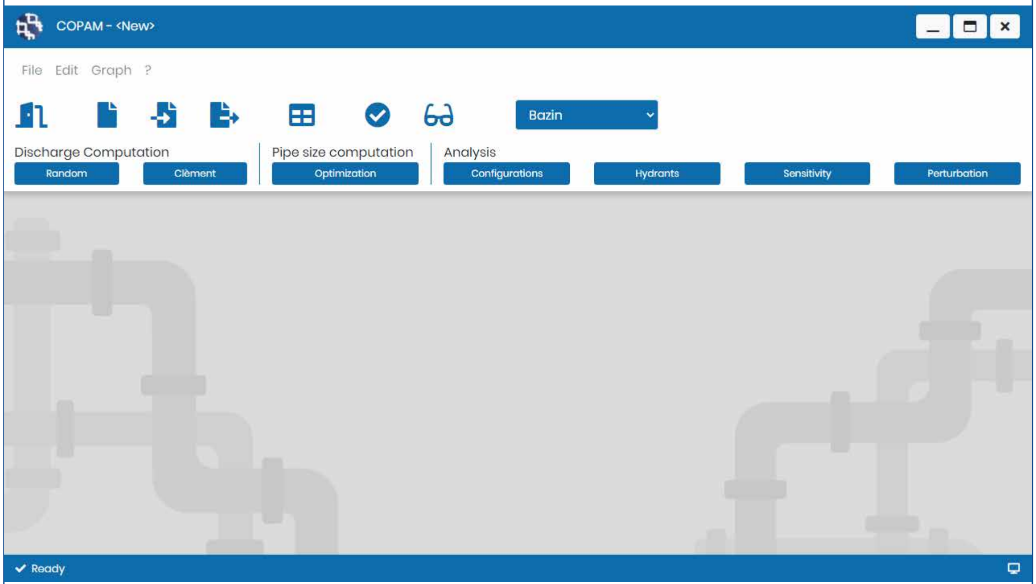



*Source: Authors' own elaboration.*

Figure 4.2 illustrates the 'homepage' of COPAM v4.0 software package. In this publication, only modules related to performance analysis are described and illustrated. See FAO-I&D Paper n. 59 for full details of other modules.

Modules are already available to calculate discharges and pipe sizes and can be used for new designs and supporting appraisals of existing schemes.

FIGURE 4.2
**Homepage of Combine optimization and performance analysis model v4.0 software package**




*Source: Screenshot of COPAM v4.0.*

## 4.3 SETTING THE SYSTEM BOUNDARIES

Boundary conditions require that: I) all hydrants are equipped with flow regulators with a nominal discharge established according to the downstream cropping pattern, the irrigated area, the type of soil, and all the uncertainties related to the weather conditions and the farmers' behavior; II) the system is branched, and III) one single upstream water source is available. Both on-demand and rotational delivery schedules can be assessed according to the actual operational mode of the system.

## 4.4 HYDRAULIC PERFORMANCE INDICATORS

COPAM v4.0 includes a Random Generation Model to generate different discharge configurations and modules to compute relative pressure deficit and reliability indicators (Lamaddalena and Sagardoy, 2000), equity, hydrant sensitivity, and perturbation indicators:

**Relative pressure deficit** concerns the pressure at the farm hydrant and the deficit ($\Delta H_{j,r}$), at each hydrant, j, in each configuration, r. It describes the deviation between the actual pressure head at the hydrant and the minimum pressure head requested by the farmer according to the requirements of his farm irrigation equipment.

**Reliability** describes the probability of maintaining pressure at the farm hydrant, *i* over time t.

**Equity** assesses the quality of service distribution among farmers. This indicator is related to the relative pressure deficit and assesses variability across the irrigation system.

**Hydrant sensitivity**, $S_{hyd}$, is related to the reliability indicator. It defines the rate of change in reliability as the upstream pressure/discharge changes.

**Perturbation** assesses pressure changes in the pipe system under unsteady flow conditions due to changes in discharge when opening and closing farm hydrants, shutting down pumps, and pipes burst.

# 5. Appraising system capacity

A pressurized irrigation distribution system must deliver water through a complex, branched pipe network from source to farm hydrants and meet the pressure and discharge requirements for every design configuration. Failure to meet the pressure and/or discharge requirements at farm hydrants will impact irrigation performance on farms. Just how much impact will depend on the extent of the changes and time over which they occur.

Therefore, the question is: does the pipe system have sufficient capacity to achieve the desired hydraulic requirements at each hydrant in a specified configuration?

COPAM v4.0 software enables irrigation managers to answer this question by assessing the theoretical system performance of a system based on the design criteria and comparing this with what happens in practice to identify any deficiencies. For this, COPAM uses two models. The first, the Indexed Characteristics Curve (ICC) model, provides information on the overall performance of the irrigation system. The second, the AKLA model, provides more precise information about the performance at the hydrants, the percentage of unsatisfied hydrants, their position, and the magnitude of their pressure deficit.

A brief description of the ICC and AKLA models follows. More detailed descriptions are available in FAO Irrigation and Drainage Paper 59 (Chapter 5).

## 5.1 INDEXED CHARACTERISTICS CURVE MODEL

The ICC model simulates system operation for comparison with results observed in practice. It is based on steady-state flow conditions in the network and assumes that all hydrants incorporate a flow regulator, so the hydrant delivers the nominal discharge even when the pressure changes. There are many operating conditions to consider as farmers decide to irrigate on-demand. The model takes account of changes in ground level across the system, which has important implications for pressure measurements, and can assess the discharges and pressures in the system for various configurations (groups of hydrants operating at the same time) and generates a set of characteristic curves that define an envelope or range of operating conditions for the network (Box 5.1).

BOX 5.1

**The Indexed characteristics curves model**

When hydrants incorporate a flow regulator, it can be assumed they deliver the nominal discharge, d [l $s^{-1}$], even when the pressure head changes. A "configuration" (r) is defined as a group of operating hydrants corresponding to a fixed value of the discharge, Q [l $s^{-1}$], at the head of a network.

A configuration is considered satisfied when all operating hydrants in a configuration, respect the following relationship:

$$(H_j)_r \geq H_{min} \qquad (5.1)$$

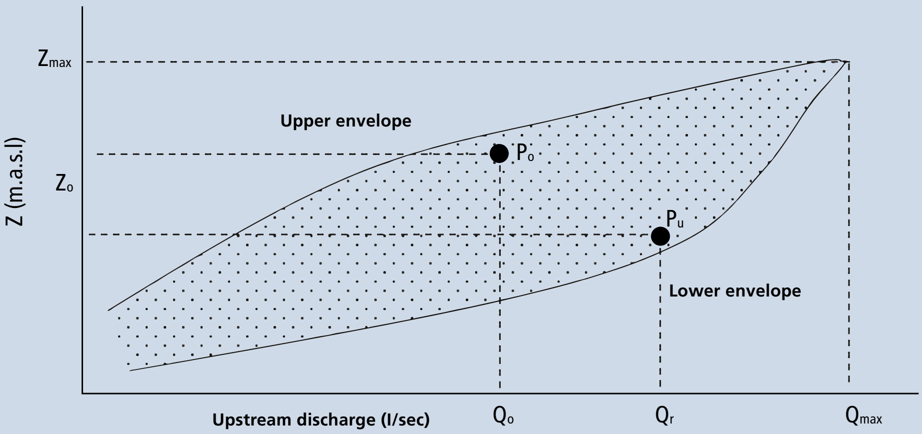
Where $(H_j)_r$ [m] represents the pressure head at the hydrant j within the configuration r, and $H_{min}$ [m] represents the minimum required pressure head for the appropriate operation of the on-farm system.

Satisfying the condition depends on the layout of the network, the plano-altimetric conditions, the location, and the number of hydrants operating simultaneously.

For any value of discharge Q at the head of the network, different values of the piezometric elevation, $Z_r$ [m a.s.l.], satisfy the relationship.

For all possible configurations r, the pairs ($Q_r$ , $Z_r$) refer to discharges ranging between 0 and $Q_{max}$ are calculated, and a cloud of points is obtained (see Figure). These points are contained within an envelope. The upper part corresponds to 100 percent satisfied configurations, and the lower part corresponds to no configuration is satisfied.

**Representative points of the hydraulic performance of a network**




*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

Other curves can be drawn within this envelope, called Indexed Characteristic Curves (ICC), each representing a certain percentage of satisfied configurations.

To calculate the ICCs a preselected number of configurations are investigated, along with a discrete number of discharges to be checked, corresponding to a number, K, of hydrants open at the same time:

$$K = Q_r / d \qquad (5.2)$$

Assuming all the hydrants have the same nominal discharge, d

In the case of different hydrant discharges, the number of hydrants simultaneously opened will vary as a function of the classes of hydrants drawn. In this case, a random drawing will be performed to satisfy the relationship:

$$|Qtir - Qi| < e$$

Where Qtir [l $s^{-1}$] is the discharge corresponding to K hydrants drawn at random and ε is the accepted tolerance, assumed equal to the value of the lowest hydrant discharge.

Experience shows that the number configurations (C) to be investigated for each discharge should be close to the total number of hydrants (R) for large irrigation systems (> 600 hydrants). It is recommended to increase C when small systems are analysed.

Once C is established, a random number generator having uniform probability distribution can generate K hydrants ranging between 1 and R for each configuration.

Steady-state flow conditions are assumed. A piezometric elevation at the head of the network is required for each discharge configuration to satisfy the pressure head relationship.

Once the C configurations are investigated, a series of piezometric elevations ($Z_r$) at the upstream end of the network can be associated with each discharge $Q_r$, so that each one represents the piezometric elevation able to satisfy a given percentage of C configurations.

The ICCs can be drawn in the plane (Q, Z), the discharge values chosen and the corresponding vectors, the points having the same percentage of configurations satisfied can be joined up.

ICCs with gentle or steep gradients can be obtained depending on the geometry and the topography of the network.

Let $Z_0$ [m a.s.l.] be the design piezometric elevation at the head of the network and $Q_0$ [l $s^{-1}$] be the upstream design discharge. Then define $P_0$ ($Q_0$, $Z_0$) as the "operating point" of the network (usually, these are the design conditions). The network's performance is then linked to the percentage of satisfied configurations corresponding to the operating point.

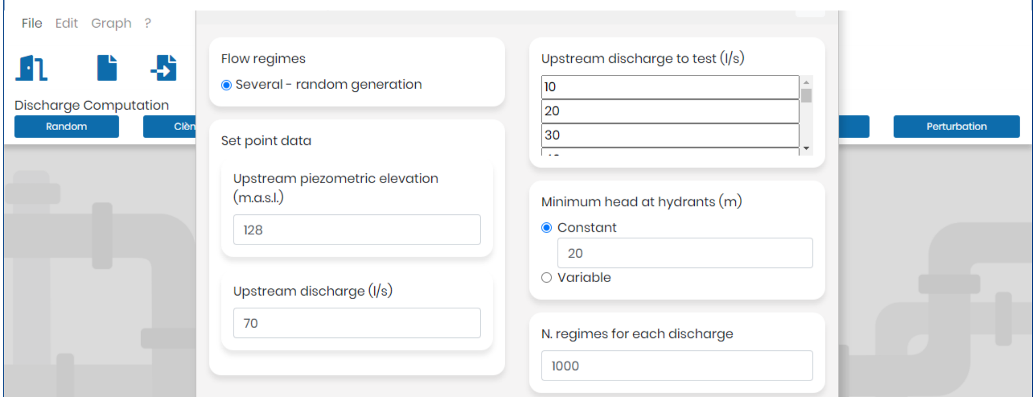
The ICCs provide information on the overall performance and capacity of the system.

Note that the ICCs assume that a configuration is said to be unsatisfied if the head $H_j$ of one hydrant is lower than the minimum required head $H_{min}$. Therefore, if the operating point ($Q_0$, $Z_0$) falls on an ICC corresponding to a low percentage of satisfied configurations, this model cannot give a precise assessment of the actual performance and capacity of the network.

*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

Figure 5.1 illustrates the input data required for the ICC analysis.[4]

FIGURE 5.1
**Layout of the input data for the ICC analysis**




*Source: Screenshot of COPAM v4.0.*

4 All models presented in this publication have been validated and tested in the field (Lamaddalena, 1997) and also reported in the OFIDO Technical Assessment Report (Salman *et al.*, 2020b)

The hydrostatic condition, i.e., the upstream piezometric elevation, must be measured when all hydrants are closed, possibly at the end of the irrigation season.

Pressure heads at pre-selected hydrants must be measured for different operating configurations and compared with the simulated results for the same configurations. If field measurements and simulations differ, then changing the pipe roughness coefficient is one option to ensure the pressure head at the pre-selected hydrant is different, then adjusting the roughness coefficient can bring them into line.

## 5.2 AKLA MODEL

The AKLA model offers a more in-depth performance assessment of individual farm hydrants. The Random Number Generator module is used to select the number of hydrants operating at any one time (configuration), and this assumes a uniform distribution of discharge. Rather than analyzing the whole configurations of hydrants, it is used to determine the pressure head at each hydrant under different operating conditions.

Comparing the model results with the minimum pressure specified at the farm hydrant enables the model to calculate the PUH and the relative pressure deficit (RPD).

BOX 5.2

**Computing the percentage of unsatisfied hydrants**

The AKLA model is based on simultaneous operation of a pre-defined number of hydrants (configurations). The hydrants are generated using a random number generator having a uniform distribution function.[5] A hydrant (j) is considered satisfied within each generated configuration (r), when the following relationship is verified:

$$H_{j,r} \geq H_{min} \qquad (5.3)$$

Where $H_{j,r}$ [m] is the pressure head of hydrant, j, within configuration r, and $H_{min}$ [m] the minimum required head for the appropriate operation of the on-farm systems.

With the same criteria and hypotheses of the ICC model, if the discharge $Q_r$ [l s$^{-1}$] is fixed at the head of the network, the number of hydrants simultaneously operating ($K_r$) can be generated:

$$K_r = Q_r / d \qquad (5.4)$$

Starting from the upstream piezometric elevation ($Z_0$) and the upstream discharge ($Q_0$), the head losses are computed together with the pressure head available at each hydrant in each selected configuration. This identifies those hydrants having a pressure head lower than the minimum ($H_{min}$).

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5 In addition, COPAM v4.0 has an internal procedure to enable access to an external file for hydrants' configuration. This procedure is relevant when rotational delivery schedules need to be analysed

These are defined as "unsatisfied hydrants." The PUH out of the total number of open hydrants in a configuration is plotted in a plane (Q, Z). Selecting a large number of configurations for the upstream discharge ($Q_0$), the analysis provides a variable number of unsatisfied hydrants and hence a range of PUH for that given discharge.

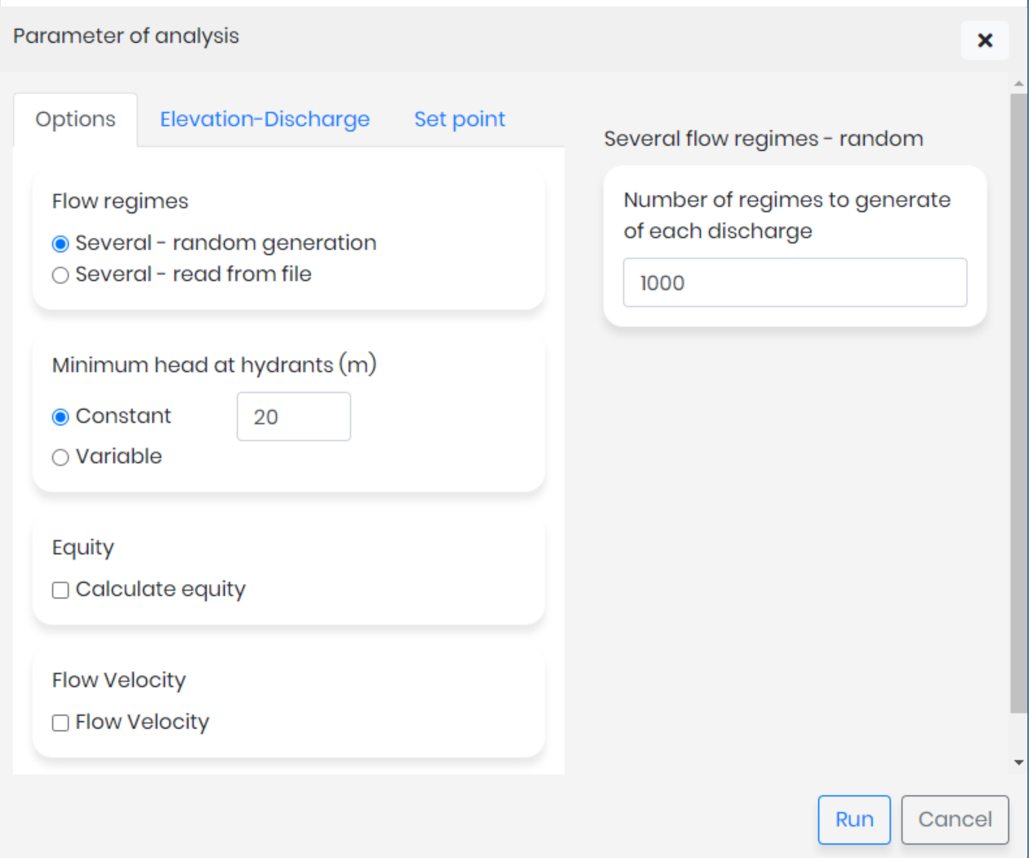
Repeating this procedure for several discharges ($Q_{up}$), can produce a cloud of points. An upper and a lower curve will envelope all these points. The upper envelope would represent the maximum PUH, the lower envelope would represent the minimum PUH. Intermediate envelopes can be easily identified ranging between 10 percent and 90 percent.

*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

The results of the AKLA model complement those of the ICC model and offer a more detailed assessment of irrigation system capacity. A graphical interface allows all information from the AKLA model to be presented diagrammatically: the PUH curves (one elevation), PUH curves (all elevations).

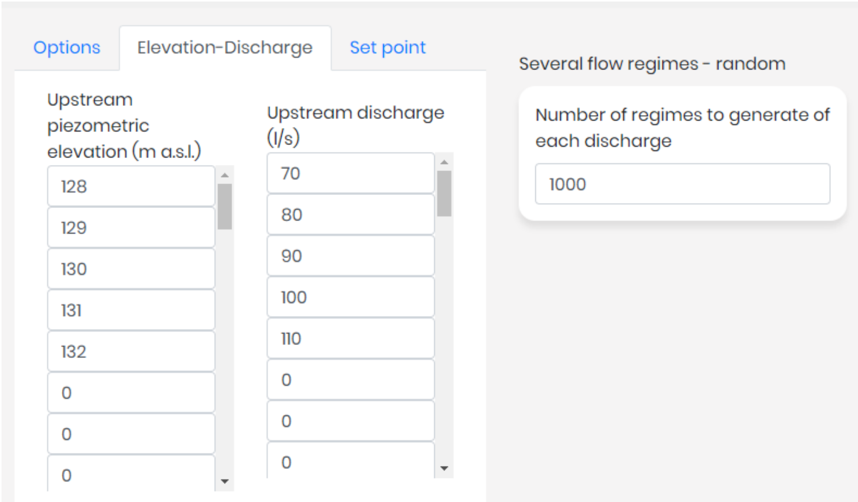
Figure 5.2, Figure 5.3, and Figure 5.4 illustrate the layout of input data required for the AKLA model.

FIGURE 5.2
**Layout of input data for analyzing hydrants: options**



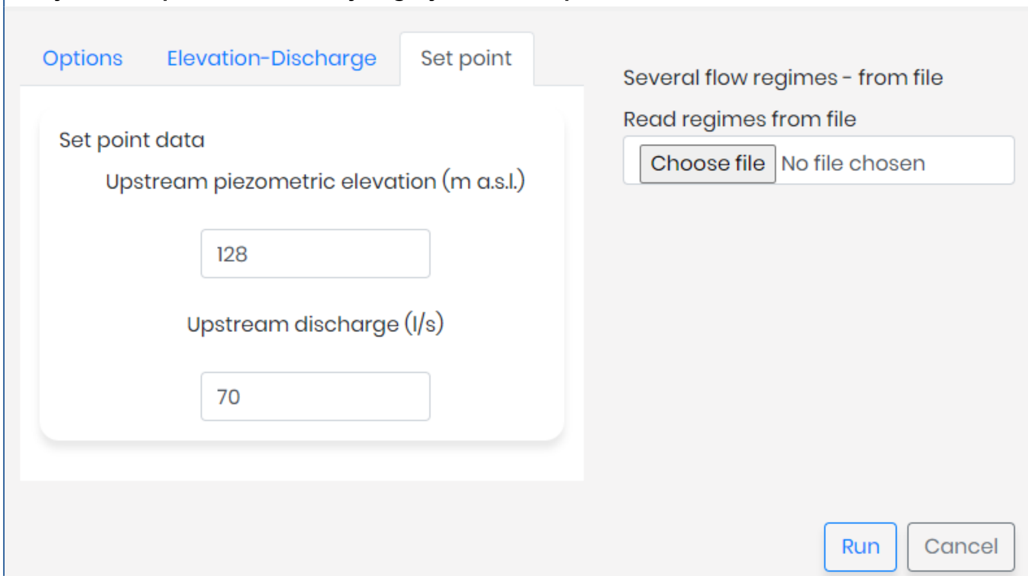

*Source: Screenshot of COPAM v4.0.*

FIGURE 5.3
**Layout of input data for analyzing hydrants: elevation-discharge**




*Source: Screenshot of COPAM v4.0.*

FIGURE 5.4
**Layout of input data for analyzing hydrants: set point**




*Source: Screenshot of COPAM v4.0.*

Several possible discharges with several possible upstream piezometric elevations can be selected and tested to determine the PUH under varying discharge and piezometric elevation criteria.

## 5.3 INPUT DATA

Input data includes topographic data from maps of the irrigated area, pipes materials, nominal pressure (see Annex 4), hydraulic characteristics of the pumping station, the water delivery schedule, and peak discharge. The latter is often not directly available as few systems install flow meters at the head of the system to record the hydrograph, which can also provide valuable insights into farmer behavior.

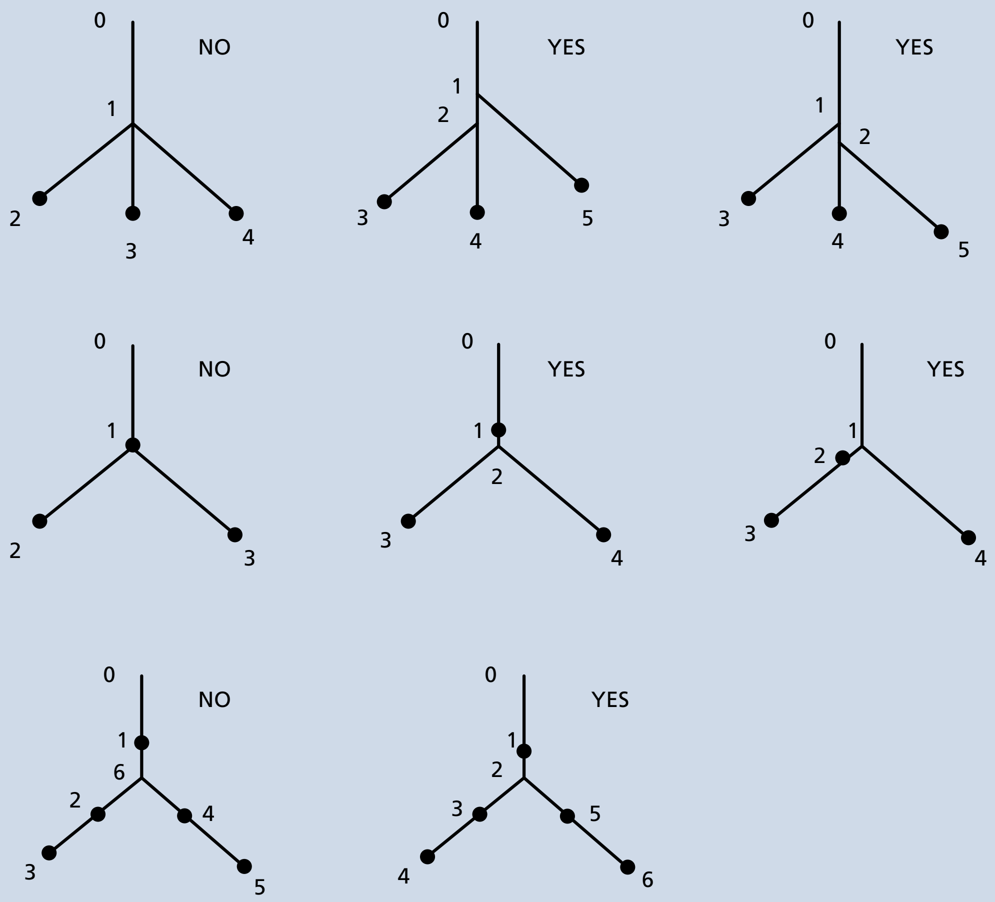
If the delivery schedule is by rotation, the peak discharge can be estimated by adding the discharge of hydrants operating at the same time within their turn. If the delivery schedule is on-demand, estimation is difficult, and so more reliance is placed on the design report to provide these data rather than from operating experience.

Data collection is part of the RAP phase and is prepared as input files for computation. The models assume that networks are branching, and each node (both hydrants and/or linking sections) is identified by a number (Box 5.3).

BOX 5.3

**Input data for system capacity appraisal**

**Examples of node numbering**




*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

The upstream node (source) must have number "0".

The other nodes are numbered consecutively, from upstream to downstream. Any node may be jumped.

The number of the section is equal to the number of the nodes downstream.

All terminal nodes of branches must have a hydrant.

If hydrants have two or more outlets, an additional column is required in the input file indicating the number of outlets for each hydrant. An internal procedure will randomly allocate the number of outlets operating simultaneously for each hydrant for each simulation.

No more than two sections may be derived by an upstream node. If so, an imaginary section with minimum length (i.e.: $l_{min}$ = 1 m) must be created, and an additional node must be considered. This node must have a sequential number.

No hydrants may be located in a node with three sections joined. If so, an additional node with a sequential number must be added.

Other data requirements include:

Area irrigated by each hydrant (in ha); if no hydrant occurs in the node, Area=0 is allocated

Hydrant nominal discharge ($ls^{-1}$).

Section length (m).

Land elevation of the downstream node (m a.s.l.)

Nominal pipe diameter (mm). This information is needed when the program is used to analyse the network. In the design stage, ND=0 must be considered.

A list of commercial pipe diameters (mm), in increasing order.

The thickness (mm) of the pipe walls.

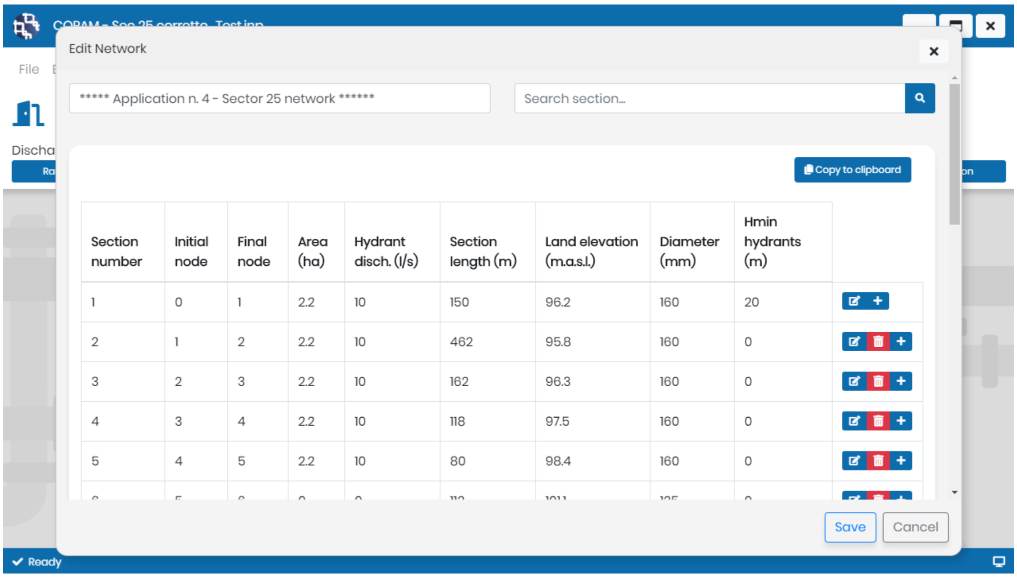
The roughness (Bazin coefficient) identifies the type of pipe; See FAO Irrigation and Drainage Paper No. 59 (Lamaddalena and Sagardoy, 2000) and/or Annex A4.1).

The unit cost of pipes in increasing order.

*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

Figure 5.5 and Figure 5.6 illustrate the templates used to input basic data for assessing system capacity.

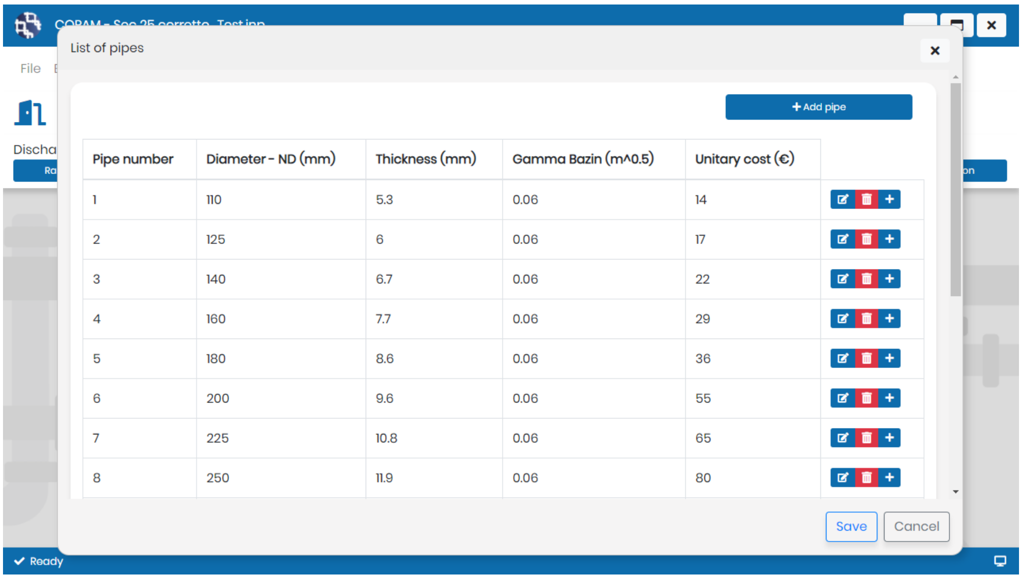
FIGURE 5.5
**Example of the basic input data needed to run COPAM v4.0 (network layout**




| Section number | Initial node | Final node | Area (ha) | Hydrant disch. (l/s) | Section length (m) | Land elevation (m.a.s.l.) | Diameter (mm) | Hmin hydrants (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 2.2 | 10 | 150 | 96.2 | 160 | 20 |
| 2 | 1 | 2 | 2.2 | 10 | 462 | 95.8 | 160 | 0 |
| 3 | 2 | 3 | 2.2 | 10 | 162 | 96.3 | 160 | 0 |
| 4 | 3 | 4 | 2.2 | 10 | 118 | 97.5 | 160 | 0 |
| 5 | 4 | 5 | 2.2 | 10 | 80 | 98.4 | 160 | 0 |

*Source: Screenshot of COPAM v4.0.*

FIGURE 5.6
**Example of the basic input data to run COPAM v4.0 (list of pipes)**




| Pipe number | Diameter - ND (mm) | Thickness (mm) | Gamma Bazin (m^0.5) | Unitary cost (€) |
|---|---|---|---|---|
| 1 | 110 | 5.3 | 0.06 | 14 |
| 2 | 125 | 6 | 0.06 | 17 |
| 3 | 140 | 6.7 | 0.06 | 22 |
| 4 | 160 | 7.7 | 0.06 | 29 |
| 5 | 180 | 8.6 | 0.06 | 36 |
| 6 | 200 | 9.6 | 0.06 | 55 |
| 7 | 225 | 10.8 | 0.06 | 65 |
| 8 | 250 | 11.9 | 0.06 | 80 |

*Source: Screenshot of COPAM v4.0.*

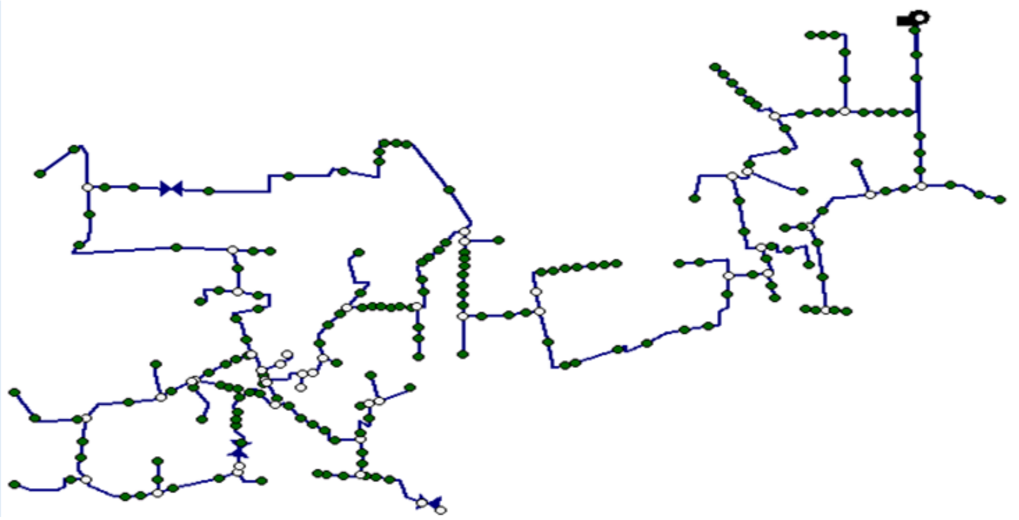
## 5.4 APPRAISAL EXAMPLES

Two examples illustrate how irrigation system capacity can be reported using the ICC and AKLA models. In the first example, the ICC model provides enough information for a satisfactory assessment to be made. In the second example, ICC alone was insufficient, and the AKLA model provides more detailed information on hydrant performance.

### 5.4.1 A pressurized irrigation system in Lecce (Italy)

This system is located in the province of Lecce (Italy) and serves an irrigable area of 582 ha equipped with 174 hydrants with nominal discharges of 5, 10, and 20 $ls^{-1}$ (Figure 5.7). The area slopes downwards from the pump station with land elevations ranging from 24 m a.s.l. to 15 m a.s.l. The pump station designed maximum discharge is 325 $ls^{-1}$ with an upstream piezometric elevation $Z_0$ = 66.7 m a.s.l. The minimum pressure head at each hydrant ($H_{min}$) is 20 m and is designed to operate low-pressure sprinklers and trickle irrigation systems on the farm.

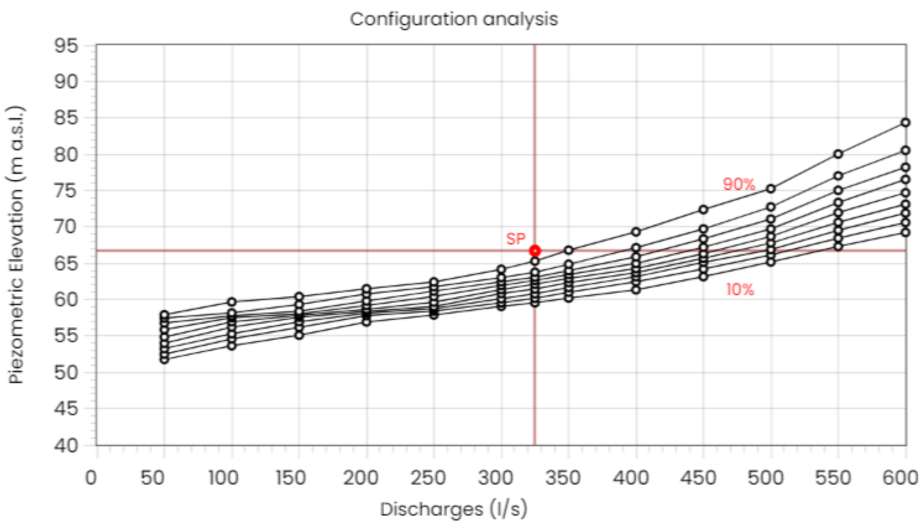
FIGURE 5.7
**Layout of the Lecce network**



*Source: Lamaddalena, N. & Piccinni, A. F. 1993. Indexed characteristic curves of an irrigationnetwork for the lifting plant design. Riv di Ing Agr, 3:129-135.*

Using the ICC model, 500 different random configurations were assessed with discharges ranging from 100 $ls^{-1}$ to 600 $ls^{-1}$. The resulting ICC are shown in Figure 5.8 and demonstrate that the observed performance is good as more than 90 percent of configurations are fully satisfied. The red lines defines the design parameters and the system is capable to accomodate increased irrigation demand due to possible changes in cropping pattern.

FIGURE 5.8
**Indexed Characteristic Curves**




*Source: elaborated with COPAM v4.0.*

Based on the author's experience, ICC capacity is good if it is more than 80 percent (Table 5.1). For this system, the appraisal indicates that system capacity is good, and no additional investigation is required.

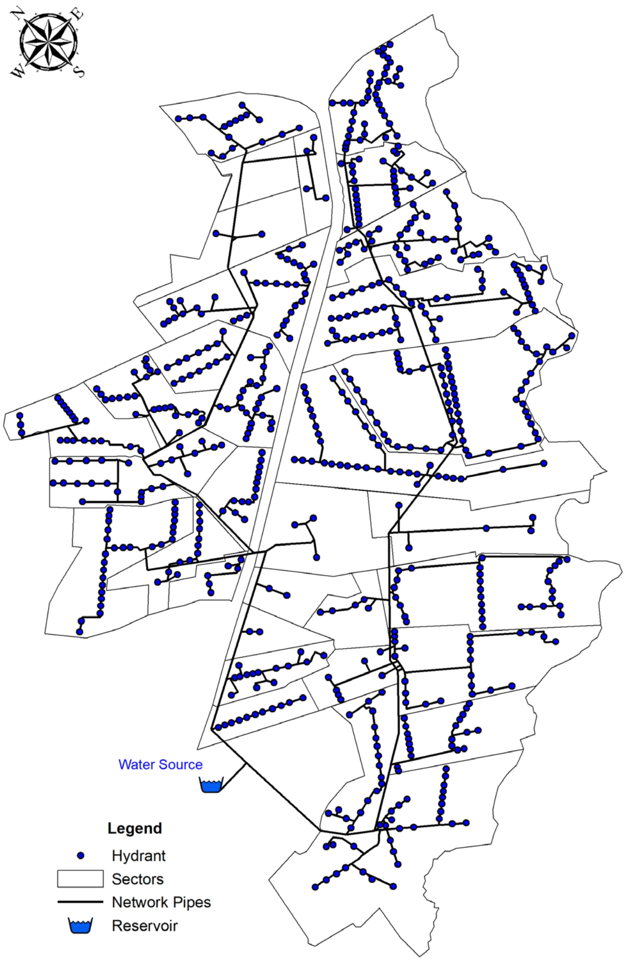
TABLE 5.1
**ICC capacity assessment**

| ICC | Capacity assessment |
|---|---|
| > 80 percent | Good |
| < 80 percent | Additional investigation is required |

## 5.4.2 A pressurized irrigation system in Foggia (Italy)

This system, called "District 4", is located in the province of Foggia (Italy). It covers 3 250 ha and is equipped with 660 hydrants with a discharge requirement of 10 $ls^{-1}$ (Figure 5.9), all equipped with flow regulators. It is served by a daily storage reservoir of 28 000 $m^3$ with an upstream piezometric elevation of $Z_0$ = 139 m a.s.l. The minimum design pressure at the hydrants is 2 bar (20m head). Because of the topography, the system is pressurized without a pumping station. The maximum recorded discharge at the upstream station is 1 200 $ls^{-1}$. The area slopes downwards with land elevations ranging from 50 m a.s.l. to around 102 m a.s.l.

FIGURE 5.9
**Layout of the District 4 network**

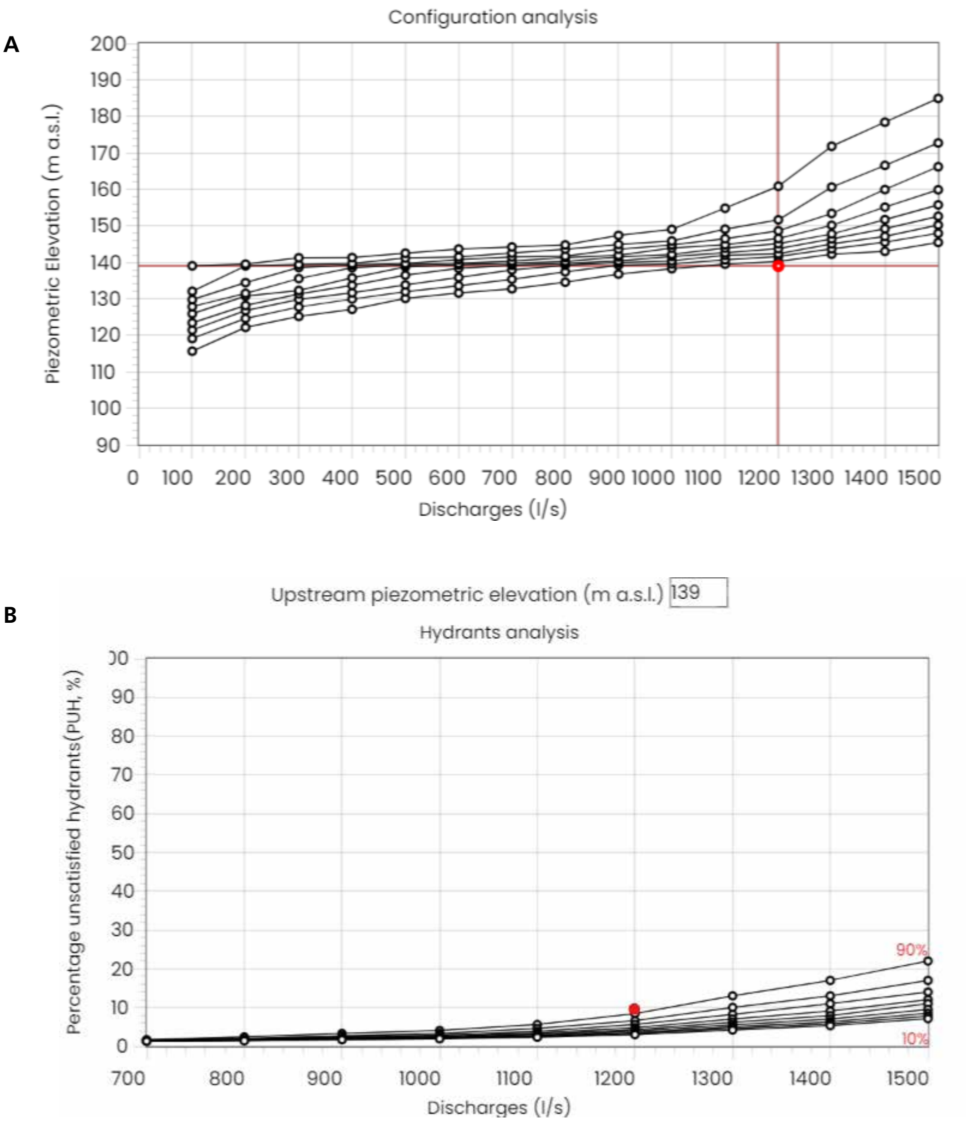



*Source: Lamaddalena, N. & Piccinni, A. F. 1993. Indexed characteristic curves of an irrigation network for the lifting plant design. Riv di Ing Agr, 3:129-135.*

The ICC model generated 500 different random discharge configurations with discharges at the upstream reservoir ranging from 100 $ls^{-1}$ to 1 500 $ls^{-1}$. The resulting ICCs are shown in Figure 5.10a. They demonstrate that the observed performance is poor, and less than 10 percent of configurations are fully satisfied during the peak period when the upstream piezometric elevation is 139 m a.s.l.and the maximum discharge is 1 200 $ls^{-1}$.

The poor results from the ICC model indicate that additional investigation at the hydrants is needed using the AKLA model. The model results, based on the PUH, indicate that, for the upstream discharge of 1 200 l $s^{-1}$ and upstream piezometric elevation of 139 m a.s.l., only 10 percent of the hydrants are not fully satisfied for 90 percent of the generated configurations (Figure 5.10b).

FIGURE 5.10
**A) indexed characteristic Curves B) PUH curves Layout of the District 4 network**




*Source: elaborated with COPAM v4.0.*

Based on the author's experience, PUH is good if less than 10 percent (Table 5.2).

TABLE 5.2
**PUH capacity assessments**

| PUH | Capacity assessment |
|---|---|
| <10 percent | Good |
| 10 percent-30 percent | Fair |
| >30 percent | Not adequate |

Based on this result, this appraisal indicates that system capacity is good despite the preliminary concerns raised by the ICC result.

### 5.4.3 Conclusions

The two examples illustrate the usefulness of both the ICC and PUH indicators for appraising irrigation system capacity. In particular, the following rules apply:

- The ICC model should be used as a first choice. If the operating point on the ICC curve is greater than 80 percent, the system can be appraised as good.
- If the operating point is less than 80 percent, use the AKLA model to investigate further and calculate the PUH to better understand the operating pressure problems during system operation. If the PUH is less than 10 percent, then the irrigation system capacity can be assessed as "Good".

# 6. Appraising system equity

Equity assesses the quality of service distribution among farmers. This indicator is based on the RPD, which assesses variability across the irrigation system in terms of volume, discharge, and pressure at hydrants. In particular:

- Pressure equity (EH) measures the spatial uniformity of pressure at all hydrants operating during the time T, i.e., corresponding to a configuration of N hydrants operating simultaneously. This can be defined for the whole system or sub-system by taking into account all generated hydrant configurations, or it can be for a pre-selected percentage of deficit occurrence (EH percent). This indicator is useful when the flow regulators are installed on the hydrants.
- Discharge equity (EQ) measures the spatial uniformity of discharges delivered to all hydrants operating during the time T, i.e., corresponding to a configuration of N hydrants. It measures the variation of actual hydrant discharges from the nominal hydrant discharge. It can be defined for the whole system or sub-system by taking into account all generated hydrants configurations, or it can be for a pre-selected percentage of deficit occurrence (EQ percent). This indicator is relevant when flow regulators are not installed on the hydrants

This publication deals only with systems using flow regulators at hydrants and so only considers pressure equity. If discharge regulators are not used, then both pressure and discharge equity would need to be taken into account in appraising the system.

## 6.1 PRESSURE EQUITY

Pressure equity is defined in terms of pressure head at farm hydrants, which are assumed fitted with flow regulators that fix the discharge (Qn) at the nominal value. EH indicator assesses the ability of the system to maintain acceptable pressures at the farm hydrants. Box 6.1 Illustrates how this is calculated based on RPD at each hydrant. The results can be presented digitally and also graphically for a predefined percentage of occurrence. Based on the authors' experience, 90 percent RPD represents a good EH level (Table 6.1).

BOX 6.1
**Computing pressure equity**

The average EH of an irrigation system is

$$EH = \frac{1}{C} \sum_{r=1}^{G} \frac{1}{N} \sum^{N} \frac{H_J}{H_{min}} \qquad (6.1)$$

If Hj > Hmin , it is assumed that Hj = Hmin.

The values of EH range between 0 (poor EH) and 1 (good EH). More precisely, this can also be defined in terms of probability of EH (i.e. EH percent).

Defining the relative pressure deficit, ($\Delta H_{j,r}$), at each hydrant (j) in each configuration (r), as:

$$\Delta H_{j,r} = \frac{H_{j,r} - H_{min}}{H_{min}} \qquad (6.2)$$

$H_{j,r}$ = Pressure head at the hydrant j in the configuration r

$H_{min}$ = minimum pressure head at the hydrants

From this equation, if $\Delta H_{j,r} \geq 0$ the pressure head at the hydrant is enough for an appropriate on-farm irrigation ($H_{j,r} \geq H_{min}$). If $\Delta H_{j,r} < 0$ the pressure head at the hydrant is not enough.

Within each configuration, the AKLA model computes the RPD at each hydrant based on the available piezometric elevation at the head of the network, $Z_0$ [m a.s.l.], and the discharge $Q_o$, for a number of selected configurations C. Using Eq.5.4, the number of hydrants corresponding to the discharge $Q_o$ is calculated. Later, the $K_r$ hydrants simultaneously operating are randomly drawn. This procedure is repeated several times for the pre-selected number of configurations[6].

For each configuration, the pressure head at each hydrant is computed. The relative pressure deficit, $\Delta H_{j,r}$ (Eq. 6.2), may be represented in a plane (hydrants numbering, ΔH). In this way the hydrants with insufficient pressure head can be identified. Also the upper (0 percent), the lower (100 percent) and the $ICC_S$ (from 10 percent to 90 percent) may be represented in the same plane.

This procedure assesses the importance of failure and identifies possible solutions to hydrants with a pressure deficit.

COPAM v4.0 also computes the $EH_{percent}$ but this is limited to systems equipped with flow regulators.

Pressure equity for a pre-defined percentage of pressure deficit occurrence is:

$$EH, percent = \frac{1}{R} \sum_{j=1}^{R} \frac{Hj, percent}{Hmin} \qquad (6.3)$$

Where:
$H_{j,\ percent}$ = Pressure head at the hydrant j in the pre-selected probability envelop (ranging from 0 percent to 100 percent). It is suggested to consider $H_{j,90}$ percent envelope.

To be noted that when $H_j > H_{min}$ than $H_j = H_{min}$ is assumed.

R = total number of hydrants in the network

Values of EH percent around 1 indicates a balanced pressure distribution among the operating hydrants and values close to and below to 0.5 indicates an unbalanced pressure distribution with consequences for operational problems (Table 6.1). Such ranges are arbitrarily assumed, based on the experience of the authors.

*Source: Authors' own elaboration based on COPAM v4.0.*

[6] Note that when generating different configurations the withdrawn hydrants are not eliminated from one generation to the next. This is in line with the theory of random generation numbers.

TABLE 6.1
**Equity assessment criteria**

| $EH_{90\%}$ | Equity assessment |
|---|---|
| 0.8 – 1 | Good |
| 0.5 < 0.8 | Fair |
| < 0.5 | Not adequate |

## 6.2 INPUT DATA

The input data required for appraising EH includes the applied water delivery schedule and peak discharge. A discharge measuring device at the head of the network is desirable to provide information on the peak discharge and an understanding of farmers' behavior.

## 6.3 CASE STUDY: FOGGIA, ITALY

The following case study illustrates how the EH indicator is computed.

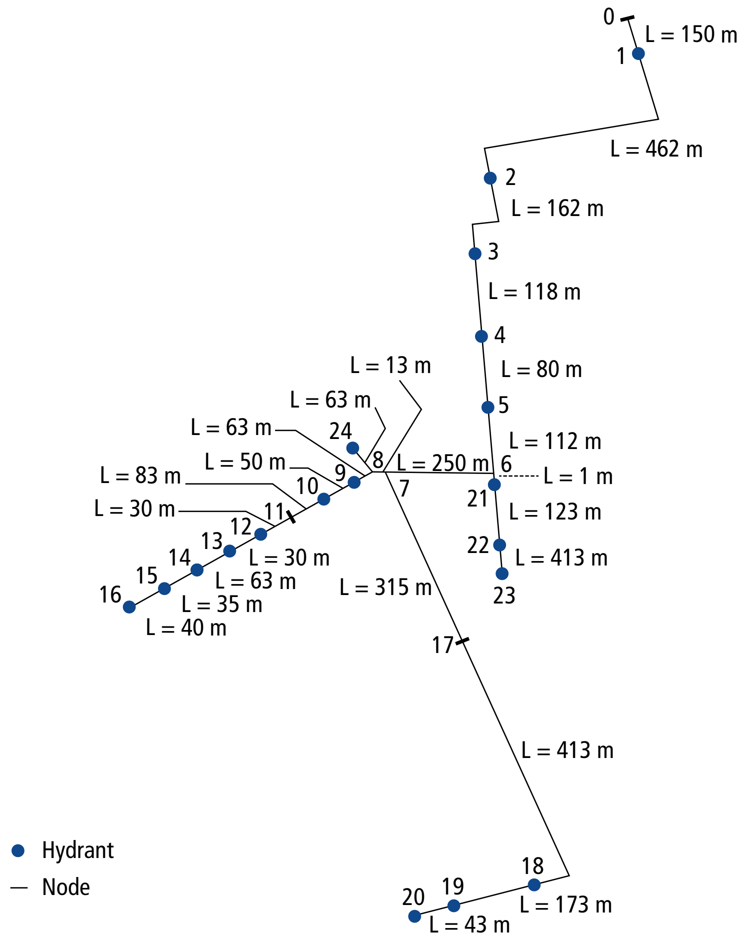
The irrigation system is located in the province of Foggia (Italy). It is called "Sector 25", it covers 60 ha and is equipped with 19 hydrants, each with a fixed discharge of 10 l $s^{-1}$ (Figure 6.1). All hydrants are equipped with flow regulators to guarantee constant hydrant discharges even when the pressure fluctuates. The upstream piezometric elevation is 128 m a.s.l. The minimum design pressure head at the hydrants is 2 bars, based on the low-pressure requirement of the on-farm irrigation systems. The maximum recorded discharge at the head of the system is 50 l $s^{-1}$. The area is almost flat, with land elevations ranging from 101 m a.s.l. to 95 m a.s.l. The AKLA model was used to compute the RPD using 100 different random hydrant operating configurations (Figure 6.2).

Assuming that 90 percent is an acceptable level of RPD, hydrants 10, 12, 13, 14, 15, 16, 18, 19, 20, 22, 23 experience failure, whereas at hydrants 18, 19, 20, 22, 23 failure can be reduced. Using the 90 percent envelope, the irrigation system EH is:

$$EH_{90\ percent} = 0.95$$

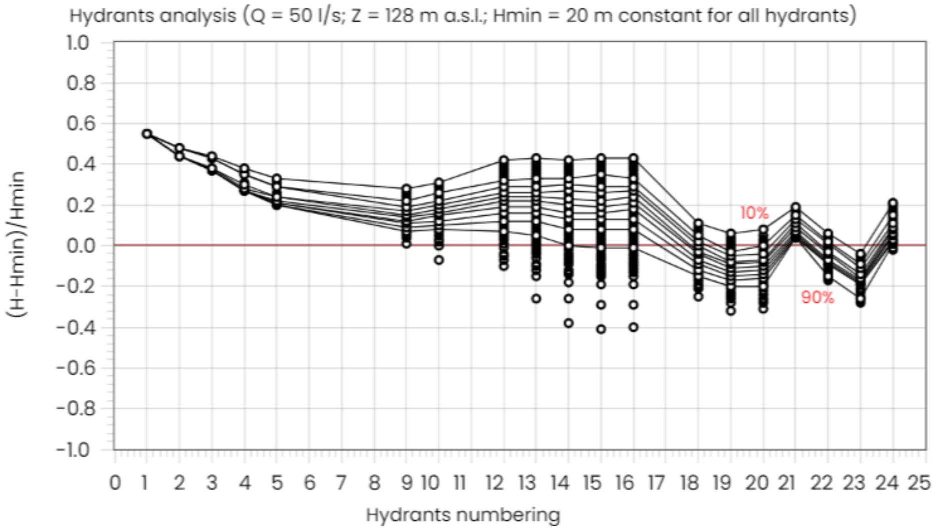
This system is assessed as good. The equity can increase or decrease if different percentage envelopes are considered.

FIGURE 6.1
**Layout of the network**




*Source: Lamaddalena, N. & Sagardoy, J. 2000. Performance Analysis of On-demand Pressurized Irrigation Systems. FAO Irrigation and Drainage Paper No. 59. Rome, Italy. (also available at http://www.fao.org/3/ah860e/ah860e00.htm).*

FIGURE 6.2
**RPD at hydrants**




*Source: elaborated with COPAM v4.0.*

# 7. Appraising system sensitivity

Providing adequate pressure at hydrants depends on many factors like the upstream discharge and pressure, which tend to fluctuate as the demand for water changes in the system. Thus assessing the sensitivity of pressure at hydrants under varying upstream conditions is a key issue (Lamaddalena and Sagardoy, 2000). Much of the early work on sensitivity focused on open channel systems (Box 7.1). However, the concept is applied here to pressurized systems by replacing upstream water level changes with changes in pressure and its impact on discharge at the farm hydrant. Hydraulically, the pressure at the hydrant determines the level of service provided to the farmer (Ramos *et al.*, 2009), and any change in pressure can affect it. Thus, hydrant sensitivity is defined as an indicator relating to the variation in pressure head at the hydrant, which is sensitive to changes in pressure at the head of the system.

BOX 7.1

**Early development of a sensitivity indicator**

Much of the early work on sensitivity focused on open channel distributions systems rather than pressurized pipe systems. Renault (2000) and Kouchakzadeh and Montazar (2005) defined the hydraulic sensitivity indicator of an irrigation structure ($S_{structure}$) as the ratio of relative (or absolute) variations of output hydraulic parameters ($V_{output}$) to the input ($V_{input}$). This is not a static hydraulic parameter of a structure as it varies with time.

$$S_{structure} = \frac{V_{out}}{V_{inp}} \qquad (7.1)$$

For open channel systems, different levels of sensitivity are used: structures, nodes, reaches, and subsystems. For instance, the sensitivity (S) of an off-take is defined as the fractional change of discharge ($q$) caused by the rate of change in water level ($dH_1$) in the parent canal. This expression refers to actual depth ($H_1$). (Kouchakzadeh and Montazar, 2005; Renault and Hemakumara, 1997).

$$S = \frac{dq}{q} \bigg/ \frac{dH_1}{H_1} \qquad (7.2)$$

Horst (1998) introduced the system response theory and presented a general approach defining the relative change of the offtake discharge ($q$) to the relative change of parent canal discharge (Q):

$$S = \frac{dq}{q} \bigg/ \frac{dQ_1}{Q} \qquad (7.3)$$

*Source: Kouchakzadeh, S. & Montazar, A. 2005. Hydraulic sensitivity indicators for canal operation assessment. Irrigation and Drainage, 54(4): 443–454 and Renault, D. & Hemakumara, H.M. 1997. Mobilization of resources, sensitivity and vulnerability in canal operation: diagnosis and preliminary analysis. Marrakech, Morocco, Modern techniques for manual operation of irrigation canals. Proceedings of the Fourth International ITIS [Information Techniques for Irrigation Systems] Network Meeting.*

Based on this early work, the authors have proposed two performance indicators to address sensitivity: RPD and reliability. RPD is described in Chapters 4 and 5. This section focuses on reliability and its relationship with sensitivity as an additional indicator of adequacy and long-term service to farmers.

## 7.1 SENSITIVITY INDICATOR

Lamaddalena and Fouial (2019) quantified hydrant sensitivity as the changes in hydrant reliability (Re) due to the changes in the upstream discharge and/or pressure. This provides important additional information to irrigation managers on the status of each hydrant for different operating conditions.

In this context, Re is defined at the hydrant level as the probability of a hydrant remaining in a satisfactory state:

$$Re = Prob\ [H_{j,\,t} \geq H_{min}] \qquad (7.4)$$

In other words, for a large number of analysed configurations:

$$Re_j = \frac{N_{s,j}}{N_{o,j}} \qquad (7.5)$$

Where $N_{s,j}$ is the number of times the pressure at hydrant *j* is satisfied, and $N_{o,j}$ is the total number of times where hydrant *j* is open.
Hydrant sensitivity, $S_{hyd}$, is assessed according to the degree of change in reliabilities under different upstream conditions, and for a hydrant (j), it is defined as:

$$S_{hyd,j} = Re_{j,t}\ (Qup_t) - Re_{j,t-1}\ (Qup_{t-1}) \qquad (7.6)$$

and/or

$$S_{hyd,j} = Re_{j,t}\ (Zup_t) - Re_{j,t-}1\ (Zup_{t-1}) \qquad (7.7)$$

Where $Qup_t$ and $Qup_{t-1}$ are upstream discharges recorded at time *t* and *t-1*, respectively; $Zup_t$ and $Zup_{t-1}$ are upstream piezometric elevations recorded at time *t* and *t-1*, respectively; and $Re_{j,t}$ and $Re_{j,t-1}$ are the reliabilities of the hydrant *j* at time *t* and *t-1*, respectively.

COPAM v4.0 can be used to compute Re for various changes in upstream pressure, and sensitivity is the difference between the computed reliabilities.

A classification for sensitivity in Table 7.1 is based on the author's experience of appraising systems and establish the spatial distribution of the most sensitive hydrants in a network.

TABLE 7.1
**Classification for sensitivity**

| Indicator | Good | Fair | Bad |
|---|---|---|---|
| Sensitivity ($S_{hyd}$) | $S_{hyd} \leq 0.2$ | $0.2 < S_{hyd} \leq 0.5$ | $S_{hyd} > 0.5$ |

## 7.2 INPUT DATA

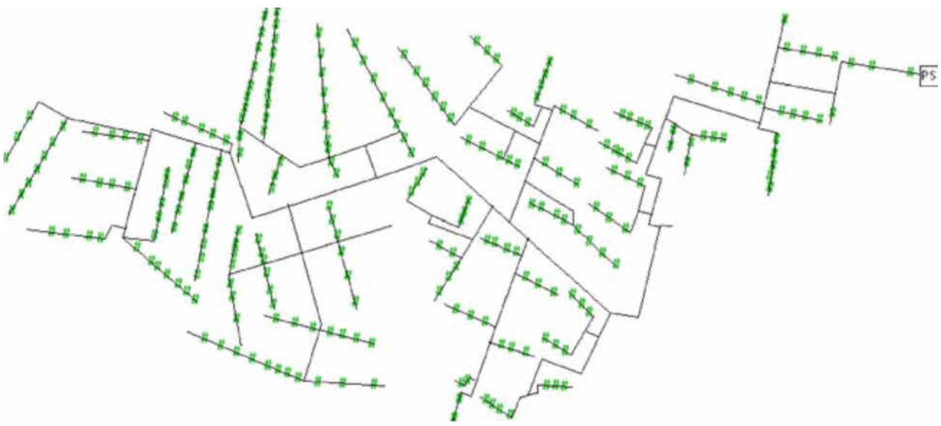
The AKLA model is used to first calculate the RPD and, in turn, can calculate Re and hydrant sensitivity. The network is assumed to be a branching type, and the hydrants are assumed to be equipped with flow regulators. Thus, the input data is the same as for previous calculations.

Graphical presentations are available for both reliability and sensitivity and can help in visualizing problem areas.

## 7.3 CASE STUDY: FOGGIA, ITALY

The following case study illustrates how hydrant sensitivity is computed to appraise the performance of irrigation "District 1a" located in the Sinistra Ofanto irrigation scheme, Foggia, Southern Italy (Figure 7.1). The system covers an irrigated area of 564 ha and is designed for on-demand operation with a peak design discharge of 300 $ls_{-1}$. All hydrants have a nominal discharge of 10 $ls_{-1}$ and are equipped with appropriate flow regulators. A pumping station with variable speed devices is installed at the head of the system and is regulated to guarantee a constant upstream pressure head of 65 m. The land elevation at the pumping station is 206 m a.s.l. The minimum design pressure head at all hydrants is 20 m, and almost all the farms are equipped for drip irrigation. The hydrant sensitivity is computed for two discharges: $Q_{0,1}$ = 300 $ls_{-1}$ being the design discharge, and $Q_{0,2}$ = 400 $ls_{-1}$ being the maximum recorded discharge during the peak irrigation period. One thousand random configurations were generated to appraise the system.

FIGURE 7.1
**Layout of the District 1a network in Foggia, Italy**

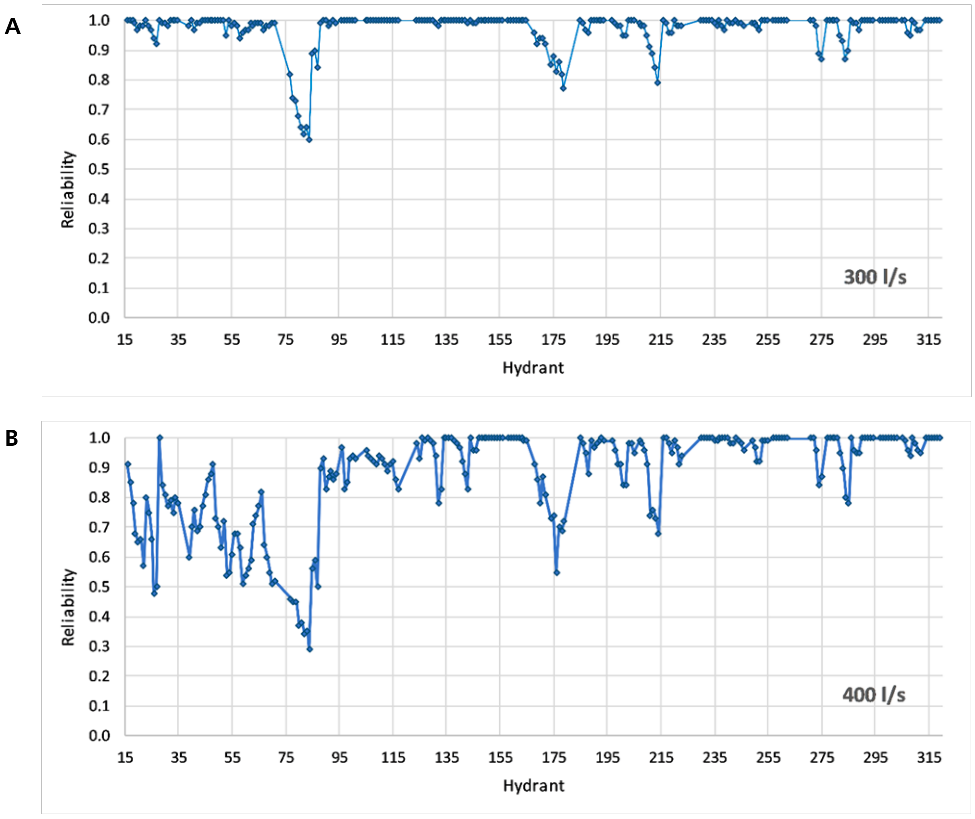



*Source: Lamaddalena, N. & Khila, S. 2011. Efficiency-driven pumping station regulation in on-demand irrigation systems. Irrig Sci, 31: 395-410, https://doi.org/10.1007/s00271-011-0314-0.*

The results for the reliability indicator for the two discharges are illustrated in Figure 7.2. For the design discharge of 300 $ls^{-1}$, 95 percent of the hydrants are above 0.8, and most are 1.0. At the higher discharge of 400 $ls^{-1}$, reliability values between 0.8 to 1 decrease from 95 percent to 75 percent, and, for some hydrants, reliability is less than 0.5.

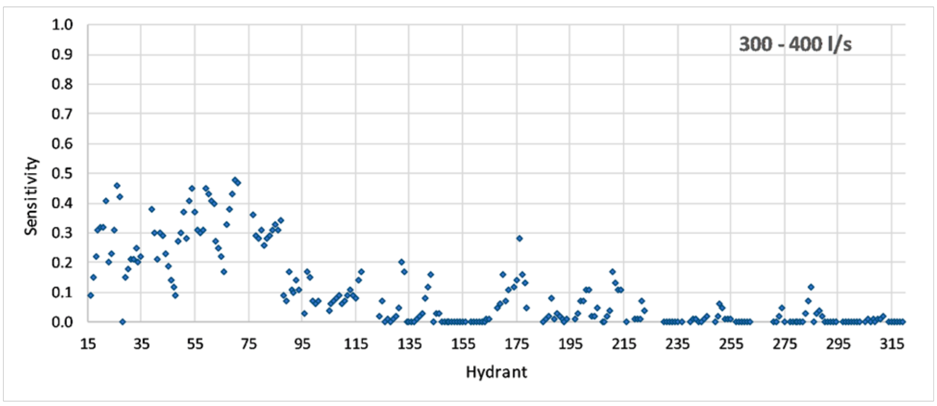
Hydrant sensitivity is illustrated in Figure 7.3 and shows that the first 90 hydrants close to the pumping station are highly sensitive to increasing the discharge from 300 $ls^{-1}$ to 400 $ls^{-1}$. However, all the values are less than 0.5, so sensitivity is defined as fair (Table 7.1).

FIGURE 7.2
**Re for discharge (a) 300 ls$^{-1}$ (b) 400 ls$^{-1}$**




*Source: elaborated with COPAM v4.0.*

FIGURE 7.3
**Hydrant sensitivity (from Q=300 ls$^{-1}$ to Q=400 ls$^{-1}$)**




*Source: elaborated with COPAM v4.0.*

Note that if the reliability value of a hydrant is zero for the initial discharge, it will remain zero for a higher discharge, and the sensitivity indicator will be zero. But this does not mean that the hydrant performance is good. Sensitivity must always be combined with reliability analysis to avoid errors when interpreting results.

# 8. Appraising perturbation risks

## 8.1 INTRODUCTION

Perturbations are unintended changes that take place in discharges and pressures in pipelines. They occur when there are sudden changes in discharge, such as opening/closing farm hydrants (sudden changes in configuration), pumps starting/stopping, or pipes becoming blocked or bursting. Sudden changes are undesirable in pipe networks as they often lead to significant increases in pressure that can result in burst pipes. Such changes in pressure are often referred to as 'water hammer'; in this publication, they are referred to as 'perturbations'.

On-demand irrigation inevitably creates unsteady flow condition in pipe networks, and controlling transients is now an essential part of designing and ensuring the safe operation of pipe systems (Abuiziah *et al.,* 2013). However, little is known about their behavior, and most modeling tools were developed for relatively simple pipeline systems. One approach that addresses complex system uses the method of characteristics (Wichowski, 2006). In 2018 researchers developed a Relative Pressure Variation (RPV) indicator as a means of identifying appropriate gate-valve closing times to avoid potential pipe damage (Lamaddalena *et al.,* 2018).

In 2019 (Derardja, Lamaddalena, and Fratino, 2019), two new indicators were established: i) the hydrant risk indicator, which describes the degree of risk of each hydrant creating pressure waves that travel through the pipe system, and ii) the Relative Pressure Exceedance indicator (RPE), that measures the variation in pressure in a pipeline relative to the nominal operating pressure for the pipe. RPE provides a warning to system managers of the potential risk of a pipe bursting due to excess pressure rise.

This section illustrates the use of RPE indicator for two upstream boundary conditions: flow directly from a reservoir into the network and from a pumping station. A user-friendly tool was developed to simulate unsteady flow in a pressurized irrigation system (Derardja, Lamaddalena, and Fratino, 2019) and integrated into the COPAM v4.0 software package.

BOX 8.1

**The perturbation module for unsteady flow**

Possible mechanisms that may significantly affect pressure waveforms include unsteady friction, cavitation, a number of fluid–structure interactions, and viscoelastic behavior of the pipe-wall material, leakages, and blockages. These are usually not included in standard water hammer software packages and are often hidden in practical systems (Bergant *et al.*, 2008).

The usual assumptions (Wylie, Streeter and Suo, 1993) have been considered to develop the software code:

The flow in the pipeline is considered to be one-dimensional with the mean velocity and pressure values in each section.

The unsteady friction losses are approximated to be equal to the losses for the steady-state condition.

No water column separation phenomenon occurs.

Constant wave speed is considered.

The pipe wall and the liquid behave linearly elastically.

The Euler and the conservation of mass equations are:

$$\frac{dV}{dt} + \frac{1}{\rho}\frac{\partial P}{dt} + g\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 \qquad (8.1)$$

$$a^2\frac{\partial V}{\partial s} + \frac{1}{\rho}\frac{dP}{dt} = 0 \qquad (8.2)$$

where, g is the gravitational acceleration ($ms^{-2}$), D (m) is the pipe diameter, V ($ms^{-1}$) is the mean flow velocity, P ($Nm^{-2}$) is the pressure, z is the pipe elevation (m), f is the Darcy–Weisbach friction factor and a ($ms^{-1}$) is the celerity. t (s) and s (m) represent the independent variables.

The variable V and its module |V| preserve the shear stress force direction on the pipe wall according to the flow direction.

The characteristic method makes it possible to replace the two partial differential Equation (8.1) and Equation (8.2) with a set of ordinary differential equations. All related theory along with equations related to the boundary conditions are reported in Annex A1.

**Boundary conditions**

The external conditions of flow velocity and/or pressure head are described by the boundary conditions at each end of the pipes. The strength of the characteristics method is the adequacy of analyzing each boundary and each pipe section separately along the unsteady flow time occurrence. The most common and relevant boundary conditions were considered:

I) Upstream reservoir with constant pressure head $H_0$; II) Hydrant gate valve closure arrangement; III) Upstream constant speed pump; V) Internal boundary conditions (i.e.: two-pipe junction and three-pipe junction)

**Calculation process**

At the beginning of the computation process, a steady-state simulation was executed for each configuration to establish the initial conditions. Starting from the upstream boundary condition (i.e.: reservoir water level or pumping station pressure head), by computing the head losses with the Darcy–Weisbach equation, the pressure head (H) and the flow velocity (V) are defined in each section of the system.

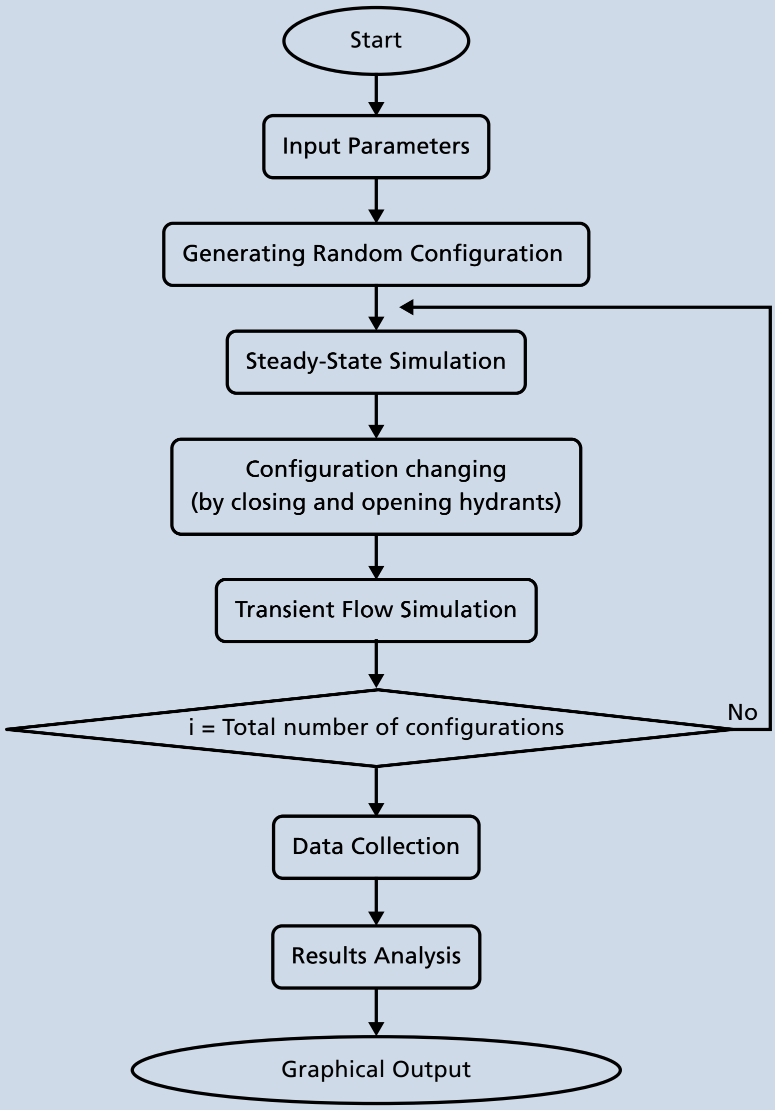
Starting with the initial H and V conditions (calculated for the steady-state flow), calculations of the new values $H_{Pn}$ and $V_{Pn}$ are carried out for each grid point with an increment of $\Delta T$ (see Figure A.1 in the Annex 1). Therefore, new values of H and V are obtained, which replace the previous ones. The process continues up to a preselected simulation time. The software selects the maximum and the minimum pressure occurring at each section through the simulation time (selection through time).

A second selection through the pipe sections for $H_{max}$ and $H_{min}$ is performed (selection through space). The analysis results are tabulated as the maximum and minimum pressure head occurred for each pipe, which will be the basis of the calculation of the indicators.

As above mentioned, in this publication Tmax has been chosen to be equal to 30s. Such value can guarantee that the non-steady flow pressure variation is no more significant. The calculation process is summarized in the software flow chart.

*Source: Authors' own elaboration based on COPAM v4.0 User's Manual.*

**COPAM v4.0 software flowchart**




*Source: Derardja, B., Lamaddalena, N. & Fratino, U. 2019. Perturbation Indicators for On-Demand Pressurized Irrigation Systems. Water, 11(3): 558. https://doi.org/10.3390/w11030558.*

## 8.2 RELATIVE PRESSURE EXCEEDANCE INDICATOR

This indicator numerically represents the pressure variation and the risk assessment with respect to the nominal pipe pressure. This can help both the designers and managers to analyse irrigation systems operating any type of water delivery schedule, including on-demand, and identify the weak points in the system:

$$RPE = 100 \times \frac{H_{max} - NP}{NP} \qquad (8.3)$$

Where:

RPE is the relative pressure exceedance (percentage)

$H_{max}$ (bar) is the maximum pressure, resulting from unsteady flow, recorded at each section, and NP (bar) is the nominal pipe pressure.

A safety coefficient (k) is introduced in the software to allow for wear and tear of pipes. Thus:

$$RPE = 100 \times \frac{H_{max} - k * NP}{k * NP} \qquad (8.4)$$

As many configurations are analysed, the RPE is presented as 10 percent equiprobability (indexed) curves. Each curve represents the probability of occurrence of a specified risk. This approach is similar to that used in previously described steady-state models. Positive values of RPE indicate a dangerous condition for the pipe.

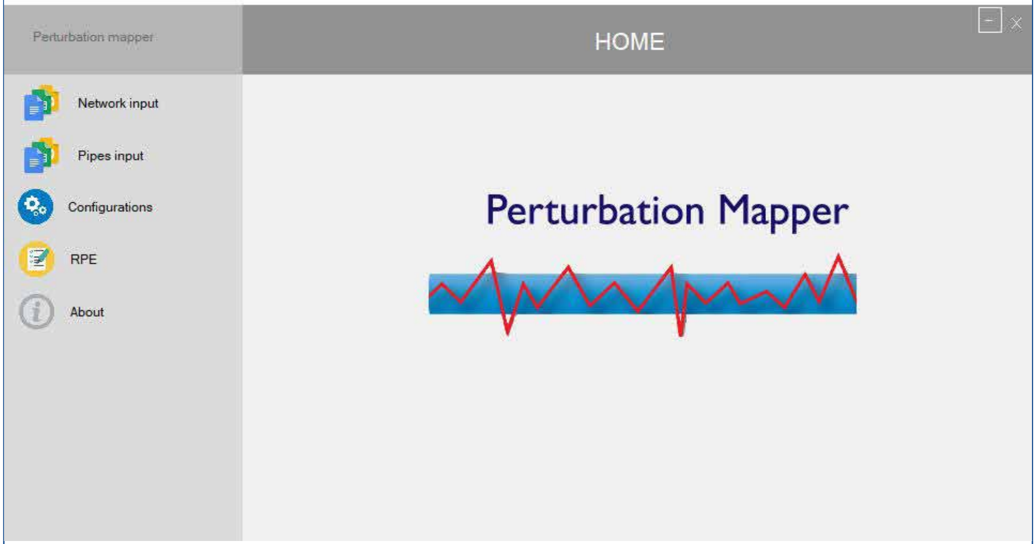
## 8.3 INPUT DATA

The Perturbation module is an integral component of the COPAM v4.0 software package. The main input file data is the same as in previous sessions. This includes the network layout, a list of pipes used and their hydraulic characteristics, hydrant discharges, and the number of configurations analysed. Two possible boundary conditions are used at the head of the system: an open reservoir and a pumping station.

## 8.4 COMPUTING PERTURBATION

Figure 8.1 illustrates the software homepage for the Perturbations module within COPAM v4.0.

FIGURE 8.1
**First screen for the perturbation module**




*Source: Screenshot of COPAM v4.0.*

Four groups of inputs options are available

### Network data input

- the initial and final node of each section
- the hydrants discharge (l/s) (at the downstream node)
- sections length (m)
- land elevation of the downstream node (m a.s.l.)

### Pipe data input

- nominal pipe diameter (mm)
- fluid bulk modulus (Pa), Young's modulus for pipe material (Pa), pipe roughness (mm)
- nominal pipe pressure (bar)
- different pipes sections are numbered consecutively
- terminal nodes of the branches must have a hydrant
- a maximum of two sections may be derived from each node
- the network is assumed to be of branched type
- each node is identified by a number

### Configuration data input

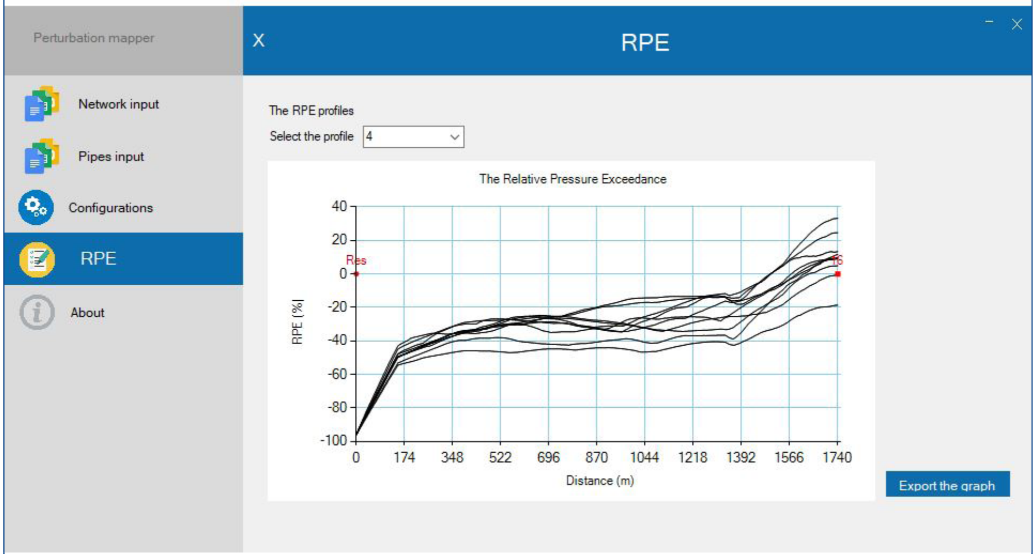
Random configurations can be automatically generated or uploaded as a file with previously generated configurations according to the type of delivery schedule applied in the area.

Information is required about the impact of valve closing time and the fraction of the valve opening. See Annex A1.

**Relative pressure exceedance profiles output**

The relative pressure exceedance provides information for each network profile selected from a drop-down list. The initial and final nodes of each profile are shown in green on the selected profile (Figure 8.2).

FIGURE 8.2
**Example of RPE Profile Res-node 16**




*Source: elaborated with COPAM v4.0.*

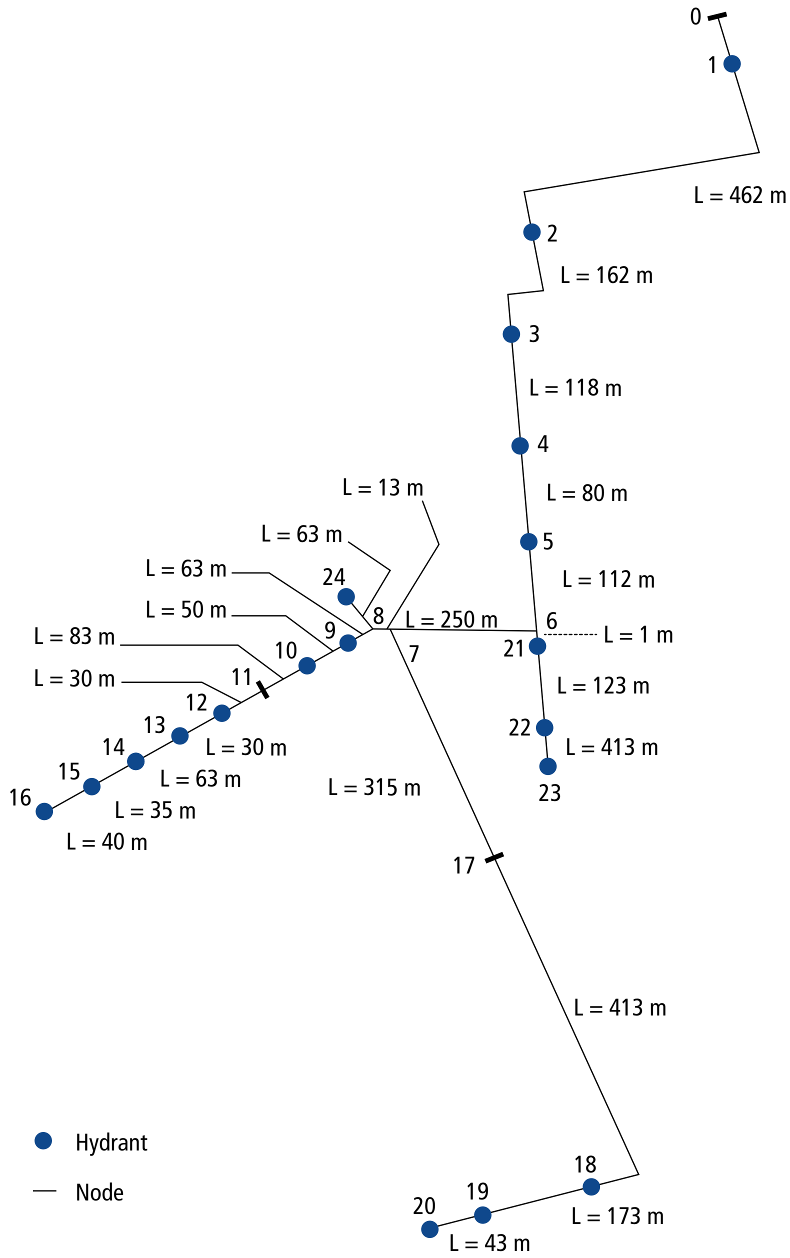
## 8.5 CASE STUDY: FOGGIA, ITALY

The following case study illustrates how perturbations can be assessed in an irrigation system using the RPE, and also the impact of hydrant valve closure times on the magnitude of perturbations for Sector 25, in the "Sinistra Ofanto" irrigation scheme, located in Foggia in Italy.

The system consists of 19 hydrants with a nominal discharge of 10 $ls^{-1}$ and an upstream piezometric elevation of 128 m a.s.l. (Figure 8.3). The nominal pressure for the pipework is 10 bar. There are four possible operating modes for this sector: open, closed, opening, and closing. The network was designed to have five hydrants open at the same time. Together these produce a large number of possible configurations. To simplify the analysis and for clarity, a smaller number of configurations was selected. Nonetheless, the software supports large-scale networks and all desired hydrant configurations.

Assuming five hydrants are open simultaneously, perturbations were generated by closing two hydrants and substituting them with opening two new ones. The variation in discharges flowing into the network due to variations in demand is presented through different hydrant configurations.

FIGURE 8.3
**Layout of the network (Sector 25)**



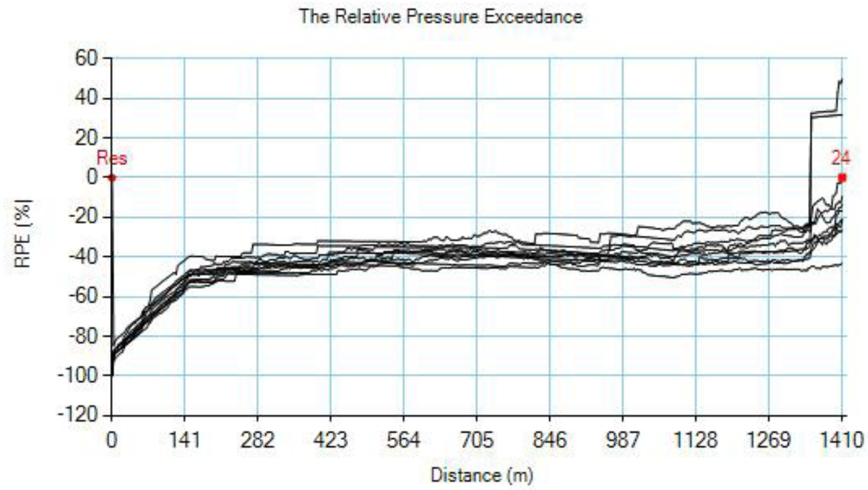

*Source: Lamaddalena, N., Khadra, R. & Tlili, Y. 2012. Reliability based pipe size computation of on-demand irrigation systems. Water Resources Management, 26: 307-328.*

Initially, the hydrant closing time Tc = 0 (instantaneous closure) provides the most extreme case from a pressure perspective. Figure 8.4 illustrates the pressure profile for the pipeline between the reservoir and hydrant Node 24 (Res-Node24). Following closure, the maximum and minimum pressure waves were recorded along the pipe (at 1 410 m) is presented as 10 percent equiprobability curves.

RPE provides a clear picture of the pipe sections at risk. Pipes are considered safe when the RPE values are negative, which means that the maximum pressure does not exceed the nominal pressure. RPE = 0 means that the transient pressure is equal to the nominal pressure. When the value rises above zero, the pipe is then at risk.

The RPE is negative from the reservoir down to Node 6 (987 m), so this section of the pipeline is not at risk. However, beyond Node 6, RPE becomes positive, it increases downstream, and the pipeline is at risk from this point onwards down the Node 24. The greatest RPE value is at Node 24, where there is the greatest risk of failure.

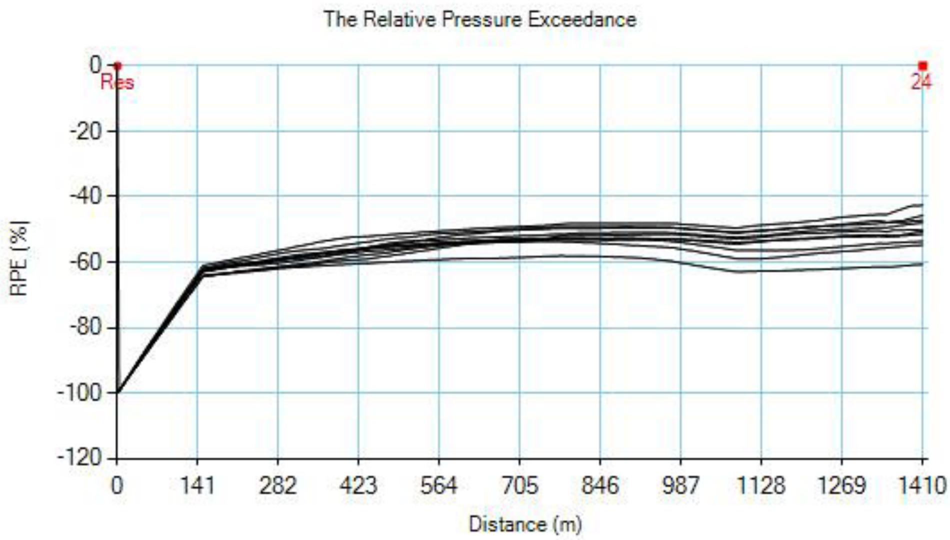
FIGURE 8.4
**RPE for 100 configurations. Tc= 0 sec**




*Source: elaborated with COPAM v4.0.*

Pressures are much lower when the hydrant is gradually closed, Tc = 6 sec (Figure 8.5), the RPE is always negative, and there is no risk from perturbation along the pipeline from the reservoir down to Node 24. This is evidence to show that farmers must learn to open and close their hydrants slowly to avoid excessive pressure rises and pipe bursts.

FIGURE 8.5
**RPE for 100 configurations. Tc= 6 sec**




*Source: elaborated with COPAM v4.0.*

# 9. Using Mapping system and services for pressurized irrigation: Case studies

Case studies illustrate the steps toward developing a plan for modernizing systems. Although irrigation systems have many unique features, they do have a lot in common and are based on the same basic principles in terms of their design and management.

The first step is to undertake a RAP to collect data and to understand how a system is managed in a qualitative sense and how farmers behave and respond to management (Chapter 3). The next steps involve a technical appraisal of the system to establish the various indicators that describe the performance. These identify weaknesses in the system and form the basis of rehabilitation and/or modernization.

Five case studies demonstrate how MASSPRES is used to appraise a range of irrigation systems and provide a sound basis to guide modernization. The systems are located in the Mediterranean countries of Egypt, Italy, Spain, and Tunisia and represent different approaches to design and management. They include:

- Sector 25, of the “Sinistra Ofanto” irrigation system, Foggia, Italy
- an irrigation system in the Nile delta in Egypt
- the Manouba irrigation system in northeast Tunisia
- District 4, of the “Sinistra Ofanto” irrigation scheme, Foggia, Italy
- Sector VII of the MD Bembézar Irrigation District, Spain.

Details about the case study areas are reported in the description below.

## 9.1 CASE STUDY: SECTOR 25, FOGGIA, ITALY

This case study presents a detailed account of how MASSPRES was applied to a small irrigation system, called Sector 25, part of the District 4 of the “Sinistra Ofanto” irrigation scheme in Foggia, Southern Italy. It brings together all the steps described in this publication to appraise this system, how deficiencies are identified, and the technical and management options recommended for improving hydraulic system performance.

Sector 25 is equipped with 19 hydrants, all with flow regulators with a nominal discharge of 10 $ls^{-1}$. The system is branched type with one water source. The upstream recorded piezometric elevation is 128 m a.s.l.

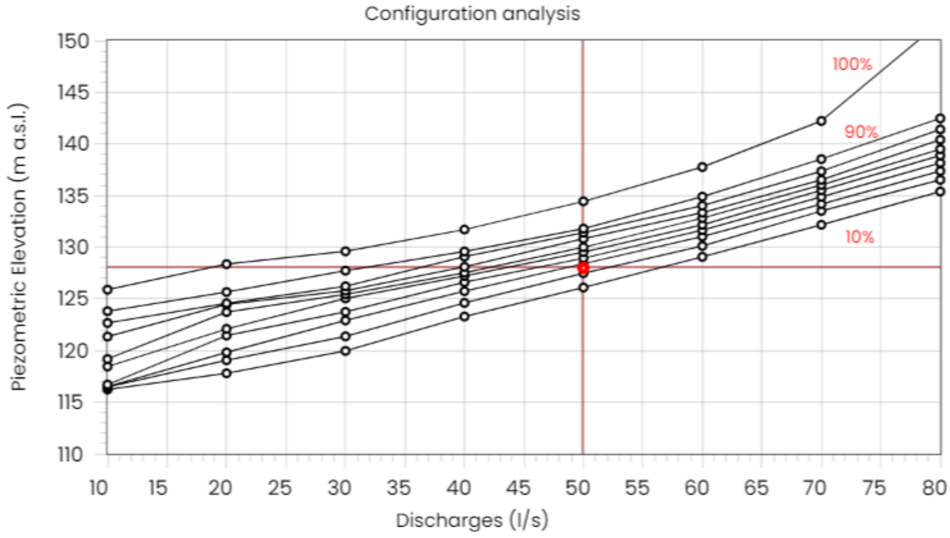
The appraisal begins with assessing the overall performance of the system, starting with the ICC model, then using the more in-depth AKLA model to assess hydrant performance in more detail.

### 9.1.1 Using the indexed characteristics curves model

The ICC model simulates the overall performance of the system by simulating pressures and discharges at farm hydrants for various operating configurations and generating a set of curves that define an envelope or range of operating conditions for the network.

Figure 9.1 illustrates the results. The red lines indicate the coordinate of the peak design discharge (50 $ls^{-1}$) and the upstream available piezometric elevation (128 m a.s.l.), which indicate that less than 30 percent of configurations are fully satisfied, and so additional investigation is needed.

FIGURE 9.1
**ICC for sector 25**

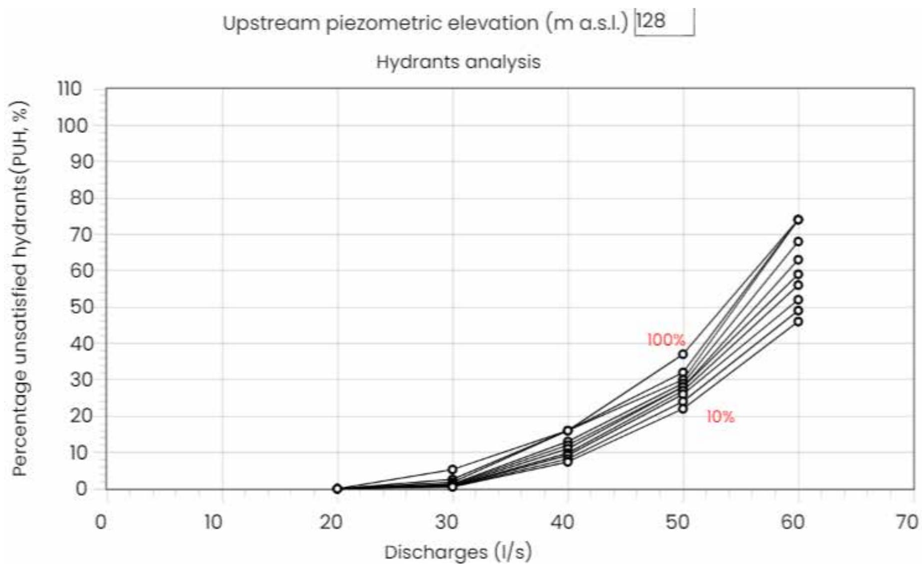



*Source: elaborated with COPAM v4.0.*

## 9.1.2 Using the AKLA model

The AKLA model offers a more in-depth performance assessment of individual farm hydrants based on the PUH. The analysis was carried out for the upstream piezometric elevation of 128 m a.s.l, and for different upstream discharges ranging between 20 $ls^{-1}$ and 60 $ls^{-1}$. Figure 9.2 illustrates the PUH results, and this indicates that for 90 percent of the configurations tested (upstream envelop curve) and for the peak discharge of 50 $ls^{-1}$ , PUH, was only 40 percent, as indicated on the Y-axes. This means that the system is not operating adequately (see Table 5.2).

FIGURE 9.2
**PUH curves for sector 25**

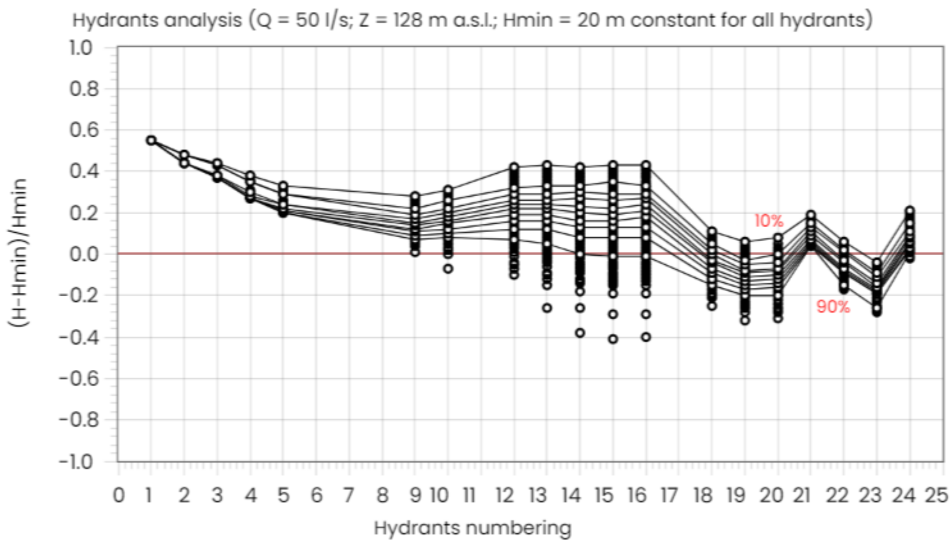



*Source: elaborated with COPAM v4.0.*

### 9.1.3 Assessing reliability

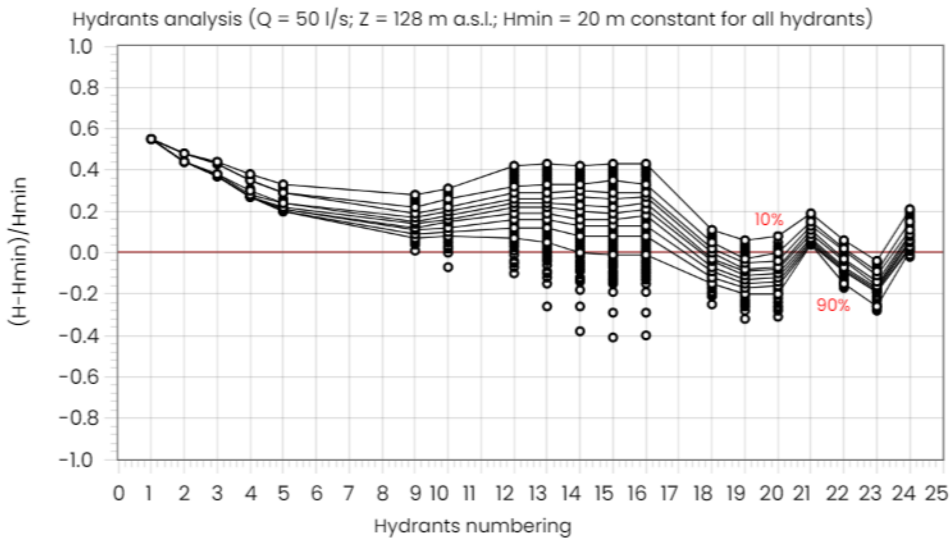
Reliability assesses the probability of a hydrant remaining in a satisfactory state based on the RPD for the peak discharge of 50 $ls^{-1}$. Figure 9.3 illustrates the results and indicates that if 90 percent of the generated configurations are considered, hydrants 18, 19, 20, 22, and 23 will fail, being the pressure head at such hydrants lower than the minimum required. Pressures at hydrants are lower when 100 percent of the generated configurations are considered (lower envelope). Reliability at such hydrants is poor (Figure 9.4).

FIGURE 9.3
**RPD for sector 25**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.4
**Re for sector 25**




*Source: elaborated with COPAM v4.0.*

### 9.1.4 Improving performance

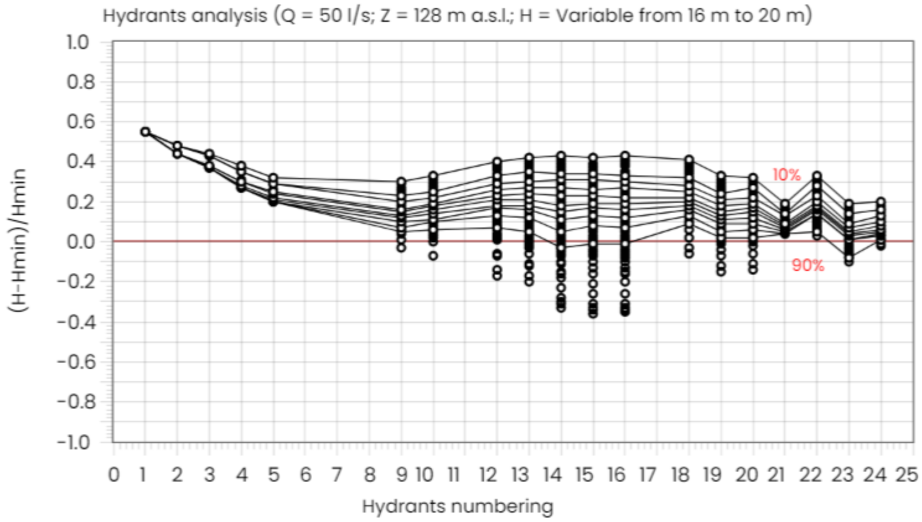
Several options are available to improve the performance of this system.

### 9.1.4.1 Changing nozzle sizes for sprinklers

Changing nozzle sizes for sprinklers on the affected farm hydrants 18, 19, 20, 22, and 23 is one option. These hydrants failed but assessing just how serious requires further investigation. The RPD for 90 percent of configurations (-0.2 m) corresponds to a pressure deficit of 4 m. This means that farm hydrants 18, 19, 20, 22, and 23 will be operating at 16 m instead of 20 m pressure. However, there are several irrigation nozzles available on the market that operate satisfactorily at 16 m pressure and produce good levels of distribution uniformity. Thus, changing nozzles on the affected farms and operating at lower pressure offers a possible solution. Re-evaluating the system and accepting the lower pressure shows that the RPD for 90 percent of the configurations significantly improves performance (Figure 9.5). The reliability at the hydrants is now greater than 80 percent (Figure 9.6).

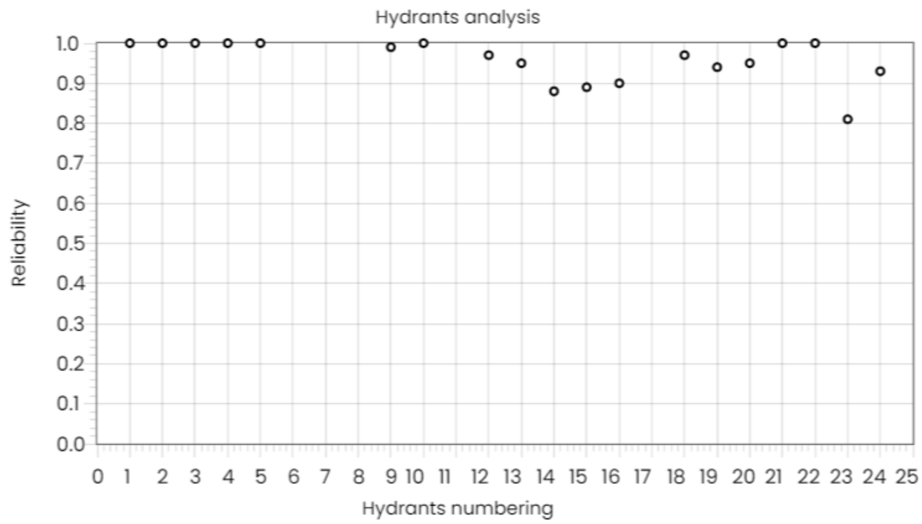
Based on this change in technology on farms 19, 20, 22, and 23, this scheme is now assessed as having good capacity.

FIGURE 9.5
**RPD for sector 25 (for variable Hmin at hydrants)**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.6
**Reliability for sector 25 (for variable Hmin at hydrants)**



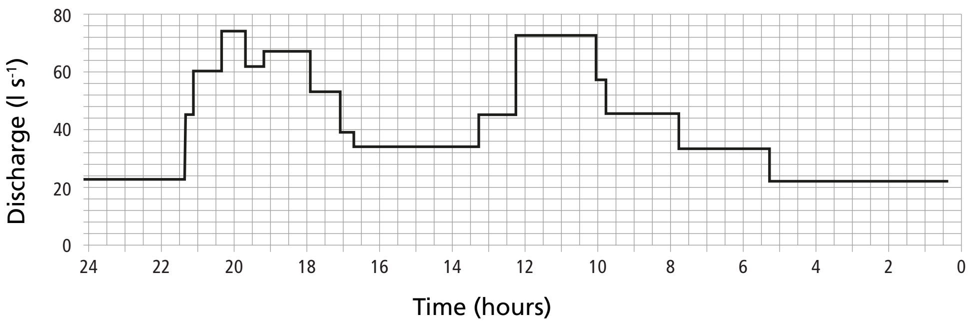

*Source: elaborated with COPAM v4.0.*

### 9.1.4.2 Reducing the discharge at the head of the system

Another option is to change the overall operating discharge for the system. A typical system demand hydrograph (Figure 9.7) indicates that discharges are much lower outside the periods of peak demand each day. Rather than assessing the system based 50 $ls^{-1}$, lowering the maximum allowable discharge may prove beneficial.

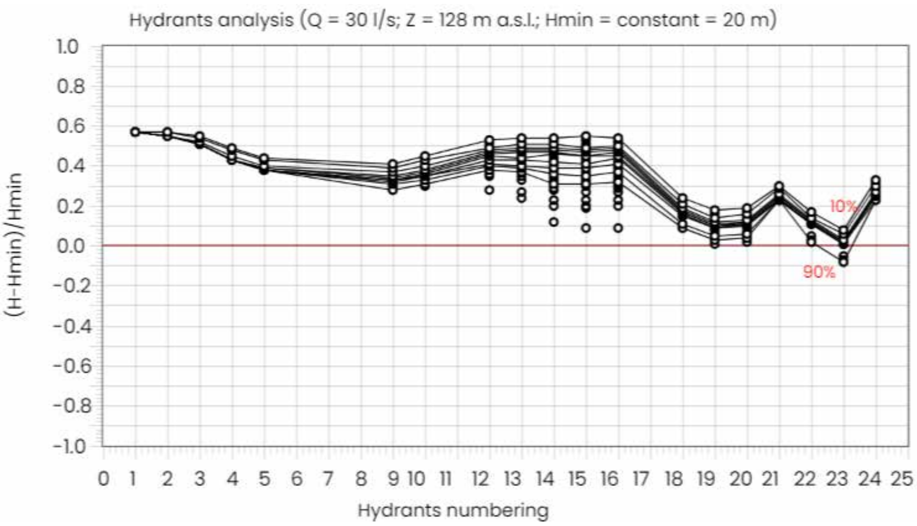
If an upstream discharge of 30 $ls^{-1}$ is considered for the analysis, the performance improves to very good in terms of RPD (Figure 9.8) and reliability (Figure 9.9). Also, advising farmers using hydrants 18, 19, 20, 22, and 23 to avoid irrigating during peak times during the day or restricting them to irrigating at night would lower the peak demand on the hydrograph and have a beneficial effect in meeting all the irrigation demands.

FIGURE 9.7
**Typical demand hydrograph recorded at the upstream end of the Sector 25**



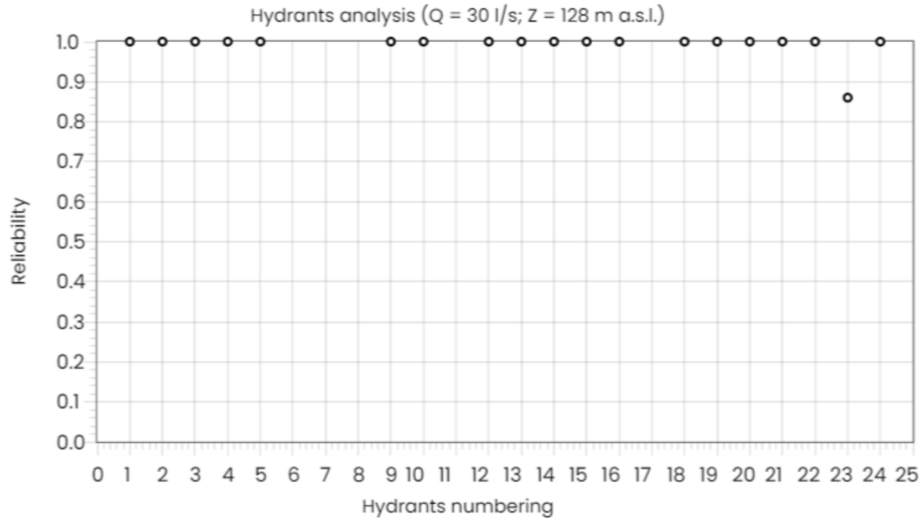

*Source: elaborated with COPAM v4.0.*

FIGURE 9.8
**RPD for the Sector 25 (upstream discharge of 30 $ls^{-1}$)**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.9
**Hydrants' reliability for the Sector 25 (upstream discharge of 30 ls$^{-1}$)**




*Source: elaborated with COPAM v4.0.*

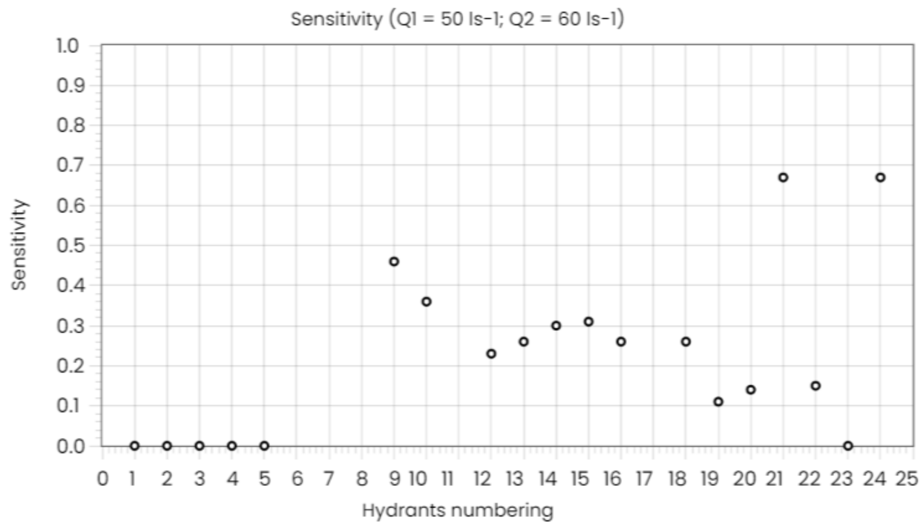
### 9.1.4.3 Introducing electronic hydrant cards to limit irrigation times

Another solution is to equip hydrants with electronic card readers that limit the times that farmers can irrigate (Lamaddalena, 1995; Nardella, 2004). The hydrants can be programmed to prevent farmers from irrigating during peak hours of the day. This would be penalizing some farmers, but they could be offered incentives to do this, such as additional irrigation water or lower water fees.

## 9.1.5 Assessing sensitivity

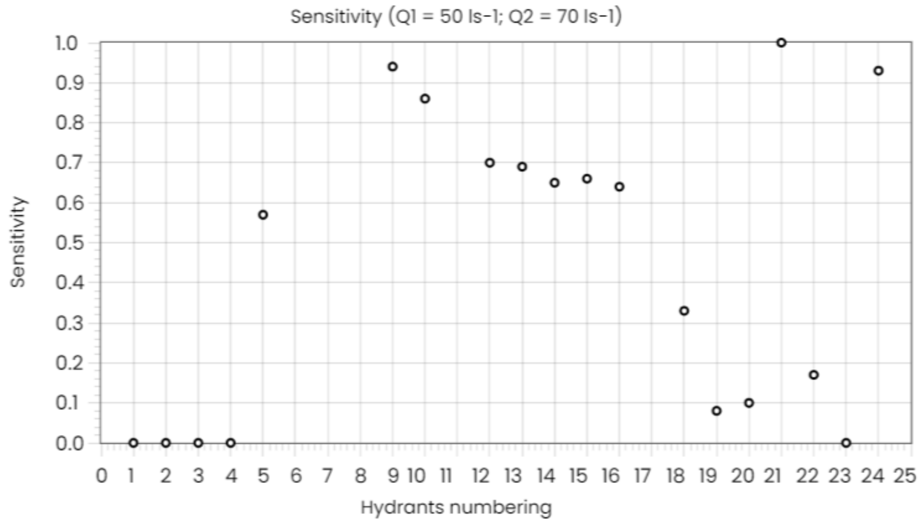
Hydrant sensitivity is an indicator of change in hydrant reliability due to the changes in the upstream discharge and/or pressure. Figure 9.10 illustrates the sensitivity of hydrants as the upstream discharge increases from 50 ls$^{-1}$ to 60 ls$^{-1}$ (i.e., six hydrants are open rather than 5). The sensitivity of hydrants 1 to 5 is good, but beyond that point, sensitivity increases for most hydrants. Figure 9.11 illustrates the significant change in sensitivity when the discharge increases to 70 ls$^{-1}$ and seven hydrants are open, and almost half the hydrants are classed as highly sensitive (above the red line).

FIGURE 9.10
**Hydrants' sensitivity for an upstream discharge from 50 ls$^{-1}$ to 60 ls$^{-1}$**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.11
**Hydrants' sensitivity for an upstream discharge from 50 $ls^{-1}$ to 70 $ls^{-1}$**




*Source: elaborated with COPAM v4.0.*

Note that no significant increases in sensitivity were recorded for hydrants 18, 19, 20, 22, and 23 when five (50 $ls^{-1}$), six (60 $ls^{-1}$), and seven (70 $ls^{-1}$) hydrants are open. This is because the reliability for those hydrants is almost equal to zero for the discharge of 50 $ls^{-1}$ and remains close to zero for higher discharges (60 $ls^{-1}$ and 70 $ls^{-1}$). But this does not mean these hydrants are in good condition. However, it does confirm that the overall analysis must be done to assess performance rather than relying on only one model/indicator.

## 9.1.6 Assessing Perturbation

This is assessed using the RPE indicator, which measures the pressure variation and assesses the risk when the pressure in a pipeline rises about the nominal pressure of the pipe. This case study illustrates RPE profiles (Figure 8.2) along the main pipeline to a downstream hydrant for the most severe case of instantaneously closing hydrants (Tc = 0). The smaller diameter pipes with the lowest discharges close to the hydrant are often ignored by designers and managers. Yet, they are the most vulnerable to perturbations and should not be overlooked. The least RPE values were close to the reservoir.

The closing time, Tc should be as long as possible to avoid the risk from perturbations. Manufacturing companies should be aware of this problem and encouraged to design valves that cannot be closed rapidly to prevent problems. Severe perturbations can cause valves and hydrants to burst and can damage people and not just the equipment. Farmers have been known to lose fingers when closing hydrants too quickly.

## 9.1.7 Management options

Following the technology assessment, the next step is to assess the management options available to improve performance. These are summarized as:

- Accept the lower operating pressure at hydrants that are not functioning well. Subsidies can encourage farmers to accept these changes and compensate them for the change in service.
- Try to encourage disadvantaged farmers to avoid irrigating during peak irrigation times and to help them change to night-time irrigation. Again subsidies and other incentives such as reduced water tariffs can encourage the change.

- Imposing limited rotations and installing electronically controlled hydrants using water cards (Figure 9.12) can also reduce the peak discharges and benefit disadvantaged farmers. This is not just a technology issue but also a management issue. Changing technologies require studies and careful management to initiate successful change.

FIGURE 9.12
**Example of an electronic card hydrant**

*Source: Lamaddalena, N. 2005. Modeling and new technologies: tools to be combined for improving irrigation systems management". In: Proceedings of the 2nd International Conference on "Cybernetics Technologies Systems and Applications (CITSA 2005)" jointly with the "11th International Conference on Information Systems Analysis and Synthesis (ISAS 2005)". Orlando, Florida, July 14 – 17, 2005.*

## 9.1.8 Infrastructure changes

Possible options from an infrastructure perspective include:

- Changing (i.e., increasing) pipe diameters. A modernization model, which forms part of COPAM v4.0, applies Labye's iterative discontinuous method to compute an optimal solution for pipe diameters (Lamaddalena and Sagardoy, 2000). It first takes the actual pipe diameters in the network and then finds the optimal solution by increasing pipe diameters according to the new constraints on the system.
- Changing (i.e., increasing) system pumping capacity. In this case, the hydrant

pressure deficit can be assessed as the pressure at the head of the network increases and the pressure deficit at the hydrant decreases. However, this does increase energy cost and may put the cost of water beyond the reach of some farmers.

### 9.1.9 In conclusion

Management solutions are usually less expensive than infrastructure solutions but require more skill to implement. If this course of action is followed, capacity development programs are likely to be needed for farmers and managers.

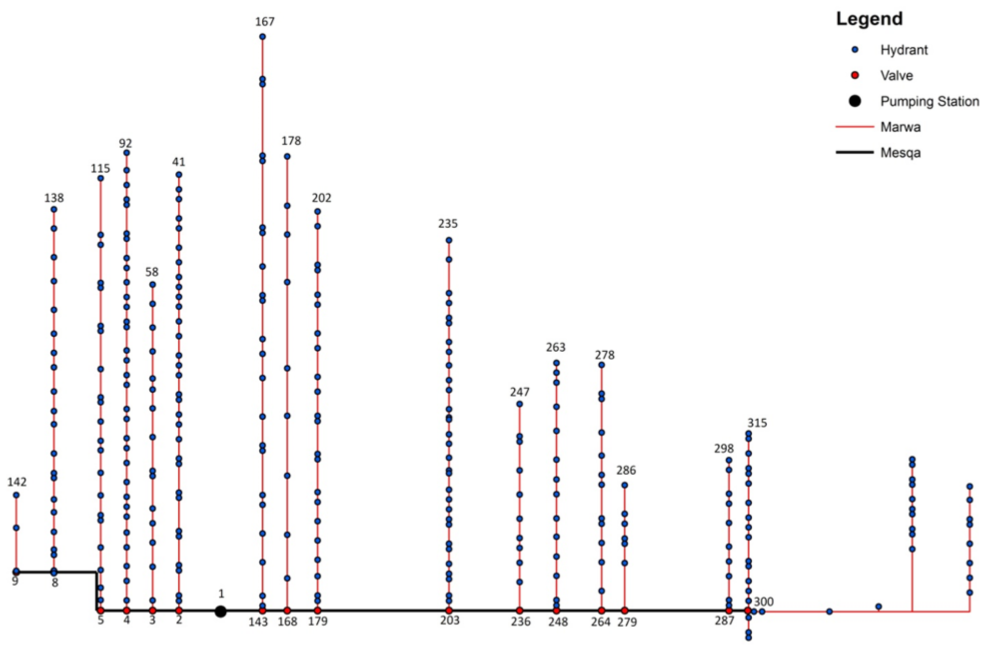
Finally, an important feature for any network and evaluation is a flow measuring device at the upstream end of the system. Unfortunately, despite its simplicity, many networks either do not have one, or they do not record the upstream hydrograph, which can provide such vital evidence for evaluation.

## 9.2 CASE STUDY: EGYPT

This case study appraises the performance of irrigation systems in the Governorates of Behira and Kafr El Sheik in Egypt following a program of modernization. The analysis was undertaken by FAO in 2017-2018 as part of the Audit of the Farm-level Irrigation Modernization Project (FIMP) funded by the World Bank.

The Al-Mazraah system is located in the El-Beheira governorate in the Nile Delta. The network was modernized by converting two levels of open canals (mesqas and marwas, which are quarternary canals on farms fed from the mesqas) to pressurized pipes supplied from a pumping station (Figure 9.13).

FIGURE 9.13
**Layout of Al-Mazraah (Beheira) irrigation scheme**




*Source: Salman, M., Pek, E., Giusti, S., Lebdi, F., Almerei, A., Shrestha, N., El-Desouky, I. et al. 2020a. On-farm Irrigation Development Project in the Old Lands (OFIDO): Technical assessment – Final report. Rome, Italy, FAO. 158 pp. https://doi.org/10.4060/cb0484en.*

The network serves 299 farm hydrants on a rotational-based delivery schedule. Hydrants of the Al-Mazraah network are not fitted with flow regulators, so the discharge to the farm fluctuates as the pressure changes, and this has created equity problems among farmers.

According to information collected during field interviews, two hydrants are operated simultaneously along the marwas with one pump operating at the head of the mesqa, and 3-4 hydrants simultaneously, with two pumps operating. The number and the location of hydrants to be opened depend on the requests managers receive from farmers.

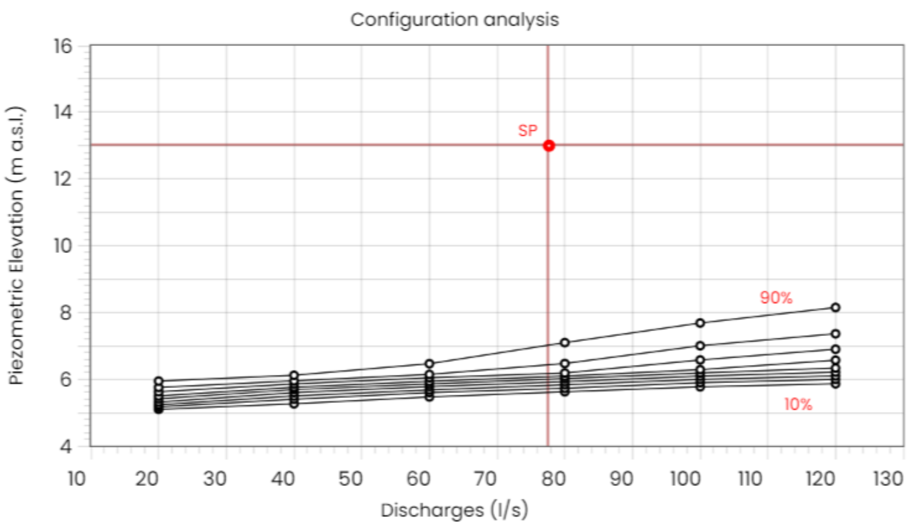
The hydraulic analysis was carried out according to the rotational delivery rules applied by the local managers. All data related to pumps, mesqas, and marwas (diameter of each section, type of pipes, length, and topography) were collected from managers, contractors, and field surveys.

A random generator produced 1 000 random configurations based on four hydrants operating at the same time along the marwas, assuming flow regulators of 20 $ls^{-1}$ are installed. According to the hydraulic characteristics of the installed pumps, the upstream piezometric elevation was 13 m, and the discharge into the system is 80 $ls^{-1}$. The flow at each hydrant was set at 20 $ls^{-1}$ with a minimum required pressure of 5 m at the hydrant.

Figure 9.14 illustrates ICCs for the existing system and shows that the upstream piezometric elevation (i.e., pressure of the pumping station) is far higher than is needed. The RPD (Figure 9.15) and reliability (Figure 9.16) show that the network is oversized for both operating strategies, i.e., two and four hydrants operating at the same time (i.e., 40 $ls^{-1}$ and 80 $ls^{-1}$, respectively). Installing pumps with smaller pressure, along with flow regulators, can overcome this problem, and in turn, it can reduce energy costs.

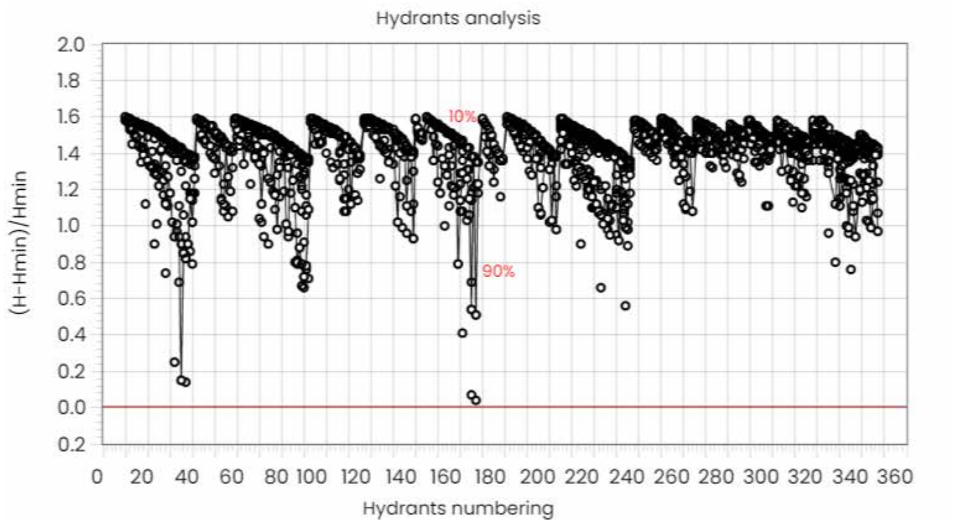
Appraising hydrant performance also indicates that, rarely, some are failing. This is due to the location and configuration of hydrants. Since managers operate a rotational-based delivery schedule, they can adjust the configurations of hydrants to overcome these failures. Also, a pressure drop below the minimum required at the hydrant level is not a problem, as farmers use surface irrigation methods, which can be successfully managed even with very low pressures.

FIGURE 9.14
**Indexed characteristic curve of Al-Mazraah network (actual network)**



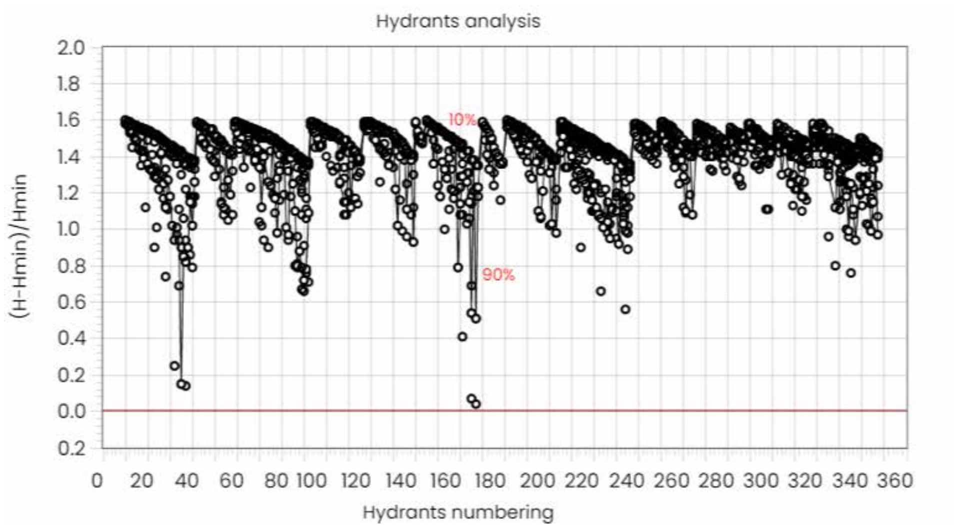

*Source: elaborated with COPAM v4.0.*

FIGURE 9.15
**RPD of Al-Mazraah network (actual network)**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.16
**Reliability of Al-Mazraah network (actual network)**

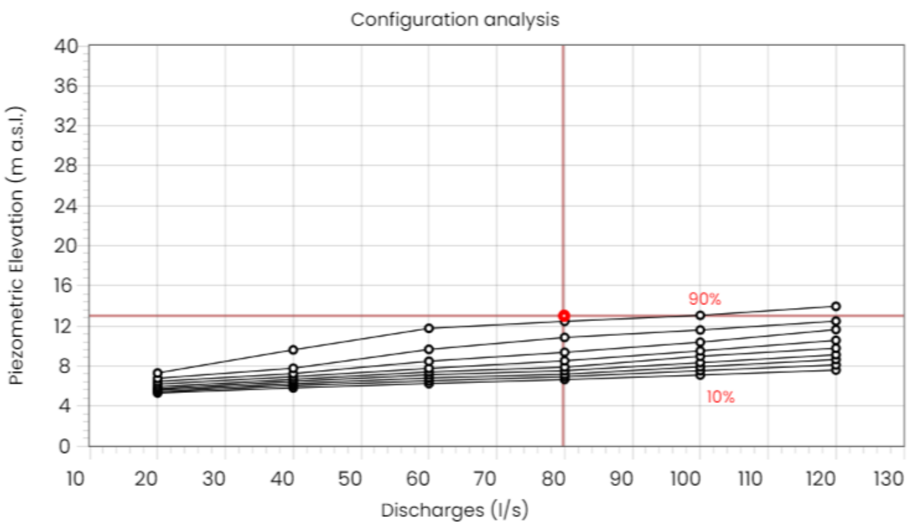



*Source: elaborated with COPAM v4.0.*

A recommended option for future projects is to include flow regulators to control discharge at farm hydrants.

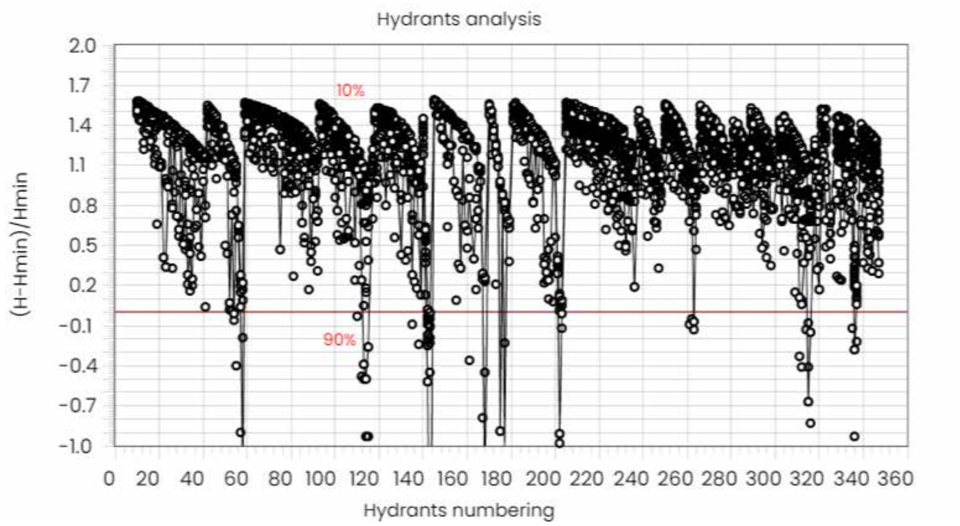
The Al-Mazraah network was also optimized using COPAM v4.0, assuming the same management and operating rules and the same pumping station. Optimizing reduces pipe sizes and hence the capital cost of the network with savings up to 40 percent when compared to the cost of the existing network. Figure 9.17, Figure 9.18, and Figure 9.19 illustrate the various indicators for the optimized network.

FIGURE 9.17
**Indexed characteristic curve of Al-Mazraah network (optimized network)**



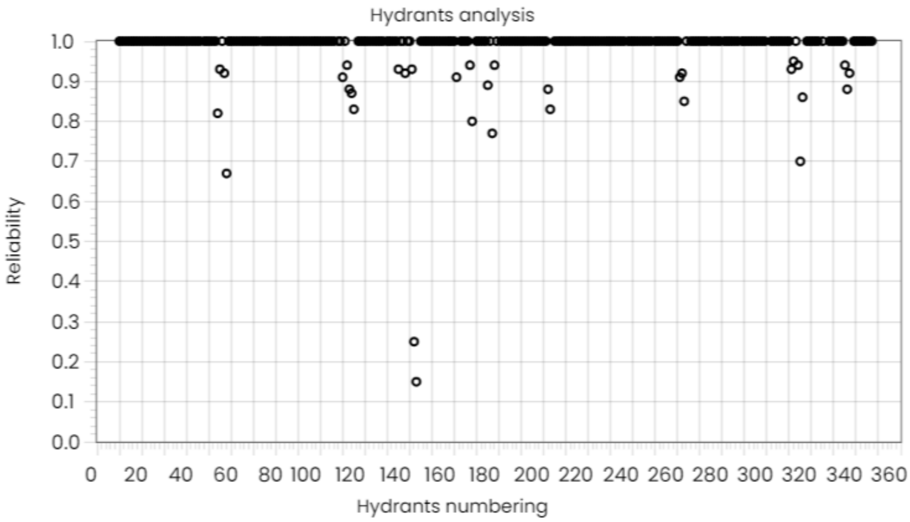

*Source: elaborated with COPAM v4.0.*

FIGURE 9.18
**RPD of Al-Mazraah network (optimized network)**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.19
**Reliability of Al-Mazraah network (optimized network)**



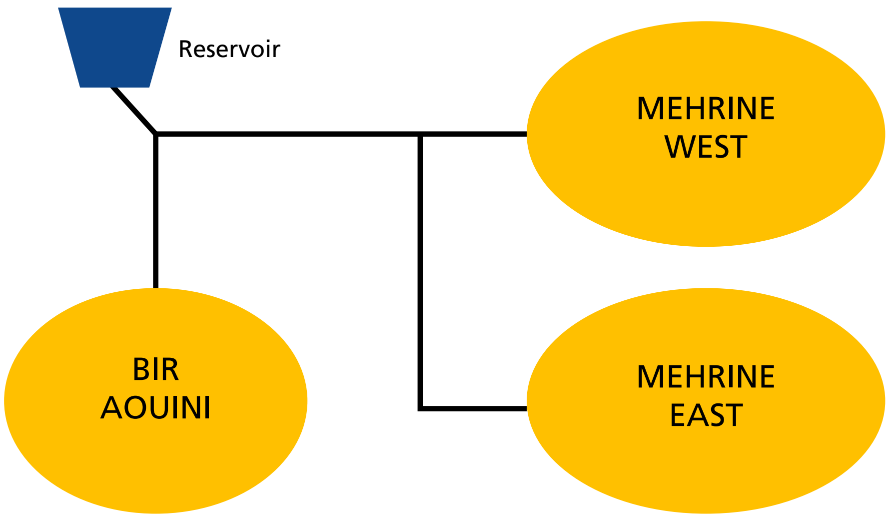

*Source: elaborated with COPAM v4.0.*

## 9.3 CASE STUDY: TUNISIA

The Manouba irrigation scheme is located in the northeastern part of Tunisia. A project for modernizing this scheme was initiated in 2008 and completed in 2015, with the main objective to improve the irrigation efficiency with respect to the old existing open canal system.

The Manouba scheme comprises two distinct hydraulic subsystems, this appraisal focuses on the Bir Aouini, Mehrine East, and Mehrine West network, supplied from the Mehrine Reservoir with a piezometric elevation of 107 m a.s.l. (Figure 9.20).

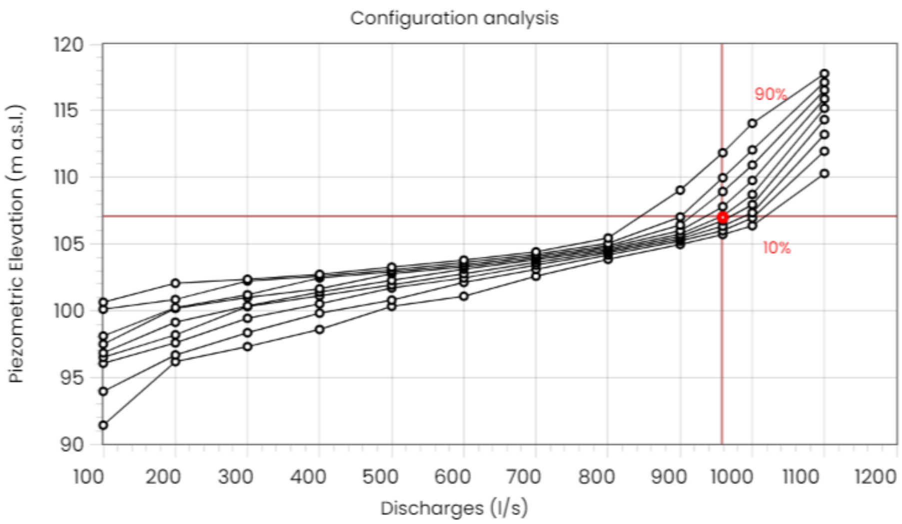
FIGURE 9.20
**Diagram of the subsystem Bir Aouini, Mehrine East, and Mehrine West**




*Source: Authors'own elaboration*

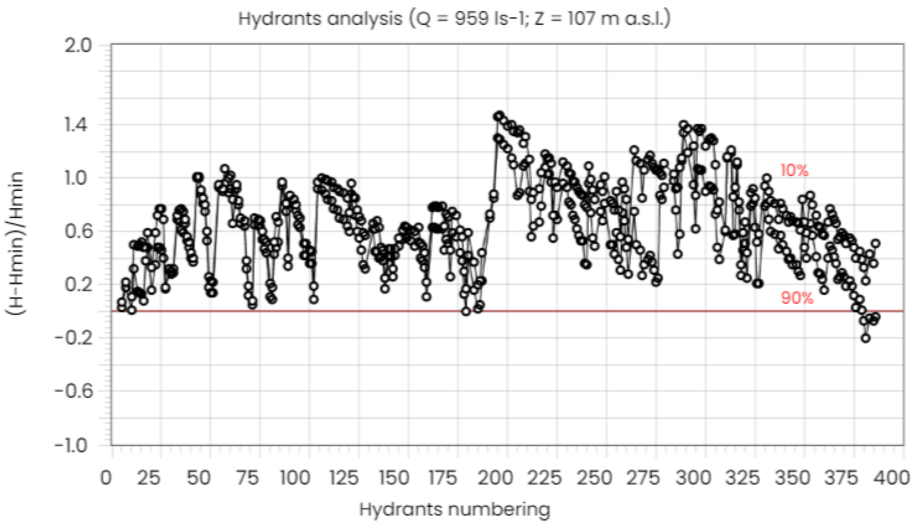
Figure 9.21 illustrates the ICCs based on generating 1 000 random configurations, an upstream piezometric elevation of 107 m a.s.l., an upstream discharge of 959 $ls^{-1}$ and a minimum pressure head at the hydrants of 25 m (the original design pressure). This indicates that 55 percent of the configurations are not satisfied. However, when analysing the hydrants in more detail, most have adequate pressure with positive RPD (Figure 9.22) and high reliability (Figure 9.23).

FIGURE 9.21
**Indexed characteristic curve for the subsystem Bir Aouini, Mehrine East, and Mehrine West**



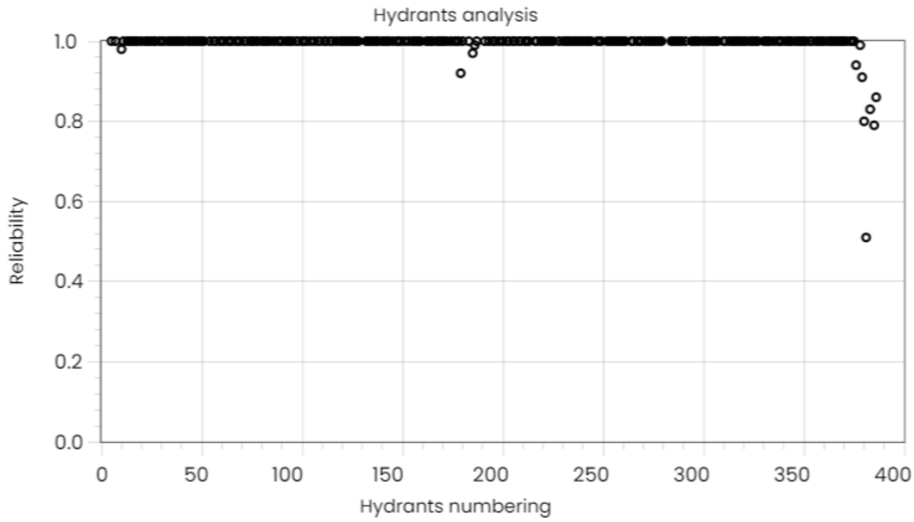

*Source: elaborated with COPAM v4.0.*

FIGURE 9.22
**RPD of the subsystem Bir Aouini, Mehrine East, and Mehrine West**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.23
**Reliability of the subsystem Bir Aouini, Mehrine East, and Mehrine West**




*Source: elaborated with COPAM v4.0.*

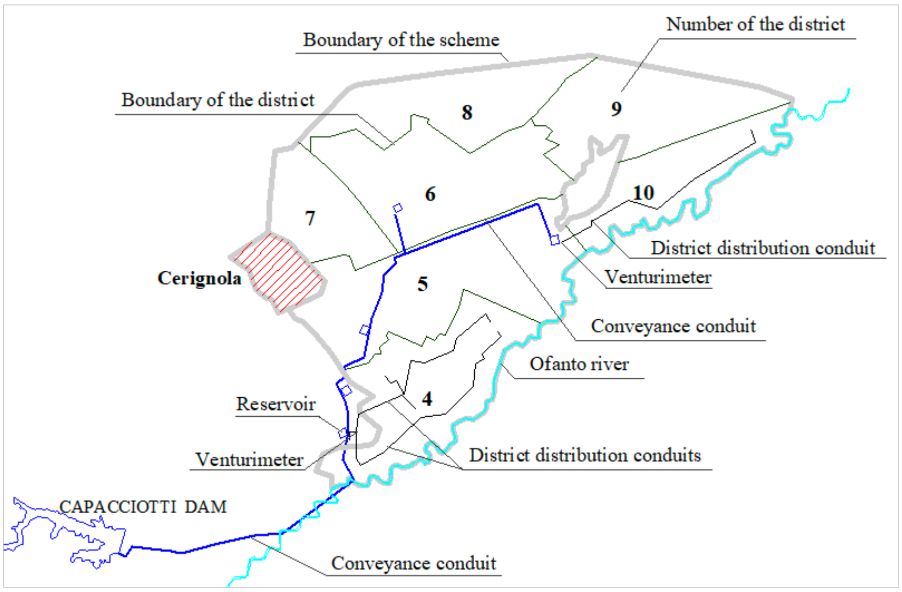
The analysis suggests the system provides a good service to farmers. Hydraulically, the system is stable, and this is demonstrated by the close range of the RPD curves (Figure 9.22). However, the ICCs indicate a high sensitivity to discharge at the head of the network. If, for example, the discharge increases from the design discharge of 959 $ls^{-1}$ to, say 1 000 $ls^{-1}$, none of the hydrant configurations are satisfied in terms of pressure.

This sensitivity has led to a rigid management system, and many farmers have responded by removing the flow regulators to try and maintain the flow they need to meet crop water requirements on their farm. However, removing the hydrant regulators would cause the system pressure to fall, which impacts the quality of service and produces poor sprinkler or drip distribution uniformity on farms.

## 9.4 CASE STUDY: ITALY

This case study covers the whole of District 4, in the Sinistra Ofanto irrigation scheme, in Foggia. It is managed by the Capitanata Reclamation Board (C.B.C., 1984; Altieri, 1995) (Figure 9.24) (case study in section 9.1 dealt only with Section 25 within District 4). The Sinistra Ofanto scheme covers an area of 22 500 ha and is subdivided into seven Districts, each being subdivided into sectors, ranging from 50 ha to 300 ha. Irrigation districts 4, 5, and 8 are each served independently by daily storage and compensation reservoirs. Districts 6 and 7 are served from a separate reservoir, as are districts 9 and 10. All the reservoirs are filled from the Capacciotti dam.

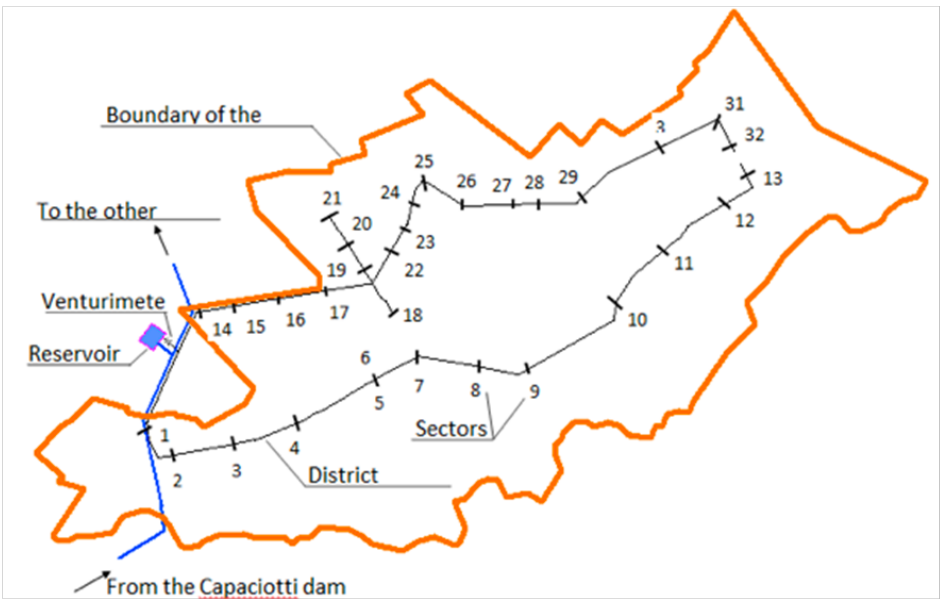
FIGURE 9.24
**The “Sinistra Ofanto” irrigation scheme**




*Source: Lamaddalena, N. 1997. Integrated simulation modeling for design and performance analysis of on-demand pressurized irrigation systems. PhD Thesis. Technical University of Lisbon, Lisbon, Portugal.*

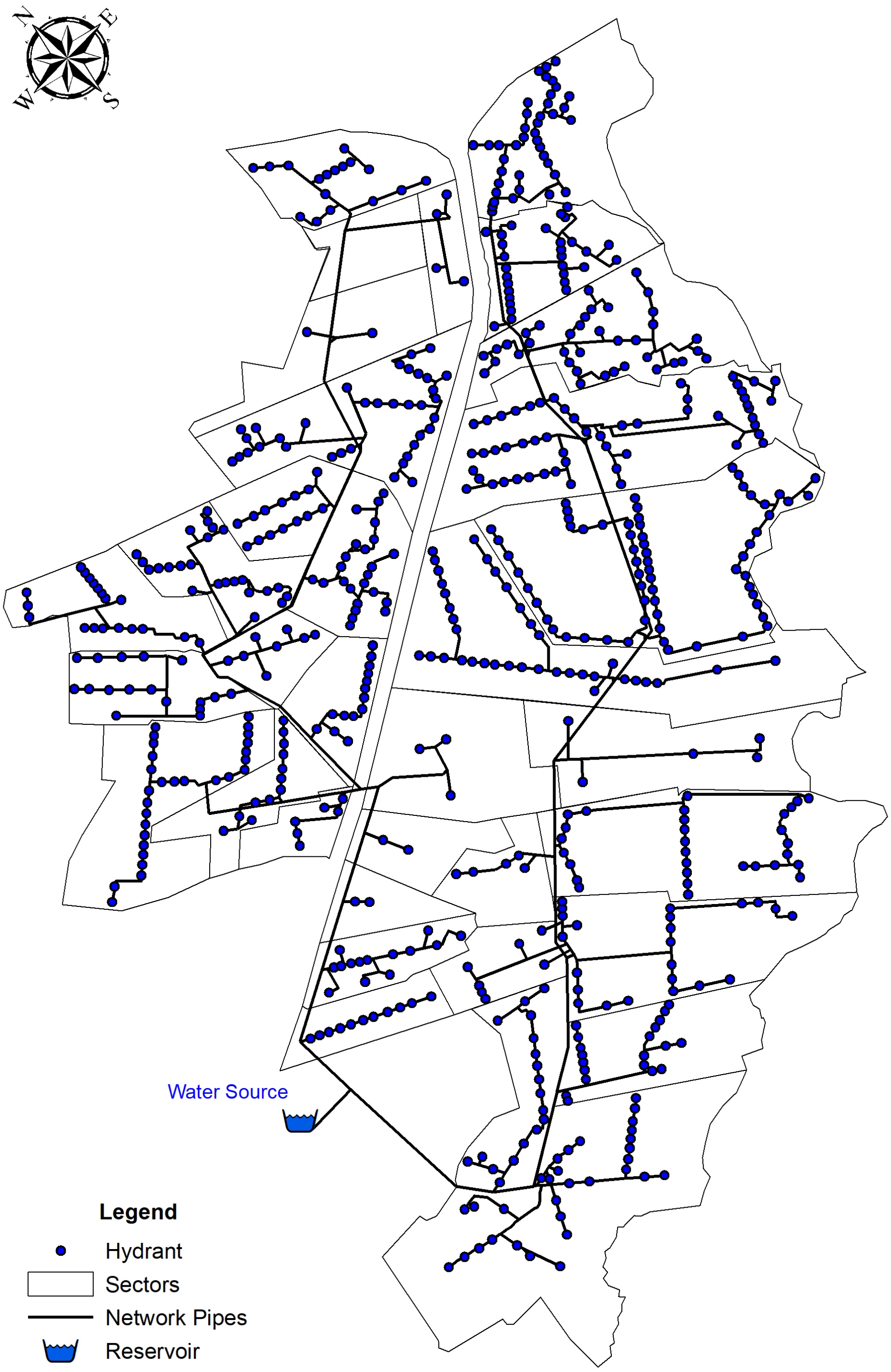
District 4 comprises 3 250 ha of irrigated land and receives water from a storage reservoir of the capacity of 28 000 m$^3$ with a maximum water level of 143 m a.s.l. and minimum water level 139 m a.s.l. Figure 9.25 illustrates the layout of the pipe network. A 1 200 mm diameter steel pipe at the head of the network includes a venturi flow meter to record discharges into the network of 32 sectors (Figure 9.26).

FIGURE 9.25
**Layout of the District 4 network**




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

FIGURE 9.26
**Layout of District 4 sectorial networks**



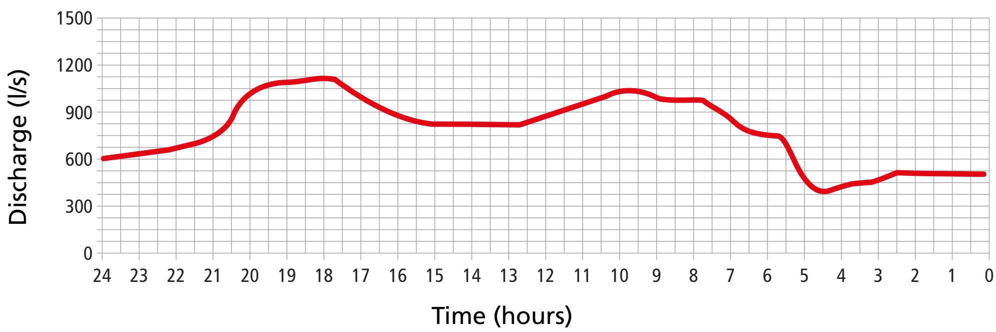

*Source: Lamaddalena, N. 1997. Integrated simulation modeling for design and performance analysis of on-demand pressurized irrigation systems. PhD Thesis. Technical University of Lisbon, Lisbon, Portugal.*

A control unit at the head of each sector comprises a gate valve, flow-meter, and a pressure regulator. Farm hydrants are designed for 10 $ls^{-1}$.

The irrigation network was designed to operate on-demand with a design discharge based on the probabilistic approach proposed by Clément (Lamaddalena and Sagardoy, 2000). This assumed an elementary probability if p = 0.157 and the cumulative probability, representing the operation quality of $P_q$ = 95 percent. The coefficient of utilization of the network was r = 0.667 (Malossi and Santovito, 1975). Pipe diameters were calculated using a linear programming formulation. The minimum pressure at the hydrants was 2.0 bar. The optimization procedure was applied only to 10 percent of the network; an empirical approach was used for the rest (Malossi and Santovito, 1975).

The hydrograph at the head of the network has been recorded for several years of operation; a typical hydrograph is illustrated in Figure 9.27.

FIGURE 9.27
**Typical hydrograph at the head of District 4**

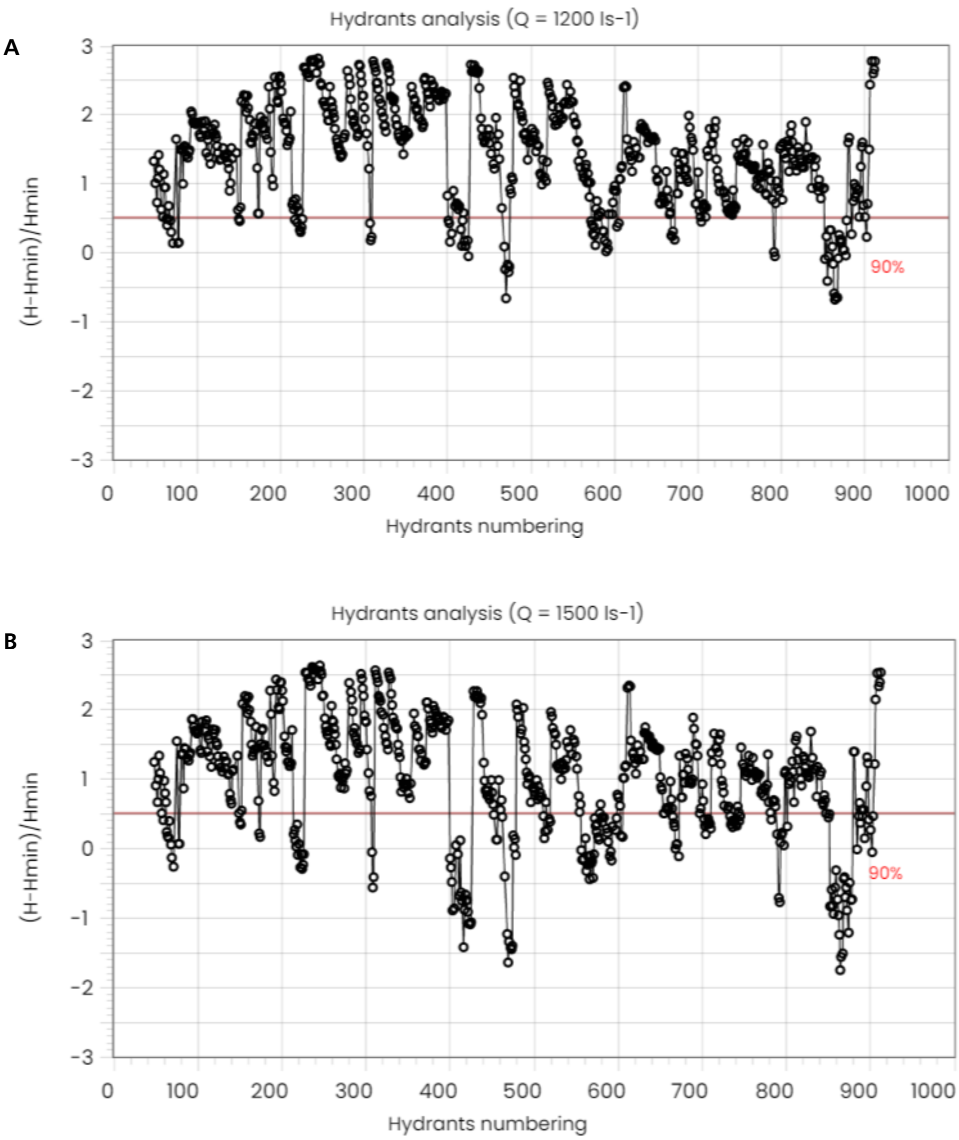



*Source: Elaborated with COPAM v4.0.*

The cropping pattern has changed since the scheme was designed. Major changes include olive trees (20 percent of the irrigated area), vineyards (63 percent), orchards (10 percent), plus tomatoes and asparagus. The maximum discharge recorded at the head of the network is 1 200 $ls^{-1}$.

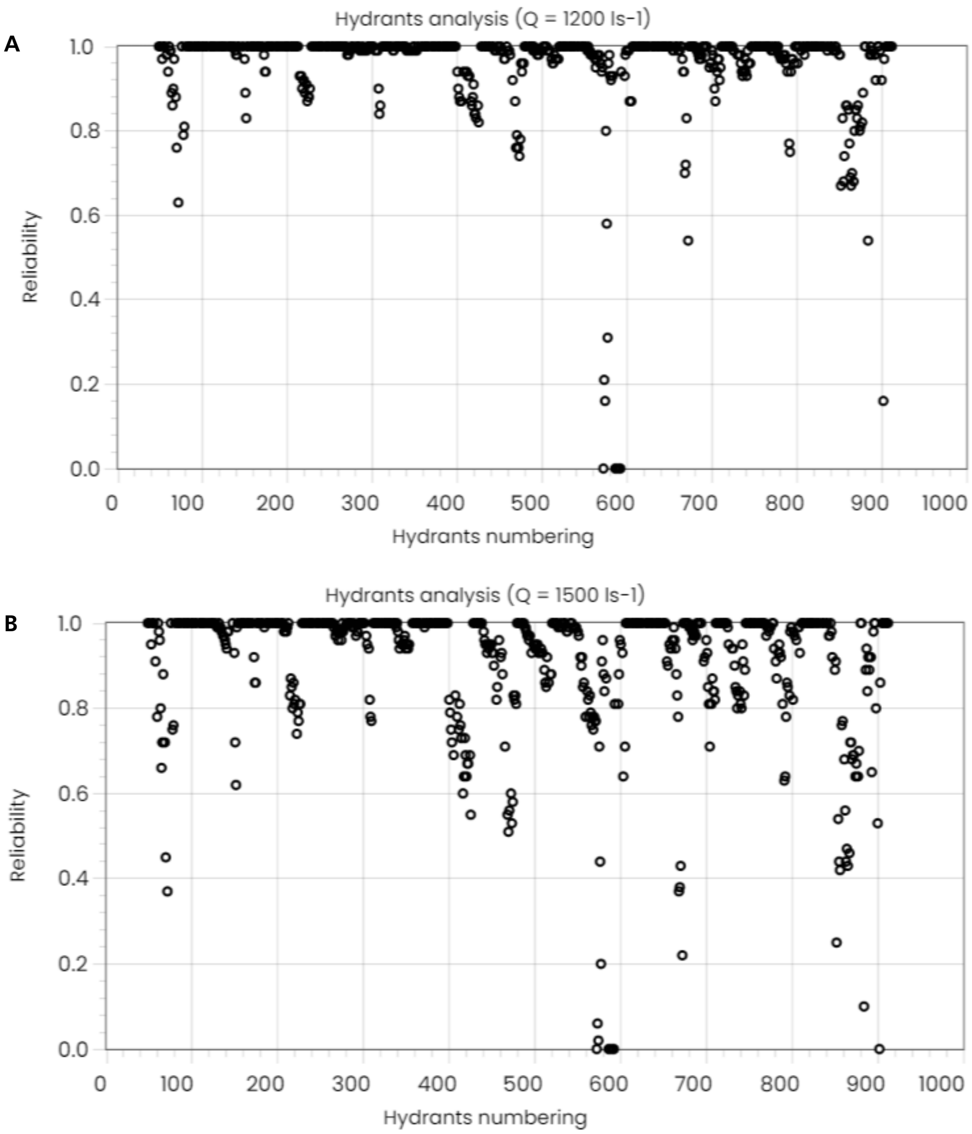
The hydraulic analysis was carried out using COPAM v4.0 by generating 1 000 random configurations based on the design demand (1 200 $ls^{-1}$) and future demand allowing from climate change (1 500 $ls^{-1}$). Figure 9.28 illustrates the RPD analysis, and Figure 9.29 the reliability analysis. Together they highlight the magnitude of failing hydrants.

FIGURE 9.28
**90 percent RPD for current (a) and future demand (b)**




*Source: Elaborated with COPAM v4.0.*

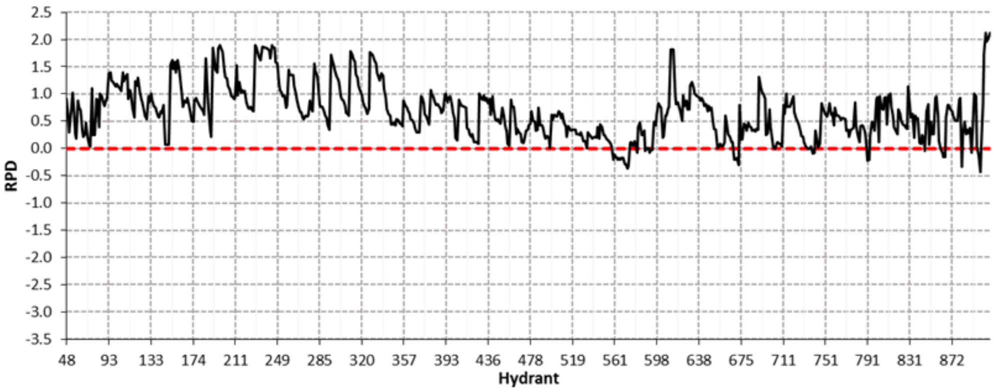
FIGURE 9.29
**Reliability a) current demand and b) future demand**




*Source: Elaborated with COPAM v4.0.*

In response to the projected worsening performance, managers must determine how best to adapt to the changes using engineering and/or management solutions. The capacity of the network can be increased by increasing the pipe sizes as the system is gravity fed from the reservoir. This is a high-cost solution but is necessary to improve the performance. Figure 9.30 illustrates the effect of the new optimized pipe system on the 90 percent relative pressure deficit, which would always be very good (above zero).

FIGURE 9.30
**90 percent RPD for future demand (new optimized network)**

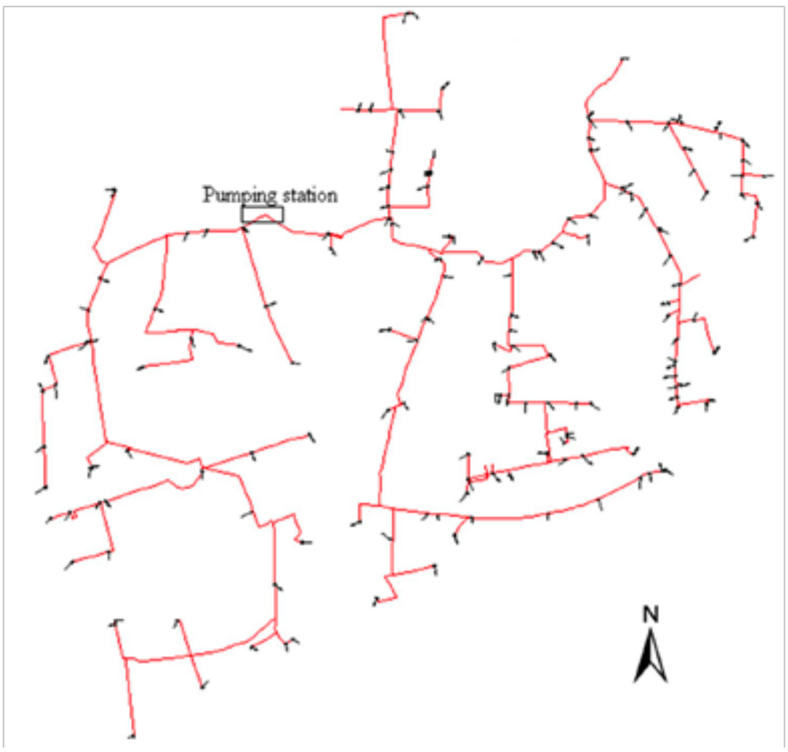



*Source: Elaborated with COPAM v4.0.*

## 9.5 CASE STUDY: SPAIN

This case study appraises Sector VII of the MD Bembézar Irrigation District (right Bembézar riverbank) in Spain (Figure 9.31). This scheme covers an area of 935 ha, including 162 hydrants. The network was designed to supply 1.2 $ls^{-1}ha^{-1}$ for on-demand operation at a minimum operational pressure head at the hydrant of 35 m. All hydrants are equipped with flow regulators. Drip irrigation is the most common irrigation method, and the main crops are citrus, cotton, maize, and fruit trees.

FIGURE 9.31
**Distribution network of the Sector VII**

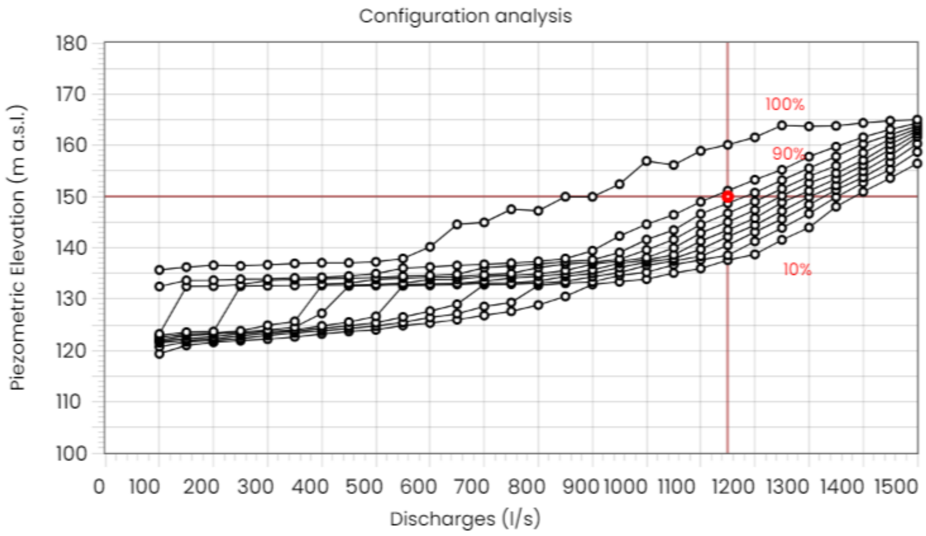



*Source: Díaz, J. A. R., Urrestarazu, L. P., Poyato, E. C., & Montesinos, P. 2012. Modernizing Water Distribution Networks: Lessons from the Bembézar MD Irrigation District, Spain. Outlook on Agriculture, 41(4): 229-236. https://doi.org/10.5367/oa.2012.0105.*

The network appraisal was conducted using COPAM v4.0. Figure 9.32 illustrates the ICC based on generating 500 random configurations, an upstream piezometric elevation of 150 m a.s.l., and an upstream discharge of 1,150 $ls^{-1}$.

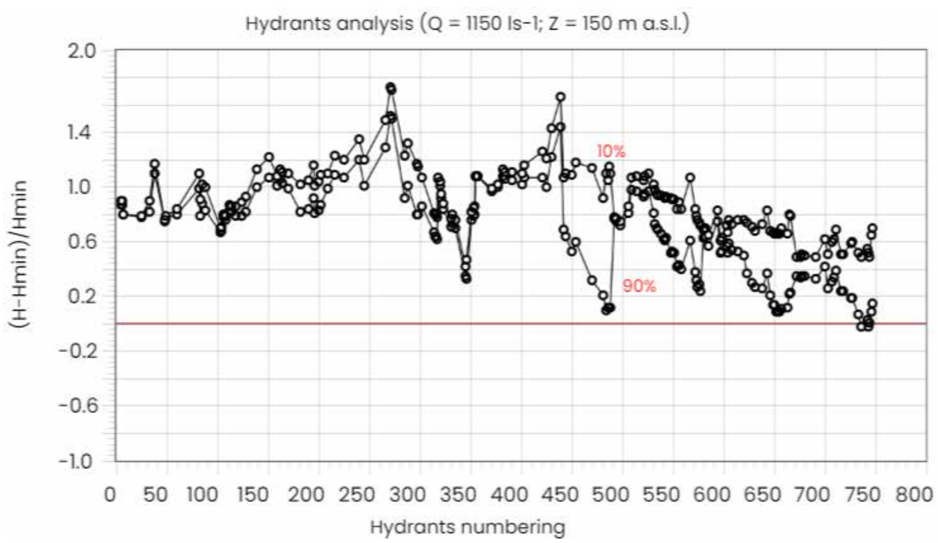
The operating point of the sector is on the 85 percent characteristic curve, i.e., which indicates that only 15 percent of the generated configurations are not satisfied. This good performance is confirmed by a more detailed hydrant analysis. Figure 9.33 illustrates the low probability of occurrence of negative RPD and Figure 9.34, the high level of reliability based on the peak discharge.

FIGURE 9.32
**Indexed characteristic curve for sector VI**



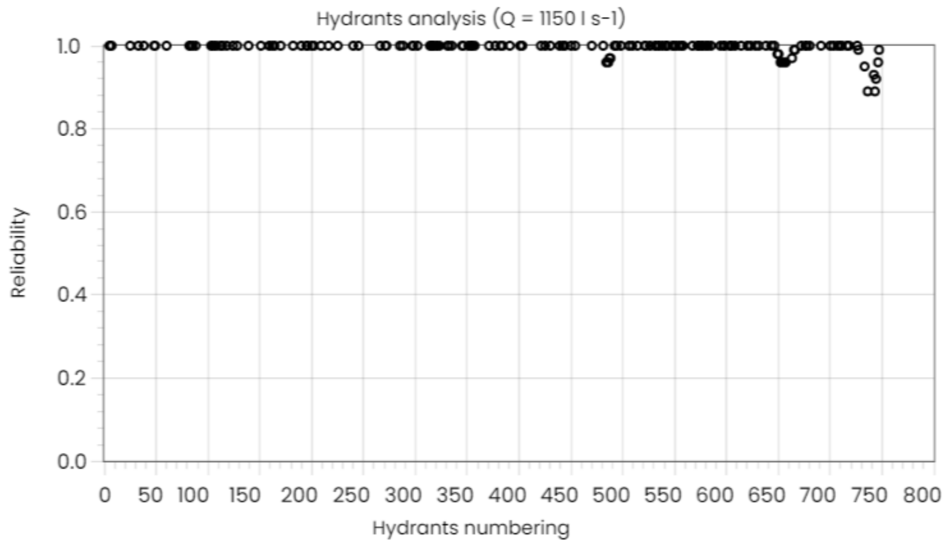

*Source: elaborated with COPAM v4.0.*

FIGURE 9.33
**RPD of sector VII, based on peak discharge (Q=1 150 $ls^{-1}$)**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.34
**RPD of sector VII, based on peak discharge (Q=1 150 ls$^{-1}$)**

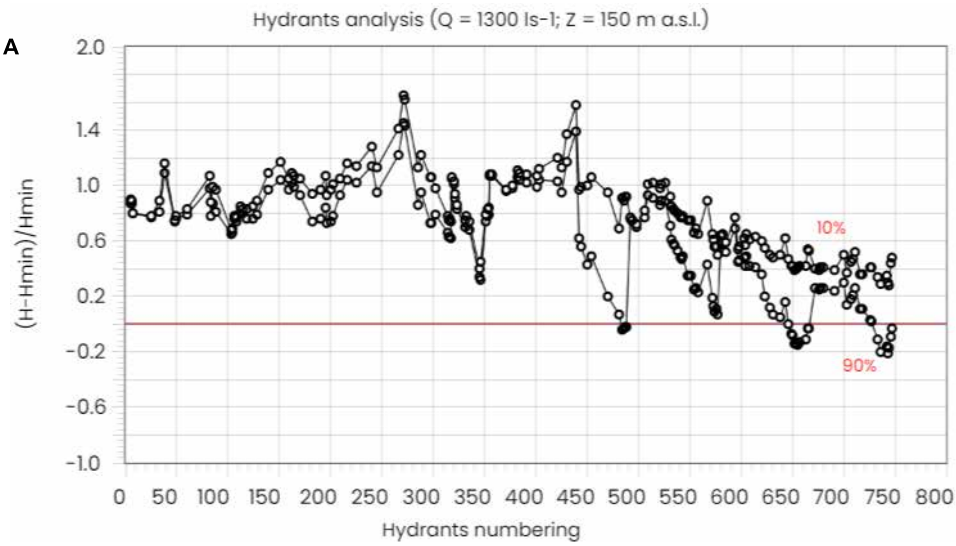



*Source: elaborated with COPAM v4.0.*

The ICC analysis indicates that, in general, hydrants are not sensitive to discharges flowing into the network. However, an analysis based on the possible increases in discharge to 1 300 and 1 500 ls$^{-1}$ illustrates that RPD (Figure 9.35) and reliability (Figure 9.36) indicate the probability of some hydrants failing. Such hydrants have high sensitivity to the discharges flowing into the network, especially when the upstream discharge exceeds 1 300 ls$^{-1}$ (Figure 9.37).

FIGURE 9.35
**RPD of sector VII, using increased upstream discharges (Q=1 300 ls$^{-1}$ and 1 500 ls$^{-1}$)**

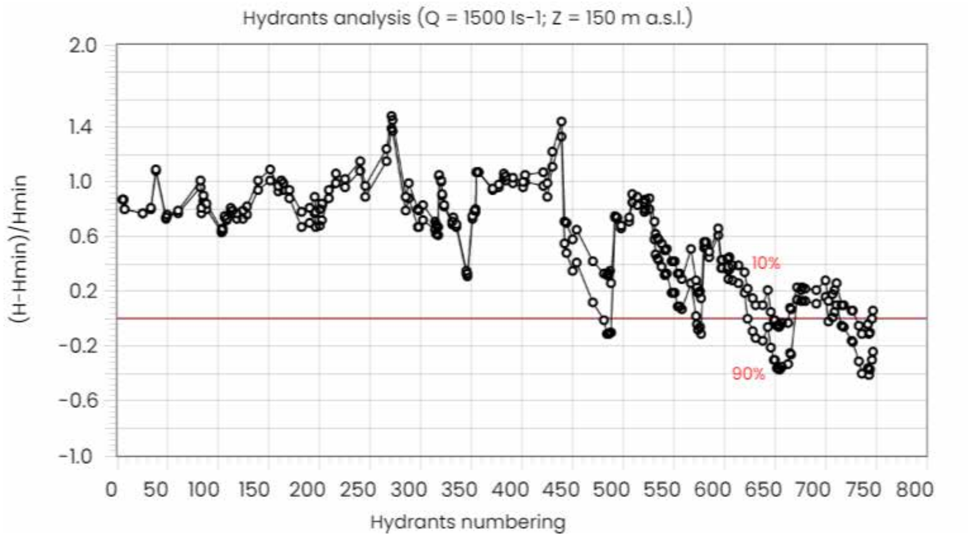
A




*Source: elaborated with COPAM v4.0.*

FIGURE 9.35 (CONTINUED)

B

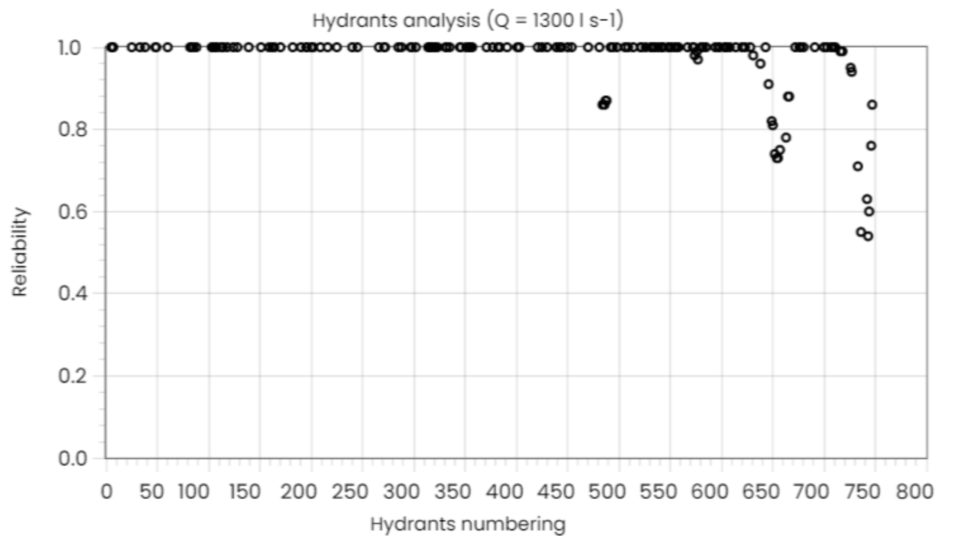



*Source: elaborated with COPAM v4.0.*

FIGURE 9.36

**Reliability of sector VII, using increased upstream discharges (Q=1 300 $ls^{-1}$ and 1 500 $ls^{-1}$)**

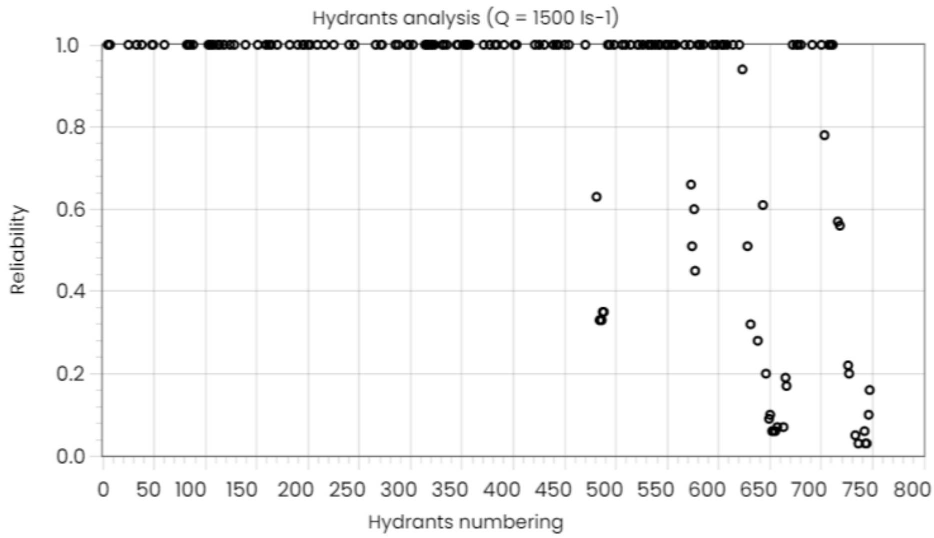
A




*Source: elaborated with COPAM v4.0.*

FIGURE 9.36 (CONTINUED)

**B**

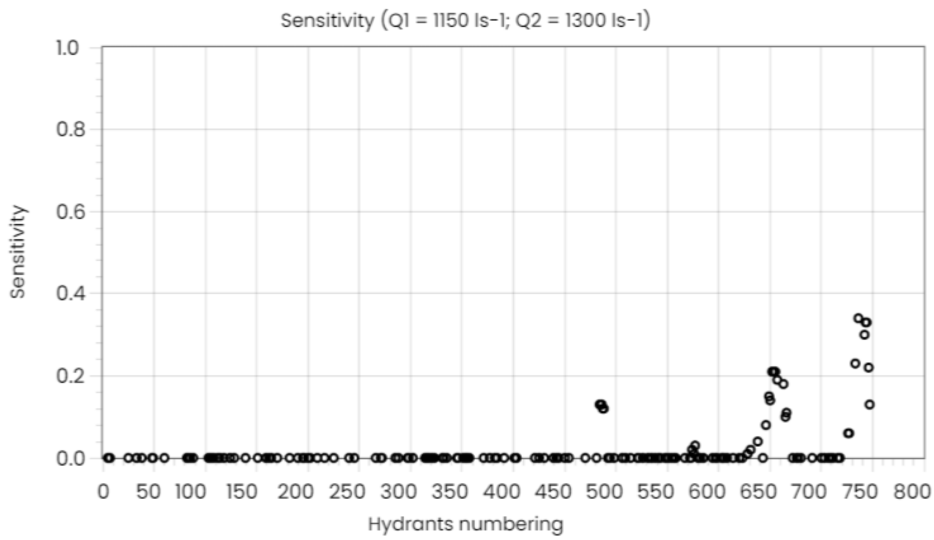



*Source: elaborated with COPAM v4.0.*

FIGURE 9.37

**Hydrant's sensitivity of sector VII (Q=1 150 ls$^{-1}$ to 1 300 ls$^{-1}$ and 1 500 ls$^{-1}$)**

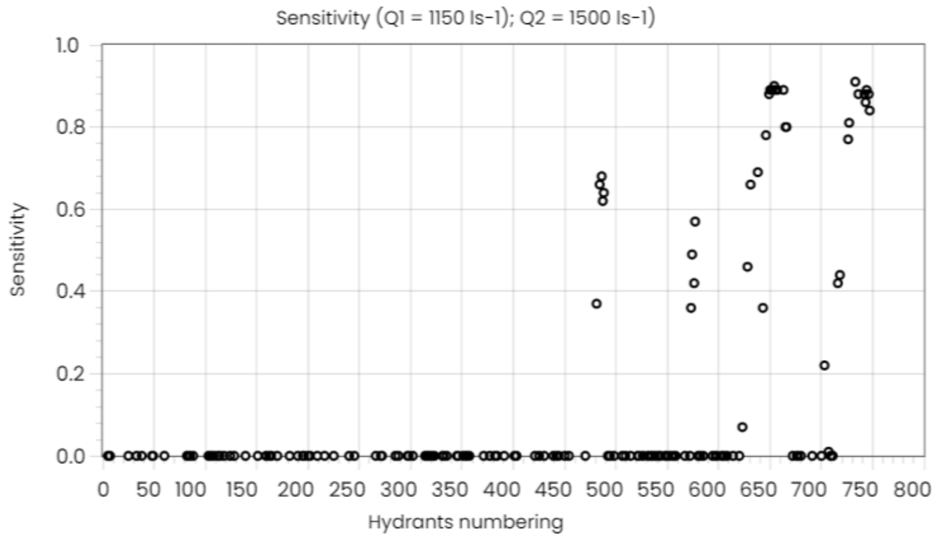
**A**




*Source: elaborated with COPAM v4.0.*

FIGURE 9.37 (CONTINUED)

B




*Source: elaborated with COPAM v4.0.*

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# 11. Annexes

## A.1 UNSTEADY FLOW THEORY[7]

The Euler and the conservation of mass equations are:

$$\frac{dV}{dt} + \frac{1}{\rho}\frac{\partial P}{dt} + g\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 \qquad \text{(A1.1)}$$

$$a^2\frac{\partial V}{\partial s} + \frac{1}{\rho}\frac{dP}{dt} = 0 \qquad \text{(A1.2)}$$

Where, g is the gravitational acceleration ($ms^{-2}$), D (m) is the pipe diameter, V ($ms^{-1}$) is the mean velocity, P ($Nm^{-2}$) is the pressure, z is the pipe elevation (m), f is the Darcy–Weisbach friction factor and a is the celerity ($ms^{-1}$). t (s) and s (m) represent the independent variables.

The variable V and its module |V| preserve the shear stress force direction on the pipe wall according to the flow direction.

The characteristic method makes it possible to replace the two partial differential equation (A1.1) and equation (A1.2) with a set of ordinary differential equations. The resulting equations will be expressed in terms of the piezometric head H (m). These equations are deeply described in any hydraulic textbook discussing the water hammer phenomenon (Chaudhary, 1970).

The slope of the characteristic curves on the space–time planes is a function of V (s, t). This is introduced in the numerical solution procedure as explained hereafter.

$$C^+ : \frac{dV}{dt} + \frac{g}{a}\frac{dH}{dt} - \frac{g}{a}V\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 \qquad \text{only when } \frac{ds}{dt} = V + a \qquad \text{(A1.3)}$$

$$C^+ : \frac{dV}{dt} - \frac{g}{a}\frac{dH}{dt} + \frac{g}{a}V\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 \qquad \text{only when } \frac{ds}{dt} = V - a \qquad \text{(A1.4)}$$

The equations

$$\frac{ds}{dt} = V + a \text{ and } \frac{ds}{dt} = V$$

are the characteristics of the equation (A1.3) and equation (4), respectively. The integration of

$$\frac{ds}{dt} = V + a \text{ gives } \frac{1}{V + a} = \times s + \textit{costant}$$

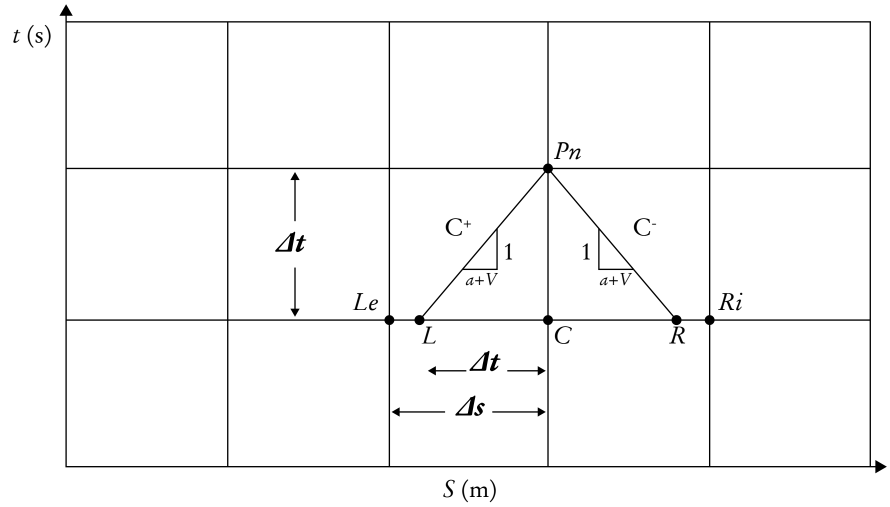
[7] Part of the theory illustrated in the Annex 1 was taken from Derardja *et al.*, 2019 and from Lamaddalena *et al.*, 2018. The published theory was integrated and updated according to needs and objectives of the present publication.

that is represented by the curve $C^+$. Similarly, for

$$\frac{ds}{dt} = V - a \qquad t = -\frac{1}{a - V} = \times s + constant$$

is determined and represented by the curve $C^-$, shown in Figure A.1.1.

FIGURE A.1.1
**Characteristic curves on the space–time plane**




*Source: Derardja, B., Lamaddalena, N. & Fratino, U. 2019a. Perturbation Indicators for On-Demand Pressurized Irrigation Systems. Water, 11(3): 558. https://doi.org/10.3390/w11030558.*

## A.1.1 The numerical solution for ordinary differential equations

The characteristic curves can be approximated to straight lines over each single Δt interval. In fact: (I) Δt may be made as small as one wishes, and (II) usually a >>

$$V, \text{ causing } \frac{ds}{dt}$$

causing dsdt to be nearly constant (Larock *et al.*, 1997). We seek to find the values of V and H at point Pn. They are calculated based on V and H at the points C, Le and Ri of the previous time following the characteristic curves $C^+$ and $C^-$. The velocity and the head at Pn become the known values for the subsequent time calculation, shown in Figure A.1.1.

The characteristic curves passing through Pn intersect the earlier time (t is constant) at the points L and R. Consequently, the finite difference approximations to equations (A1.3) and (A1.4) become

$$C^+ : \frac{V_P - V_L}{\Delta t} + \frac{g}{a}\frac{H_P - H_L}{\Delta t} - \frac{g}{a} V_L \frac{dz}{ds} + \frac{f}{2D} V_L|V_L| = 0 \qquad (A1.5)$$

$$C^- : \frac{V_P - V_R}{\Delta t} - \frac{g}{a}\frac{H_P - H_R}{\Delta t} + \frac{g}{a} V_R \frac{dz}{ds} + \frac{f}{2D} V_R|V_R| = 0 \qquad (A1.6)$$

The last two equations include six unknown terms: VP, HP, VL, HL, VR and HR. In the earlier time, values of P and V are known only at the points C, Le and Ri. Using linear interpolation, as shown in Figure 1, VL, HL, VR and HR are to be expressed as a function of $V_C$, $H_C$, $V_{Le}$, $H_{Le}$, $V_{Ri}$ and $H_{Ri}$. In detail, along the $C^+$ characteristic, we assume:

$$\frac{\Delta X}{\Delta s} = \frac{V_L - V_C}{V_{Le} - V_C} = \frac{H_L - H_C}{H_{Le} - H_C} \qquad \text{(A1.7)}$$

solving the above equations for VL and HL, the following equations are obtained:

$$V_L = V_C + a\,\frac{\Delta t}{\Delta s}\,(V_{Le} - V_C) \qquad \text{(A1.8)}$$

$$H_L = H_C + a\,\frac{\Delta t}{\Delta s}\,(H_{Le} - H_C) \qquad \text{(A1.9)}$$

An analogous approach can be applied along the C– characteristic. This leads to solving equation (A1.5) and equation (A1.6) simultaneously for VPn and HPn, as follows:

$$V_{Pn} = \frac{1}{2}\,[(V_L - V_R) + \frac{g}{a}\,(H_L - H_R)\,\frac{g}{a}\,\Delta t\,(V_L - V_R)\sin ø - \frac{f\Delta t}{2D}\,(V_L|V_L| + V_R|V_R|)] \qquad \text{(A1.10)}$$

$$H_{Pn} = \frac{1}{2}[+\frac{a}{g}(V_L - V_R) + (H_L + H_R) + \Delta t\,(V_L + V_R)\mathit{sin}ø - \frac{a}{g}\,\frac{f\Delta t}{2D}\,(V_L|V_L| + V_R|V_R|)] \qquad \text{(A1.11)}$$

Usually, the slope term

$$\frac{dz}{ds}\ \sin\ \mathit{sin}ø$$

is small and may be neglected (Chaudhary, 2014).

The complexity of irrigation systems is the non-uniformity of pipe materials and pipe sizes, which requires a pipe discretization where each elementary section has constant geometrical and physical properties. Each elementary section is divided into an integer number of elements $NS_i$, with length $\Delta s_i$, whose value is calculated, to have the same Δt in all the system (Lamaddalena and Sagardoy, 2000).

Several configurations of hydrants simultaneously operating are generated and a steady-state simulation is executed for each of them. The obtained results (H and V) constitute the initial conditions for running the transient simulation. Assuming that valves are instantaneously closed, the computer software simulate the unsteady flow process until the simulation time reaches a predefined observation time (Tmax). Tmax is generally assumed large enough to reach again the new steady-state flow conditions.

The boundary conditions described hereafter are assumed for the application of the differential equations. The variables V and H are indexed with Pi corresponding to the points, one on each side of the boundary section, which is nearly superposed (Figure A.1.2). For all the other parameters, only the number of pipes is used as an index to prevent any complication in naming. In both cases of upstream and downstream end boundaries of the systems, only one point exists following $C^-$ and $C^+$, respectively.

## A.1.2 The boundary conditions

The boundary conditions at each end of the pipes describe the external conditions of velocity and/or pressure head.

The most common and relevant boundary conditions were considered, as described below.

### A.1.2.1 Reservoir

If a reservoir with constant pressure head $H_0$ is located upstream of the network, then:

$$H_P = H_O \tag{A1.12}$$

### A.1.2.2 Valve closure arrangement

In the present publication, valves represent the hydrants of an irrigation system. The pressure downstream the valves is considered fixed at the atmospheric pressure.

Local head losses at the level of hydrants are caused by the local flow disturbance. Those losses can be relevant and, therefore, they should be considered for an accurate analysis. They are commonly expressed by the equation

$$\Delta H = K_L \frac{V^2}{2g} \tag{A1.13}$$

$K_L$ is the loss coefficient, V is the flow velocity and g is the gravitational acceleration.

To compute the magnitudes of the caused losses, experimental data needs to be introduced. In most cases, the user may have different values $K_L$ corresponding to valve position, along with opening/closing time provided by the manufacturer. So, the perturbation analysis can be achieved quite accurately. Based on the introduced values, the software simulates the continuous values of $K_L$ by a linear interpolation to cover the full range 0 percent to 100 percent opening/closing.

The flow velocity and the head variation follow the equations:

$$V_{P1} = V_{L1} + \frac{g}{a_1} H_{L1} - \frac{f_1 \Delta t}{ds} V_{L1}|V_{L1}| + \frac{g}{a_1} a_1 V_L \sin\phi_1 \tag{A1.14}$$

$$V_{P1} = C_1 - C_2 H_{P1} \tag{A1.15}$$

$$H_{P1} = H_0 + K_L \frac{V^2_{P1}}{2g} \tag{A1.16}$$

$H_{P1}$ and $V_{P1}$ are respectively the head and the velocity at the upstream side of the valve (infinitely close to the valve). Following $C^+$, V and H from the earlier time (t-Δt) are indexed with $L_i$ (where L refers to left or upstream and i to the pipe).

Integrating and simplifying the previous equations, $V_{P1}$ can be expressed as following:

$$V_{P1} = \frac{C_3}{2K_L}\left[-1+\sqrt{1-\frac{4C_4K_L}{C^2_3}}\right] \quad \text{(A1.17)}$$

$$C_4 = \frac{2g}{C_4} \quad \text{(A1.18)}$$

$$C_4 = 2g(H_0^- \frac{C_1}{C_2}) \quad \text{(A1.19)}$$

As mentioned above, $K_L$ values for different valve positions are accessible from the manufacturer. Hereafter an example of loss coefficients for a gate valve.

| Opening (percent) | $K_L$ |
|---|---|
| 25 | 24 |
| 50 | 5.6 |
| 75 | 1.15 |
| 100 | 0.19 |

Lamaddalena et al. (2018) have referred a detailed analysis with different gate-valves' closing time (from Tc = 0 to Tc = 6 s). The sudden closure clearly shown the impact of such variable on the phenomenon.

### A.1.2.3 Upstream constant speed pump

Respect to the case having a reservoir as an upstream boundary condition with a constant head, a second variable (flow velocity) will be introduced in the case having an upstream pumping station.

The pump at the upstream end of the system is represented by a quadratic equation (pressure head vs discharge):

$$hp = ApQ2 + Bpq + Cp \quad \text{(A1.20)}$$

Knowing that

$$Q = V_{P1} A \quad \text{(A1.21)}$$

And

$$h_p = H_{p1} H_{pump\ sump} \quad \text{(A1.22)}$$

The substitution in the quadratic equation leads to

$$H_{p1} = A_P V_{P1}{}^2 + B_P V_{P1} + C_P \quad \text{(A1.23)}$$

Simultaneously with the characteristic equation following $C^-$,

$$V_{P1} = V_2 - \frac{g}{a}(A_p V_{p1}^2 + B_p V_{p1} + C_p) + \frac{g}{a} H_2 + \frac{f_1 \Delta t}{2D} V_2|V_2| = 0 \quad (A1.24)$$

$V_{P1}$ will be a function of known factors. By rearranging the different variables, the following equations are obtained:

$$V_{P1} = \frac{C_3}{2}\left[-1 + \sqrt{1 - \frac{4C_4}{C_3^2}}\right] \quad (A1.25)$$

and

$$H_{P1} = \frac{V_{p3} - C_1}{C_2} \quad (A1.26)$$

While

$$C_1 = V_2 - \frac{g}{a} H_2 - \frac{f\Delta t}{2D} V_2|V_2| = 0 \quad (A1.27)$$

$$C_2 = \frac{g}{a} \quad (A1.28)$$

$$C_3 = \frac{B\rho - 1/C_2}{A_p} \quad (A1.29)$$

$$C_4 = \frac{C\rho + C_1/C_2}{A_p} \quad (A1.30)$$

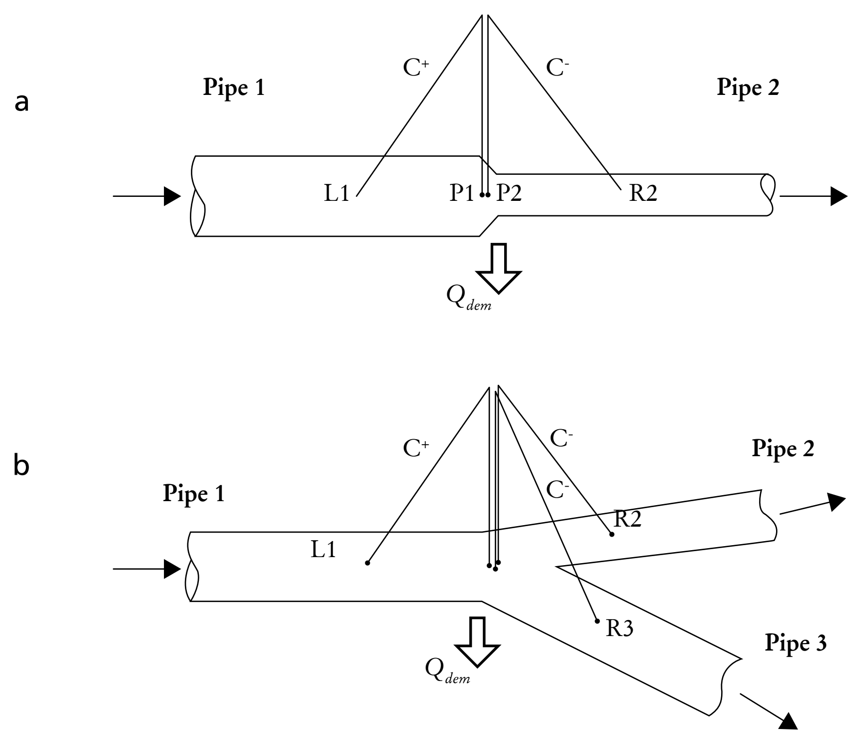
## A.1.2.4 Internal boundary conditions

Junctions with two and three pipes are considered:

Two-pipe junction:

A two-pipe junction is shown in Figure A.1.2.

FIGURE A.1.2
**Boundary conditions at a typical series of (a) two, and (b) three pipes junction**




*Source: Derardja, B., Lamaddalena, N. & Fratino, U. 2019a. Perturbation Indicators for On-Demand Pressurized Irrigation Systems. Water, 11(3): 558. https://doi.org/10.3390/w11030558.*

In the case of no external demand, the values of the four unknowns can be found by solving the set of equations below:

Following the $C^+$ equation (equation (A1.5)):

$$V_{P_1} = ( V_{L_1} + \frac{g}{a_1} H_{L_1} - \frac{f_1 \Delta t}{2D_1} V_{L_1}|V_{L_1}|) - (\frac{g}{a_1}) H_{P_1} \qquad \text{(A1.31)}$$

Following the $C^-$ equation (equation (A1.6)):

$$V_{P_2} = \left( V_{R_2} - \frac{g}{a_2} H_{R_2} - \frac{f_2 \Delta t}{2D_2} V_{R_2}|V_{R_2}| \right) (\frac{g}{a_1}) H_{P_2} \qquad \text{(A1.32)}$$

The conservation of mass equation:

$$V_{P_1} A_1 = V_{P_2} A_2 \qquad \text{(A1.33)}$$

The energy equation at the points $P_1$ and $P_2$, neglecting the difference in velocity heads and any local losses:

$$H_{P_1} = V_{P_2} \qquad \text{(A1.34)}$$

the head value H at the junction can be calculated as follows, solving the above system of equations:

$$H_{P_1} = H_{P_2} = \frac{C_3 A_1 - C_1 A_2}{C_2 A_2 - C_4 A_1} \qquad \text{(A1.35)}$$

where C1, C2, C3 and C4 are the functions of the known values obtained from the earlier time. Through a back-substitution, also the flow velocities can be computed.

A similar system of equations can be used in the case of a series of two pipes with an external constant demand $Q_{dem}$ ($m^3\ s^{-1}$) (delivered by one hydrant), modifying equation (A1.33), as follows:

$$V_{P_1}\,A_1 = V_{P_2}\,A_2 + Q_{dem} \qquad \text{(A1.36)}$$

$$H_{P_1} = H_{P_2} = \frac{C_3 A_1 - C_1 A_2 Q_{dem}}{C_2 A_2 - C_4 A_1} \qquad \text{(A1.37)}$$

### A.1.2.5 Three-pipe junction

A three-pipe junction is shown in Figure A1.2b.

The following equations are used to find the six unknowns, in the case of a pipe junction with one inflow and two outflows:

$$\text{Pipe 1, } C^{+}: V_{P_1} = C_1 - C_2 H_{P_1} \qquad \text{(A1.38)}$$

$$\text{Pipe 2, } C^{-}: V_{P_2} = C_3 - C_4 H_{P_2} \qquad \text{(A1.39)}$$

$$\text{Pipe 3, } C^{-}: V_{P_3} = C_5 - C_6 H_{P_3} \qquad \text{(A1.40)}$$

Conservation of mass:

$$V_{P_3} A_1 = V_{P_2} A_2 + V_{P_3} A_3 \qquad \text{(A1.41)}$$

The energy balance, neglecting local head losses between 1 and 2:

$$H_{P_1} = H_{P_2} \qquad \text{(A1.42)}$$

The energy balance, neglecting local head losses between 1 and 3:

$$H_{P_1} = H_{P_3} \qquad \text{(A1.43)}$$

Solving the previous set of equations leads to:

$$H_{P_1} = H_{P_2} = H_{P_3} = \frac{C_1 A_1 - C_3 A_2 - C_5 A_3}{C_2 A_1 + C_4 A_2 + C_6 A_3} \qquad \text{(A1.44)}$$

Equation (A1.41) has to be modified in the previous set of equations, in the case of a three-pipe junction with an outlet:

$$V_{P_1}\,A_1 = V_{P_2} A_2 + V_{P_1}\,A_1 + V_{P_2} A_2 + Q_{dem} \qquad \text{(A1.45)}$$

while equation (A1.44) becomes:

$$H_{P_1} = H_{P_2} = H_{P_2} = \frac{C_1 A_1 - C_3 A_2 - C_5 A_3 Q_{dem}}{C_2 A_1 + C_4 A_2 + C_6 A_3} \quad (A1.46)$$

# A.2 COPAM V4.0 USER'S MANUAL

## A.2.1 About the software

COPAM v4.0 is an integrated software package that includes several modules for the optimization and hydraulic analysis of large-scale pressurized irrigation distribution systems. COPAM v4.0 is an evolution of the original computer software program called COPAM (*Combined Optimization and Performance Analysis Model*) developed by Lamaddalena (1997) and published in Lamaddalena and Sagardoy (2000). This manual explains the functionality of COPAM v4.0 and its modules to address real world hydraulic problems in a pressurized irrigation system.

The following sections present system requirement, installation instructions, preparation of input data files and some general information on the use of COPAM v4.0.

### A.2.1.1 About the technology

The software consists in a cross-platform desktop app, developed using the classical web technologies and languages. The source code of the program is "compiled" using the bytecode paradigm, in order to protect it and to make it more efficient. The application is packaged for distribution with Electron, a chromium-based open source framework capable of build native exe files for Windows (x64 and x86), Linux and MacOS.

### A.2.1.2 System Requirement

Systems that meet or exceed the following specifications are recommended:

Processor (CPU): Intel Core i5 (sixth generation or newer) or equivalent

Operating System: Microsoft Windows 10 Professional (64 bit)

Memory: 8 GB RAM

Storage: 512 GB internal Solid State Drive (SSD) or 1 TB internal HDD

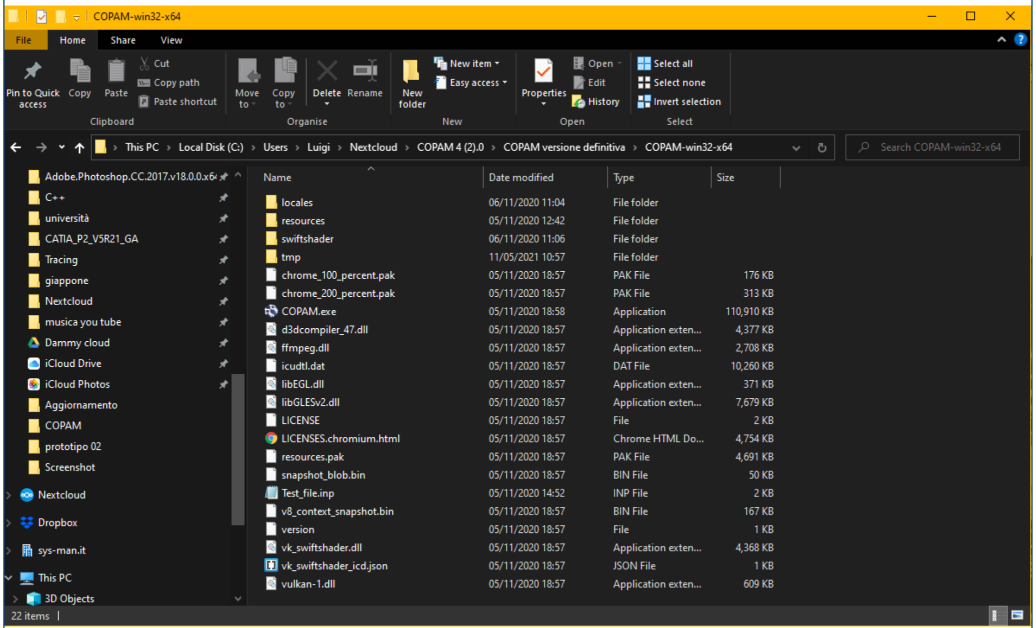
Monitor/Display: 24" LCD monitor

### A.2.1.3 Installation and Start-up of COPAM v4.0

Download the latest version of the software according to your operating system from the website or install it from the enclosed CD . Then extract all the content from the zip folder in any location on your PC.

Explore the COPAM v4.0 environment folder and select the COPAM.exe icon (Figure A.2.1).

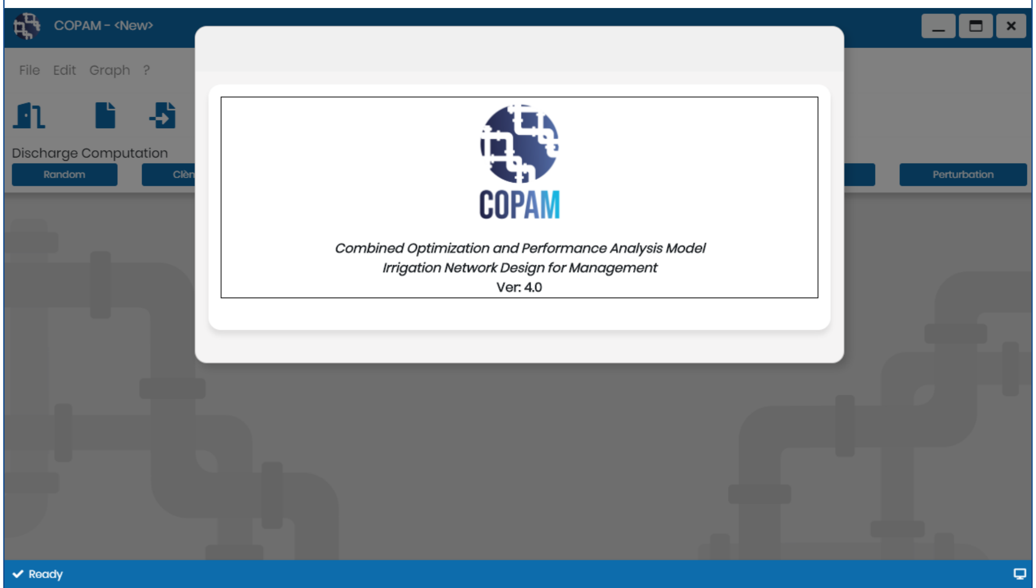
FIGURE A.2.1
**Copam v4.0 folder**




Source: Authors'own elaboration.

After launching the program, a pop-up window (Figure A.2.2) will provide information about the current software version.

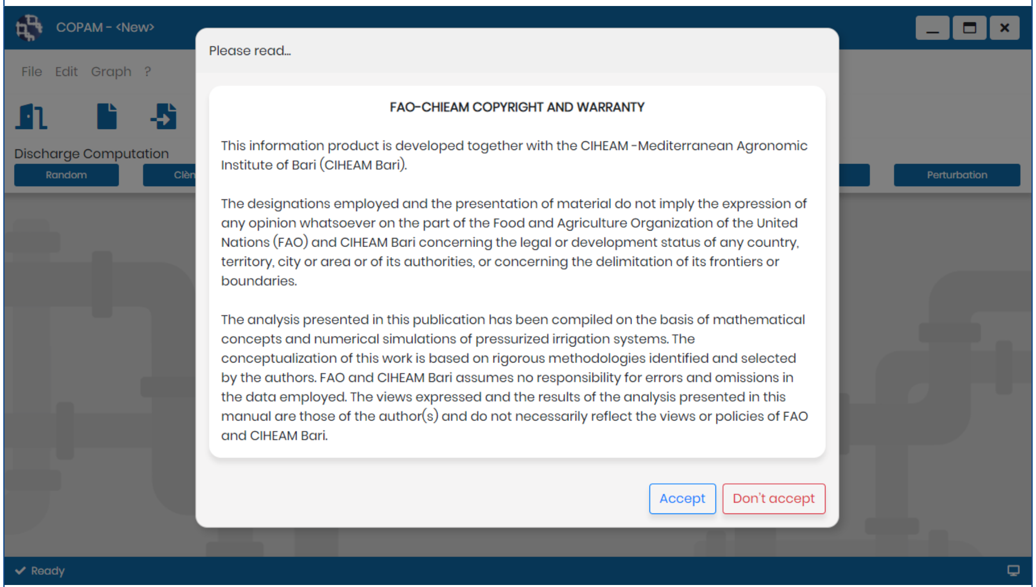
FIGURE A.2.2
**Software presentation window**




Source: Screenshot of COPAM v4.0.

The condition of use follows (Figure A.2.3). The user must read and "Accept" these to gain access to the software.

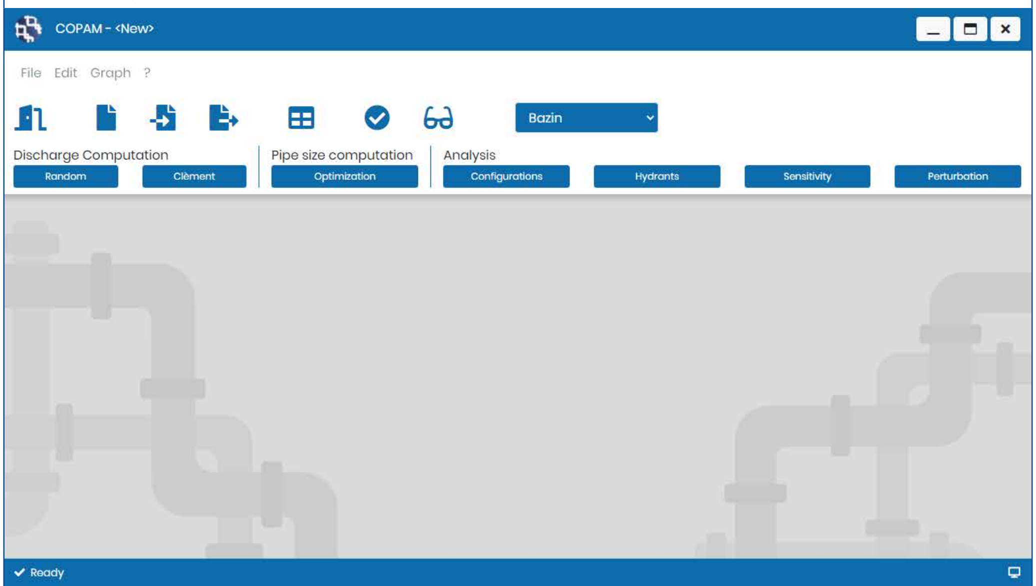
FIGURE A.2.3
**Conditions**




*Source: Screenshot of COPAM v4.0.*

Once the user has accepted the conditions, Figure A.2.4 (*Home page*) will appear.

FIGURE A.2.4
**Home page**




*Source: Screenshot of COPAM v4.0.*

Three programs are available in the COPAM v4.0 package:

- Discharges computation;
- Pipe size computation; and
- Analysis.

Two programs are available for "Discharges computation":

- Clément; and
- Random.

One program is available for "Pipe size computation":

- optimization.

Four programs are available for "Analysis":

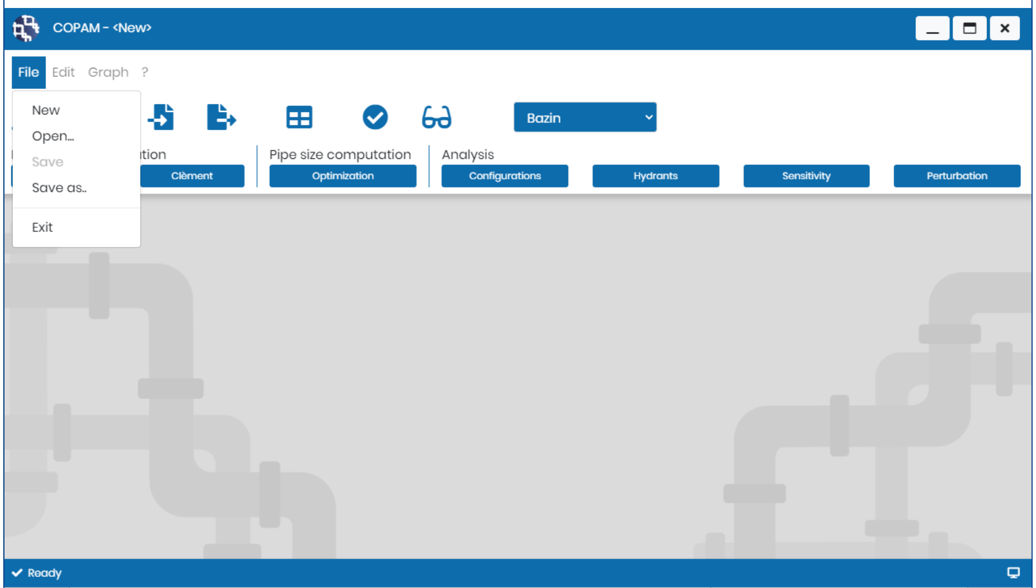
- configurations;
- hydrants;
- sensitivity; and
- perturbation.

The data input file is the same for all the programs and is explained below.

## A.2.2 Preparation of the input file

The program's menu bar contains three options, starting with "*File*." This will show the sub-menu (Figure A.2.5).

FIGURE A.2.5
**File sub-menu**




*Source: Screenshot of COPAM v4.0.*

Options available in the File menu:

- *New;*
- *Open;*
- *Save;*
- *Save as; and*
- *Exit;*

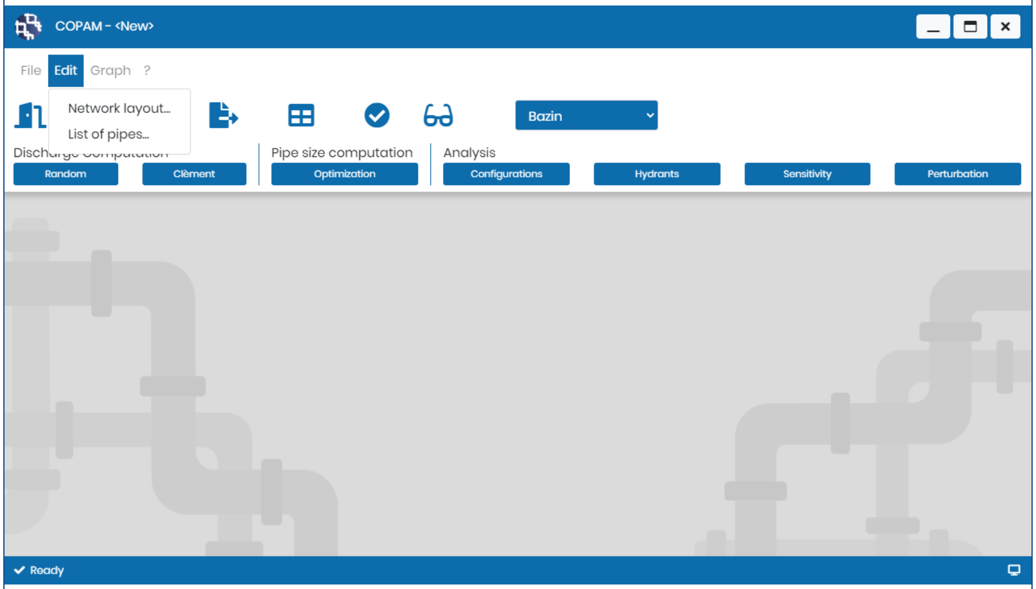
To define a new network, there are two basic actions to complete:

1. List of pipes definitions
2. Network layout definitions

### A.2.1.1 List of pipes definitions

To define the list of pipes, select the option "*list of pipes*" in the sub-menu edit (Figure A.2.6).

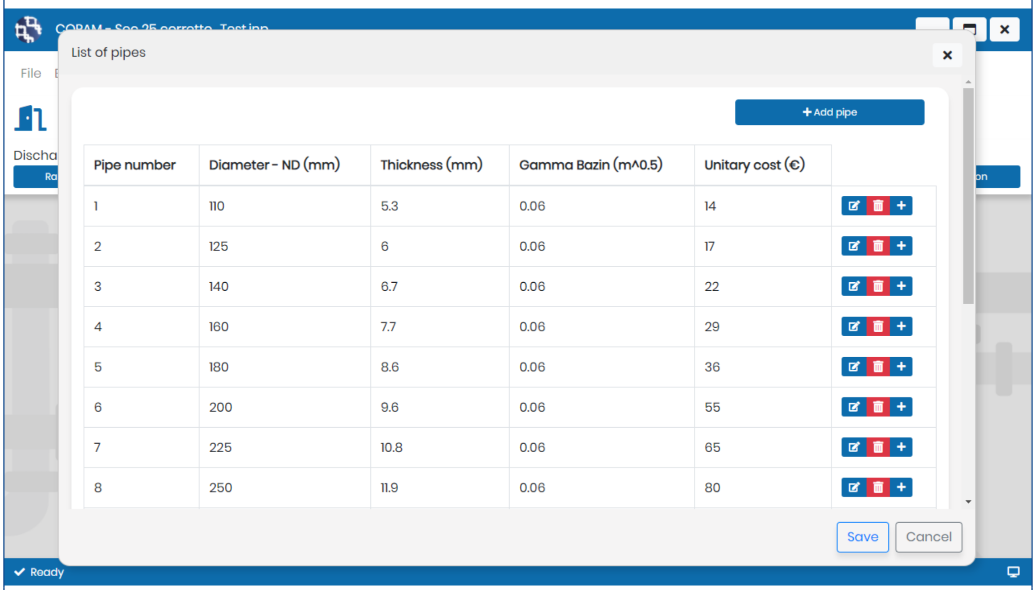
FIGURE A.2.6
**Edit sub-menu**




*Source: Screenshot of COPAM v4.0.*

"*List of pipes*" window will automatically appear (Figure A.2.7).

FIGURE A.2.7
**List of pipes option**




*Source: Screenshot of COPAM v4.0.*

To fill the list, provide the pipe diameters (mm), the wall thickness of each pipe (mm), the roughness (Γ, Bazin coefficient), and the unit cost of the pipes. The pipes must be inserted in ascending order (arranged from smallest to largest diameter). If the nominal diameter of pipes corresponds to the internal diameter, the pipe thickness is considered equal to zero. The Bazin roughness coefficient identifies the type of pipes.

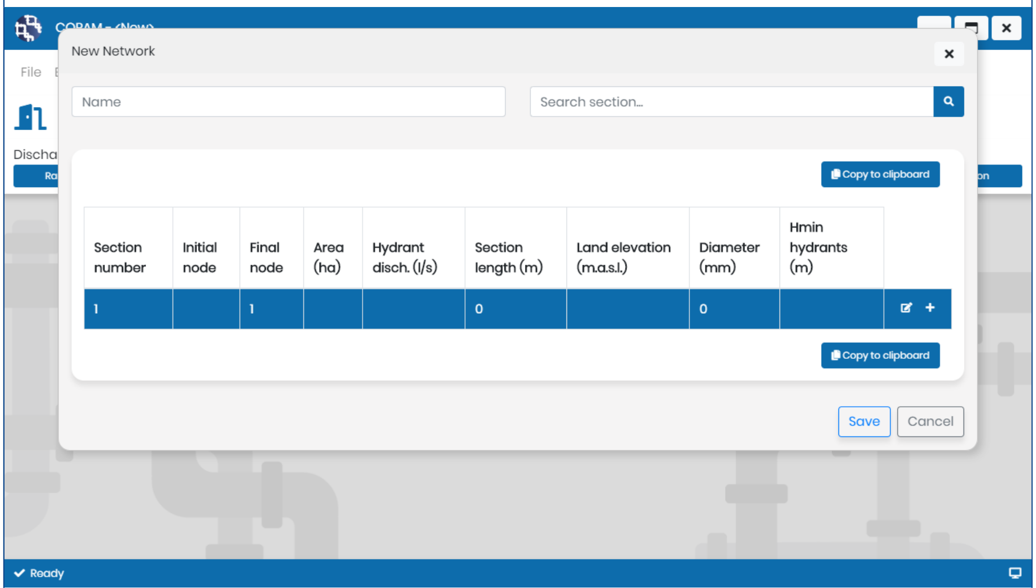
Remember to save the list once it is complete.

### A.2.2.2 Network layout definition

Next, define the network layout.

Select the option "*New*" from the file sub-menu (Figure A.2.8).

FIGURE A.2.8
**New network definition window**




*Source: Screenshot of COPAM v4.0.*

An alternative way (shortcut) is to open a new network is to select the icon  on the home page menu.

The "*New Network*" screen menu allows the user to define each section of the network. It is strongly recommended to prepare and clearly define the input data before using the program.

The program assumes that the network is a branch type. A number defines each node (hydrants and/or section connections). The node numbering is essential as follows:

- The upstream node (water source) must have numbered as 0.
- The other nodes are numbered consecutively, from upstream to downstream.
- The number of any section must be the same as the number of its downstream node.
- All terminal nodes of the branches must have a hydrant.
- No more than two sections may be derived from an upstream node. If so, a section with negligible length (i.e.maximum of 1 m) must be created, and an additional node must be considered. This node must have a sequential number.

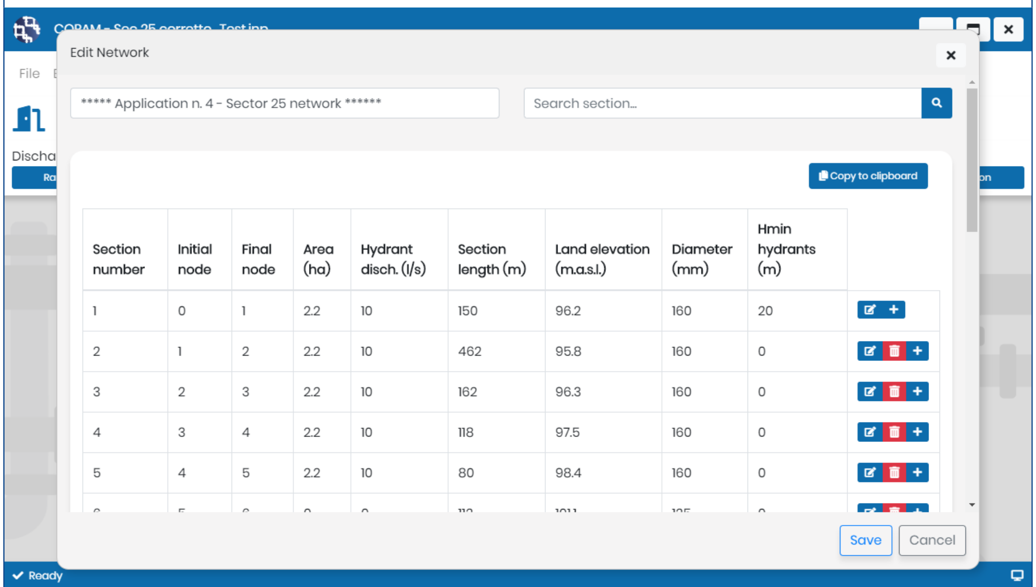
- No hydrants may be located in a node with three joined sections. If so, an additional node with a sequential number must be added.
- If hydrants with two or more outlets exist in the network, one number for each outlet needs to be allocated by creating an imaginary section with negligible length.

When the numbering is completed, the following information must be entered in the "Edit/Network layout":

- Area irrigated by each hydrant (in hectares); if the node is not a hydrant, the area must be considered as 0.
- Hydrant discharge (l/s).
- Section length (m).
- Land elevation of each node (m a.s.l.).
- Nominal pipe diameter of the section (mm). This information is needed for the analysis of the network. In the design stage, the pipe diameter of each section is considered as 0.
- Minimum head required at the hydrant (Hmin (m)).
- Number of outlets. This information is needed when the user wants to define the number of hydrant outlets, the default number is 1 (no multiple outlets) and the maximum is 4. The user can select the number of outlets thanks to a drop-down menu and select from 1 to 4.

An example of the "*New Network*" screen menu is shown in Figure A.2.9.

FIGURE A.2.9
**New network definition example**




*Source: Screenshot of COPAM v4.0.*

A new section can be added using the button “*Add section*” at the right of each section; a descriptive name of the network can be added in the text box “*Name*”.

To insert section data, select a section line (or through the icon ), Data includes *Section number, Initial node, Final node, Area, Hydrant discharge, Section length, Land elevation, Diameter, Hmin hydrants.*

A section may be deleted by clicking on the icon On completing the network layout description, make sure to press “*Save*.”

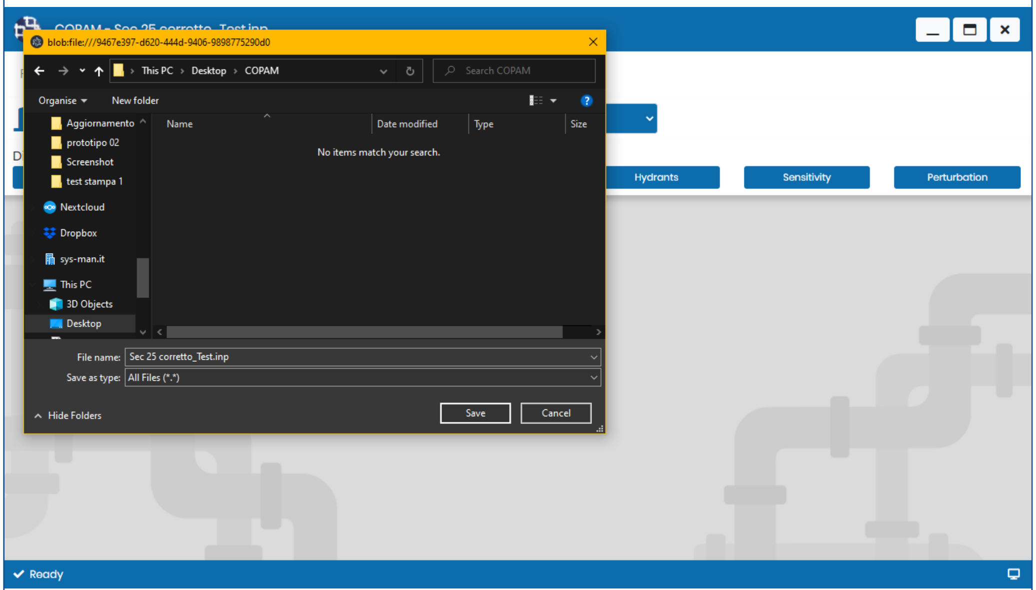
“*Copy to clipboard*” enables a text version of the network to be copied and pasted into any document.

Next, save the project and export a file containing all the network information.

To export the information click on "*File/Save As*" or the icon on the main menu. The file explorer window will appear (Figure A.2.10).

Select the local directory to save the file and assign a new file name; the extension *.inp* is automatically assigned to the file.

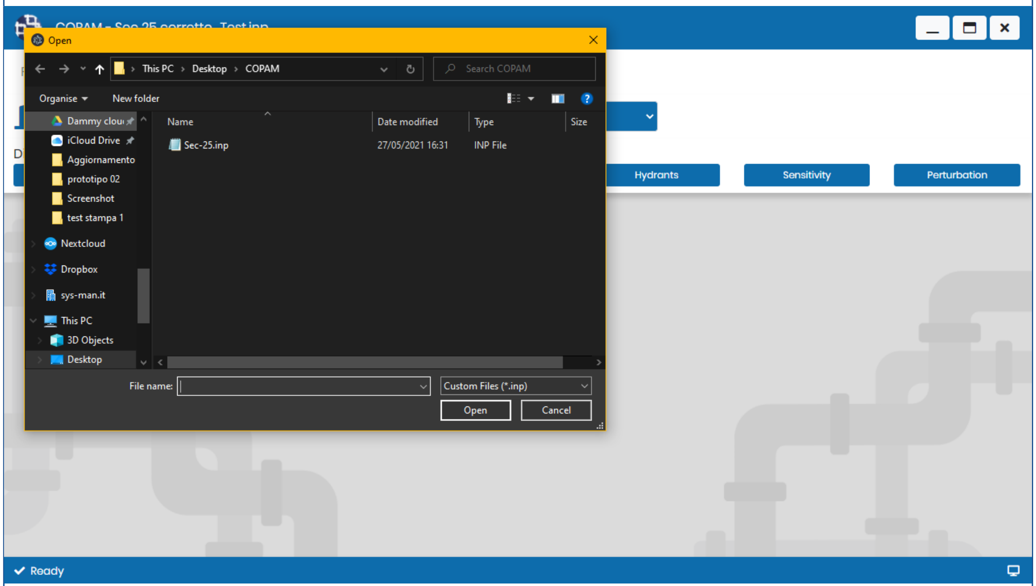
FIGURE A.2.10
**Save and export**




*Source: Screenshot of COPAM v4.0.*

COPAM v4.0 allows the user to import an input file (*.inp*) previously generated; the import procedure can be initiated by clicking on "*File/Open*" or by clicking the icon on the main page. The local file explore window will appear on the screen (Figure A.2.11) to find the proper file and import it in COPAM v4.0.

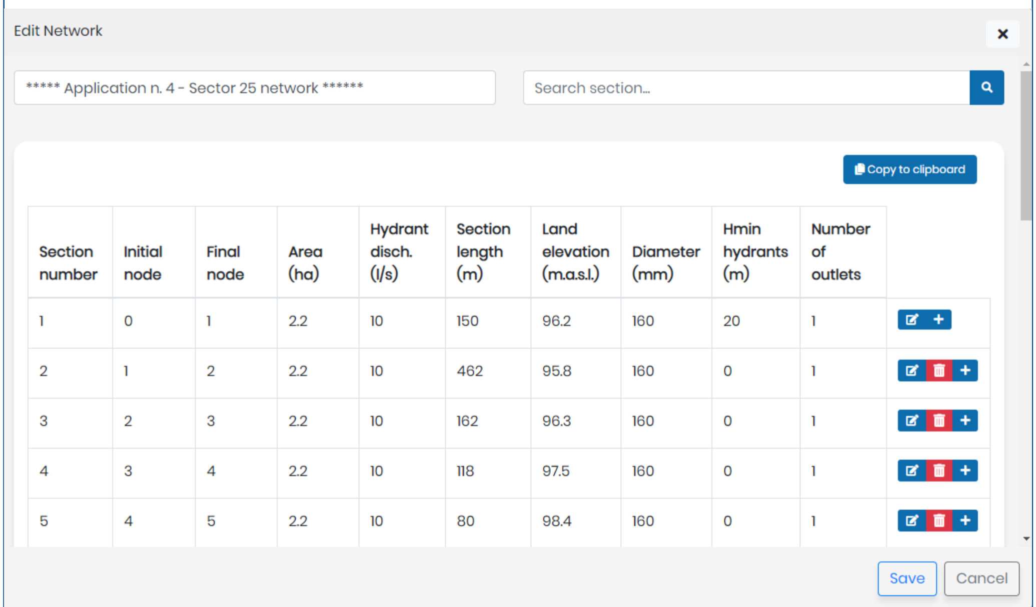
FIGURE A.2.11
**Import file window**




*Source: Screenshot of COPAM v4.0.*

Following the import, the network can be edited by opening the edit network window (Figure A.2.12), and clicking on "*Edit/Network layout...*" or the icon on the main page.

FIGURE A.2.12
**Edit Network**




| Section number | Initial node | Final node | Area (ha) | Hydrant disch. (l/s) | Section length (m) | Land elevation (m.a.s.l.) | Diameter (mm) | Hmin hydrants (m) | Number of outlets |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 2.2 | 10 | 150 | 96.2 | 160 | 20 | 1 |
| 2 | 1 | 2 | 2.2 | 10 | 462 | 95.8 | 160 | 0 | 1 |
| 3 | 2 | 3 | 2.2 | 10 | 162 | 96.3 | 160 | 0 | 1 |
| 4 | 3 | 4 | 2.2 | 10 | 118 | 97.5 | 160 | 0 | 1 |
| 5 | 4 | 5 | 2.2 | 10 | 80 | 98.4 | 160 | 0 | 1 |

*Source: Screenshot of COPAM v4.0.*

## A.2.3. Discharge computation

Discharge computation is performed using two models: random model, Clément model.

### A.2.3.1 Random model

The Random model may be used to :

- analyse existing irrigation systems;
- design new irrigation systems.

To analyse an existing system, the model uses the demand hydrograph at the upstream end of the network. It allows the selection of the upstream discharge corresponding to various hydrant configurations.

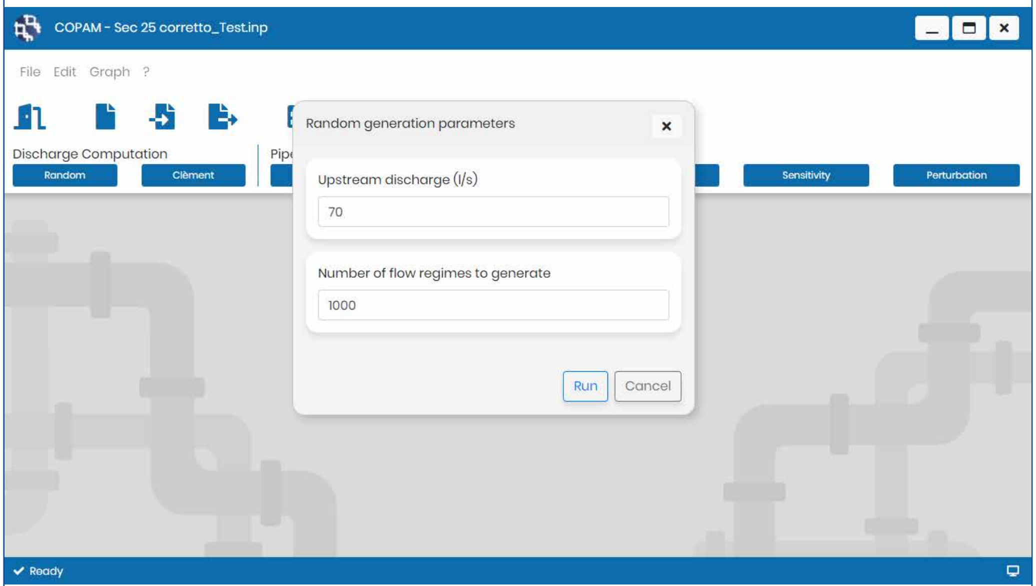
Insert the upstream discharge in“*Upstream discharge*” (Figure A.2.13).

A number of random hydrants simultaneously operating (hydrant configuration) is generated automatically.

This procedure is repeated according to pre-defined configurations and used to analyse the system performance, as detailed later in the analysis section.

Next, define the number of configurations (or flow regimes) to generate is in the “*Number of flow regimes to generate*.” This number must be a multiple of 10.

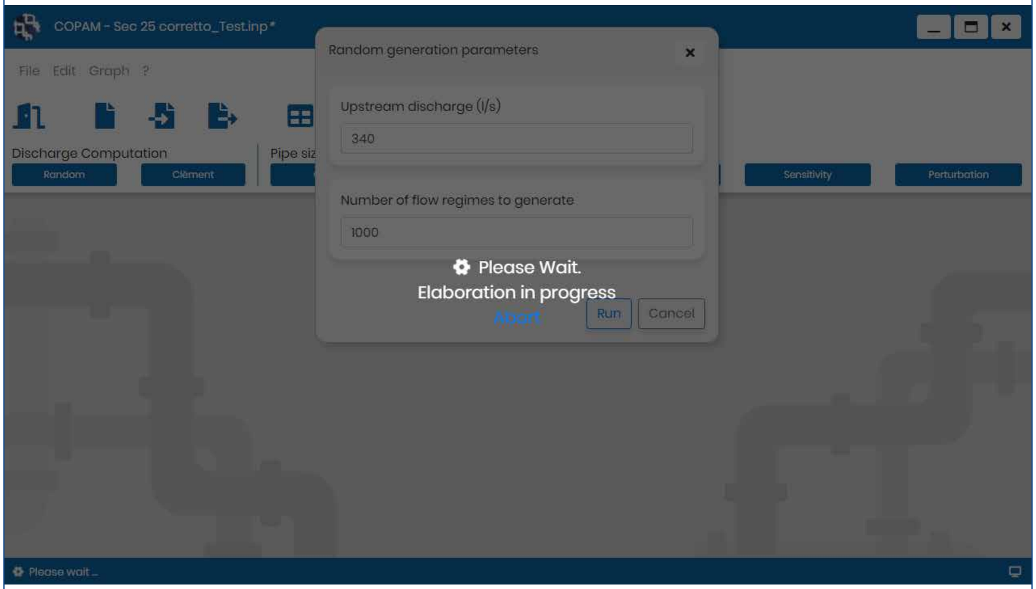
FIGURE A.2.13
**Random generation**




*Source: Screenshot of COPAM v4.0.*

Press "*Run*" to operate the program. Figure A.2.14 will appear automatically on the screen.

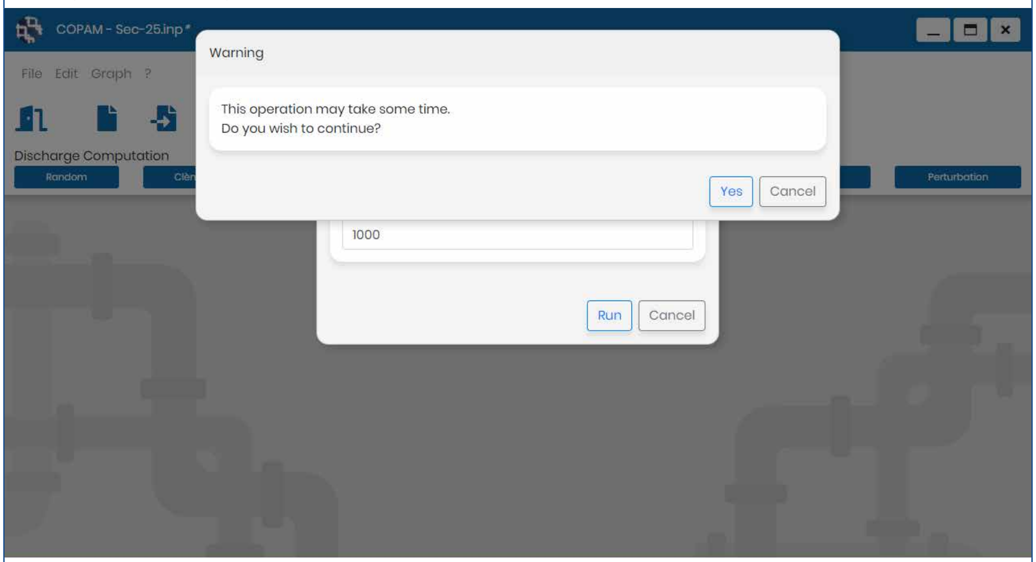
FIGURE A.2.14
**Elaboration in progress**




*Source: Screenshot of COPAM v4.0.*

Running the program can take several minutes to complete depending on the complexity of the network (See Figure A.2.15).

FIGURE A.2.15
**Long-time warning**

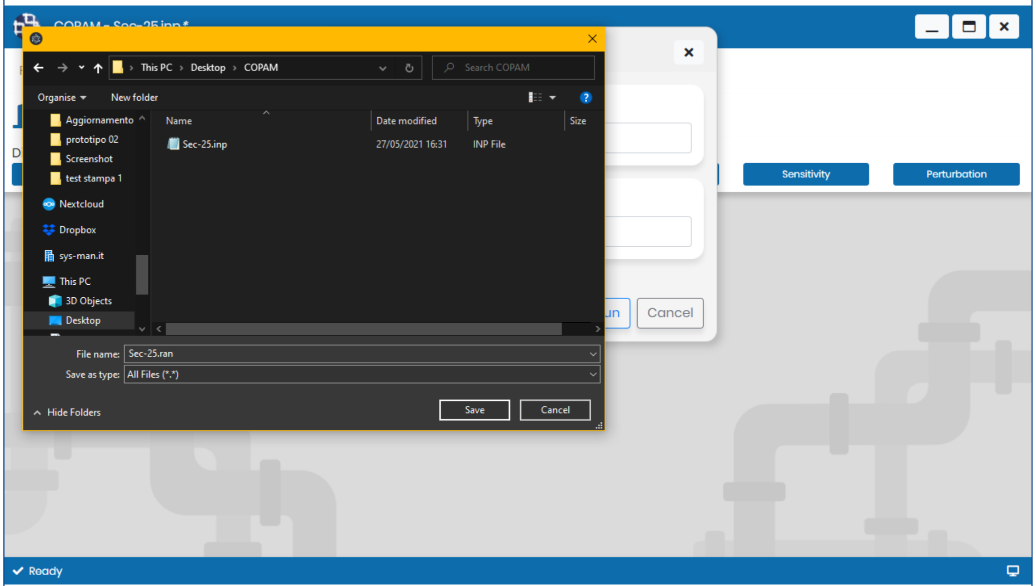



*Source: Screenshot of COPAM v4.0.*

When the program is complete, the file explorer window will appear (Figure A.2.16).

Select the local directory where to save the file and assign a new file name (The default file name is the same as the name of the input file, and the default directory is the same where the input file is stored).

FIGURE A.2.16
**Random elaboration complete**



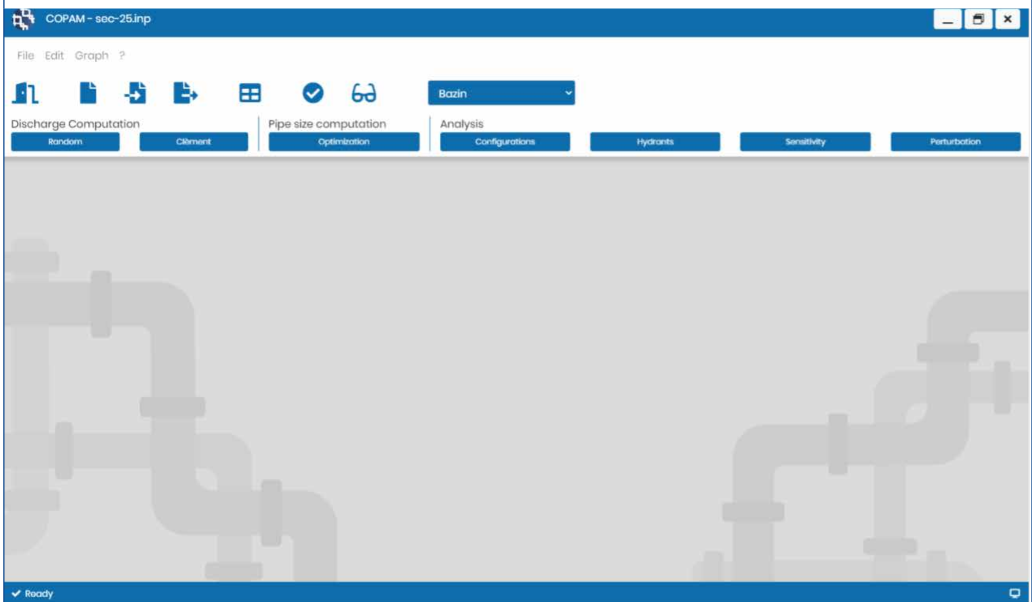

*Source: Screenshot of COPAM v4.0.*

## A.2.3.2 Clément Model

The "Clément" program allows the computation of discharges flowing into the network using either the first or the second Clément models.

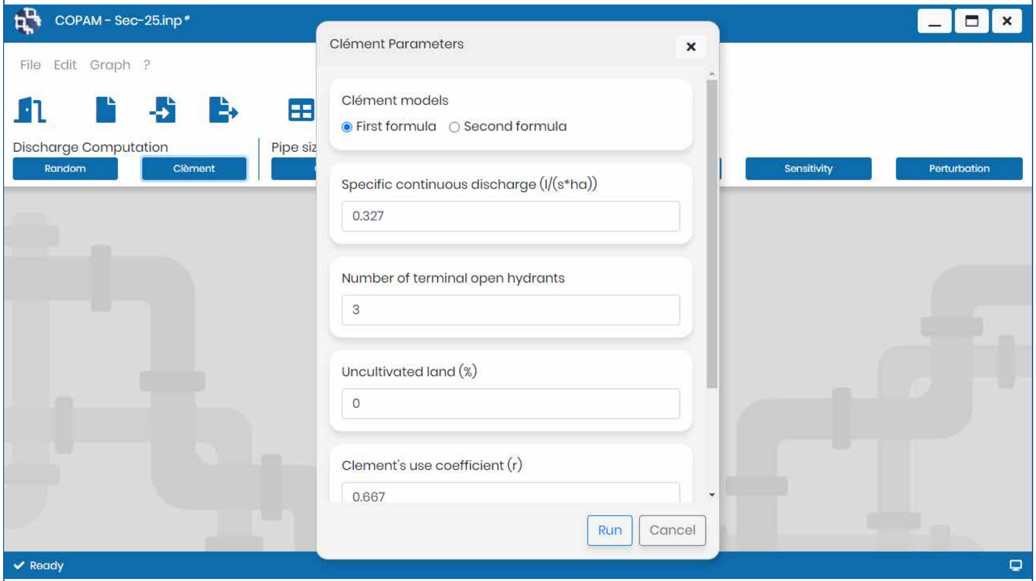
Click "*Clément*" (Figure A.2.17) to open "*Clément parameters*" (Figure A.2.18).

FIGURE A.2.17
**Clément model selection**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.18
**Clément model parameter window**




*Source: Screenshot of COPAM v4.0.*

When "*First formula*" is selected, enter the following parameters in the "*Clément parameters*" menu (Figure A.2.18).

- specific continuous discharge (l $s^{-1}$ $ha^{-1}$);
- minimum number of terminal open hydrants;
- percentage of uncultivated land;
- Clément use coefficient (r); and
- Clément operation quality, U(Pq).

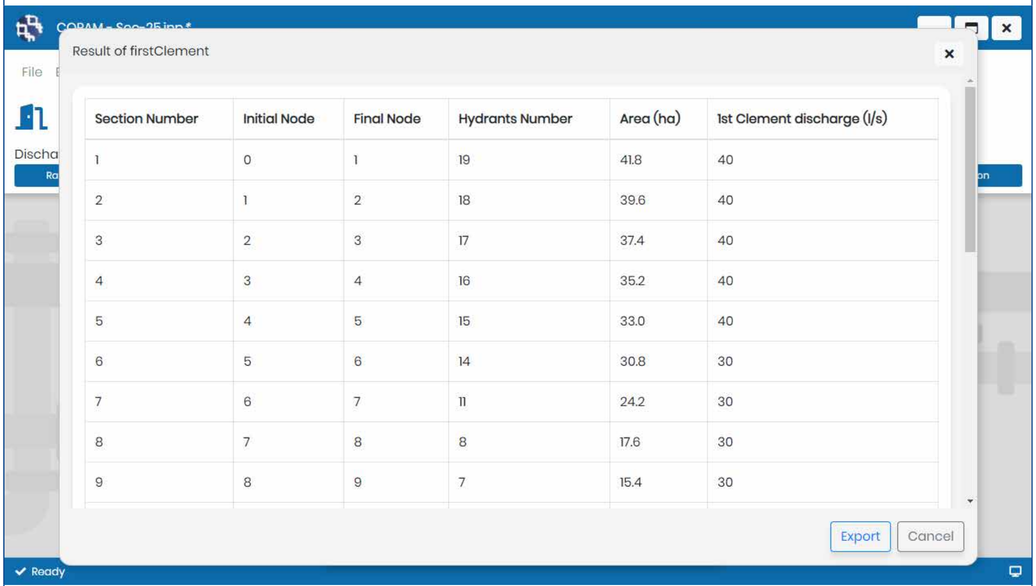
When "*Second formula*" is selected, enter the following parameters in the "*Clément parameters*" menu.

- specific continuous discharge (l $s^{-1}$ $ha^{-1}$);
- minimum number of terminal open hydrants;
- percentage of uncultivated land;
- Clément use coefficient (r); and
- probability of saturation (PA percentage).

Press "*Run*" to run the program.

When completed, the results are automatically displayed in the pop-up window "*Result of first/second Clément*" (Figure A.2.19).

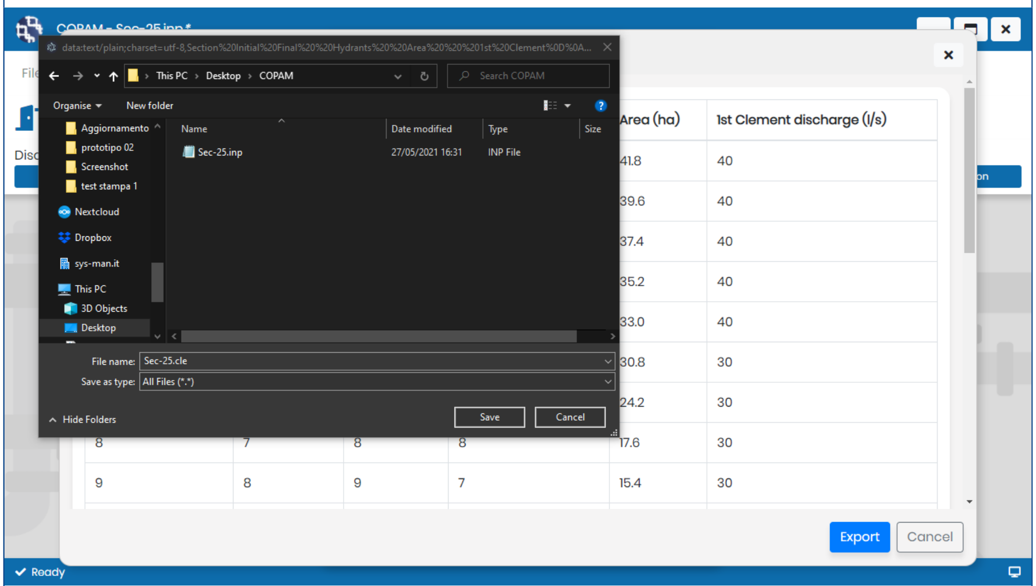
FIGURE A.2.19
**Result of Clément**




*Source: Screenshot of COPAM v4.0.*

Click on "*Export*" to export the data to the file explorer window (Figure A.2.20).

FIGURE A.2.20
**File explorer window**




*Source: Screenshot of COPAM v4.0.*

Select the local directory where to save the file and assign a new file name (The default file name is the same as the name of the input file, and the default directory is the same where the input file is stored).

Save the file. The extension .cle is automatically assigned.

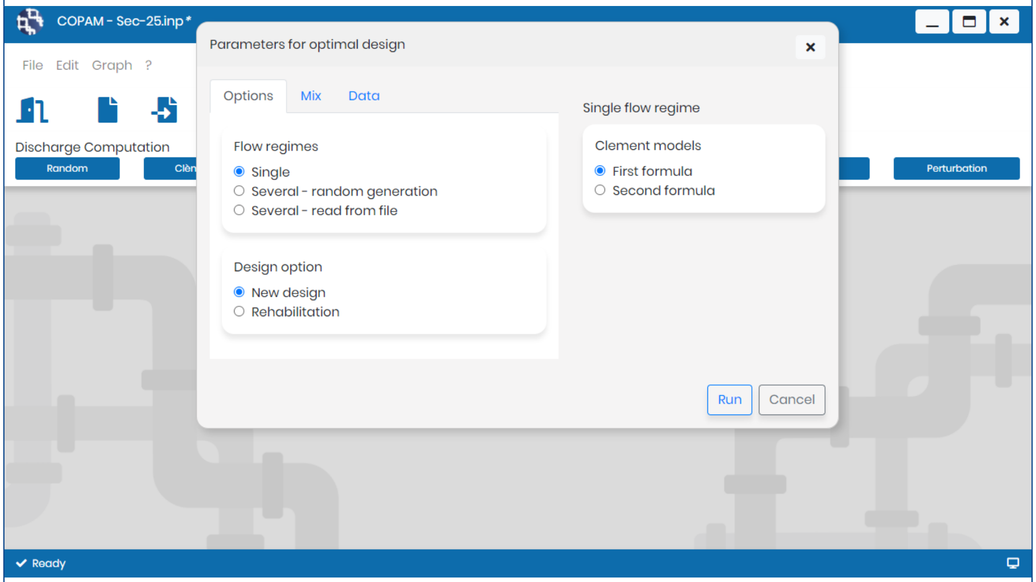
## A.2.4 Pipe size computation

The optimization model can compute the optimum pipe sizes.

### A.2.4.1 Optimization model

The optimization program is part of the COPAM v4.0 package. After completing the input file, as described in the previous section, click on "*Optimization*" and Figure A.2.21 will appear.

FIGURE A.2.21
**Optimization model options**




*Source: Screenshot of COPAM v4.0.*

Three flow regimes options are available within the "*Options*":

- *Single* flow regimes:

  The program computes discharges using the first or second Clément models. There is only one single flow regime.

- *Several – random generation:*

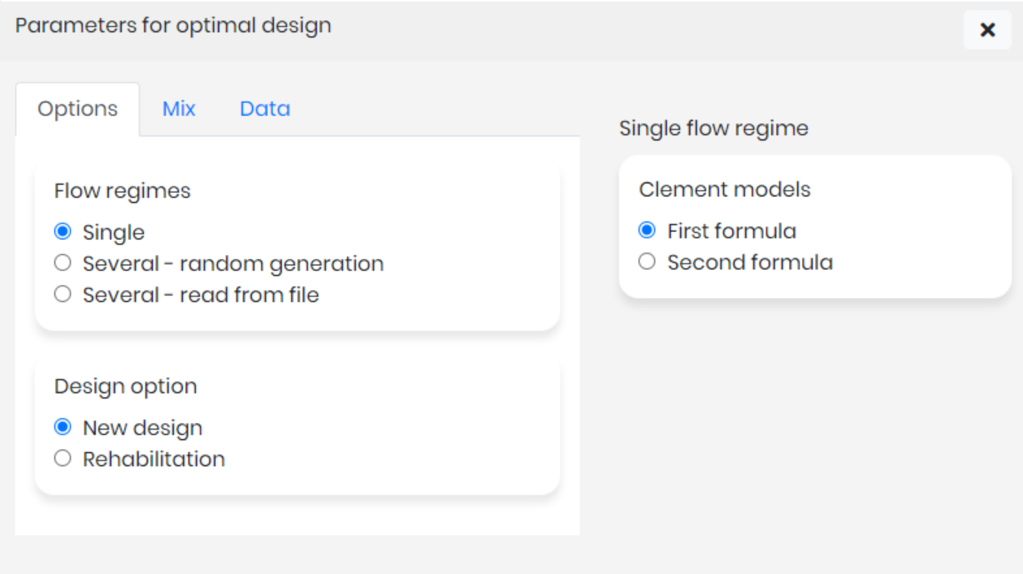
  The program automatically generates several random flow regimes; the number of regimes to generate for each "*Upstream discharge*" can be defined in the designated text box "*Number of regimes to generate for each discharge*".

- *Several – read from file:*

  The program reads the flow regimes previously generated and stored in a file. This option allows network optimization (and/or analysis) also in the case of rotation delivery schedule. The flow regimes are computed according to the planned irrigation schedule and stored in a file that will be read by the program.

Select "*Read regimes from file*" and "*Choose file*" to upload previously generated flow regimes (Figure A.2.22) using the extension "*.ran*".

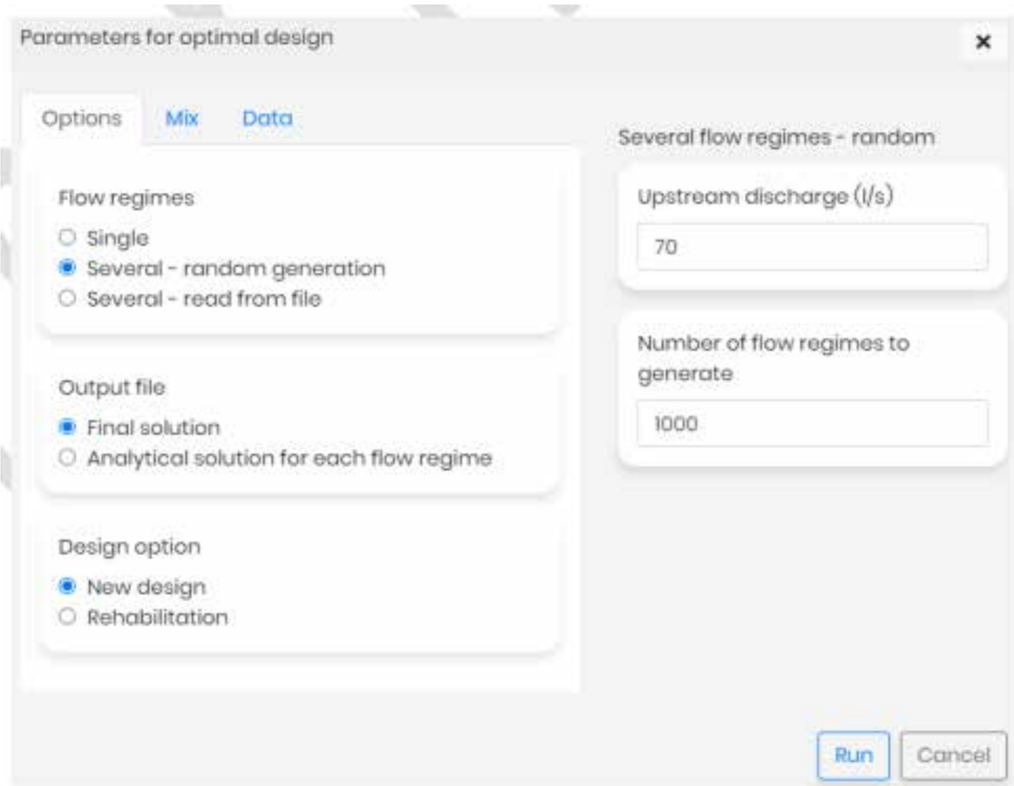
FIGURE A.2.22
**Optimization model options**




*Source: Screenshot of COPAM v4.0.*

When "*Several – random generation*" or "*Several – read from file*" are selected, either the final solution or the analytical solution for each flow regime on the output file can be printed using the appropriate radio button (Figure A.2.23).

FIGURE A.2.23
**Output file definition**

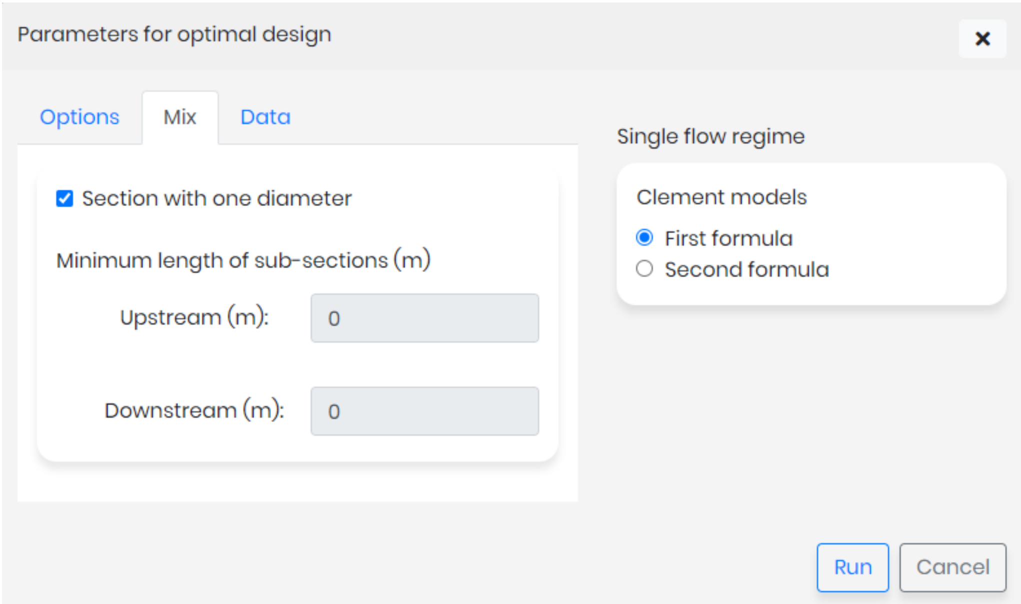



*Source: Screenshot of COPAM v4.0.*

Two additional design options are available in the program: *new design* and *rehabilitation*. In the first case, the program computes the optimal pipe size diameters starting from an initial solution obtained by using the smallest diameters respecting the maximum flow velocities constraints. For rehabilitation, the initial solution is given by the actual diameters of each section of the network.

The program, within the "*Mix*" tab control (Figure A.2.24), gives the possibility to select one diameter for each section or consider the mix with two diameters for each section. From a practical point of view, one diameter should be selected to avoid possible mistakes during the construction phase.

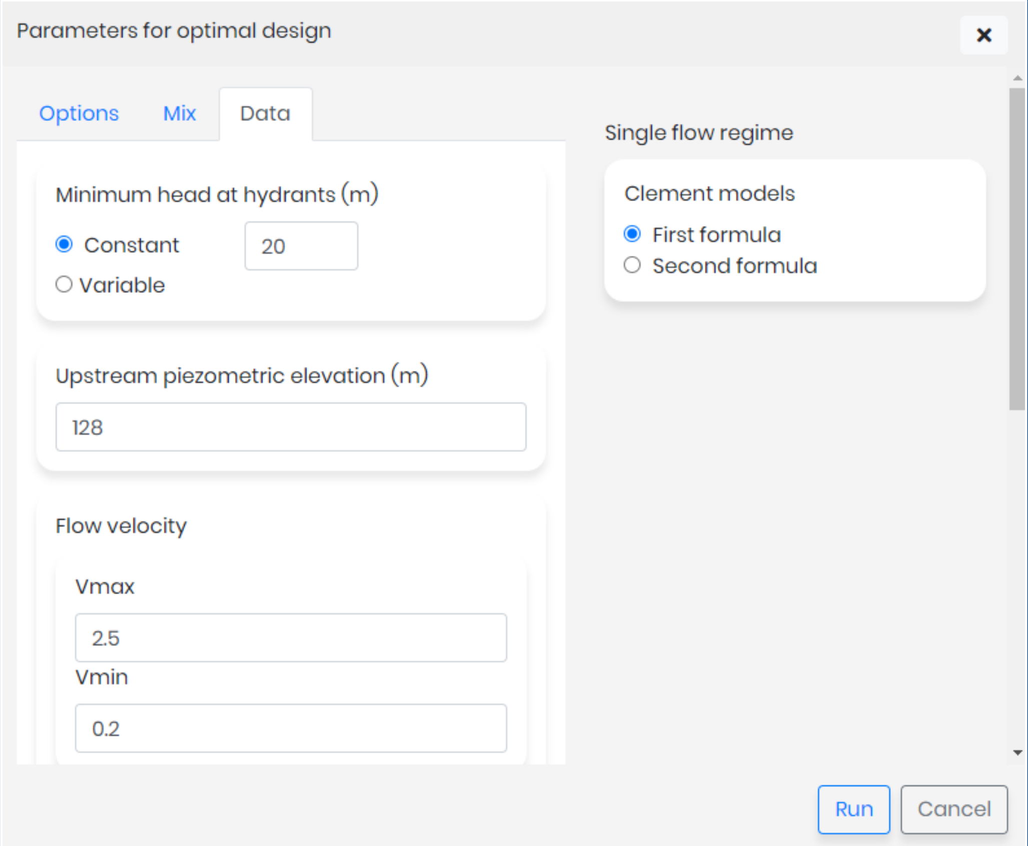
FIGURE A.2.24
**Optimization Mix tab**




*Source: Screenshot of COPAM v4.0.*

In the "*Data*" tab control (Figure A.2.25), all the parameters related to the first or second Clément formula are introduced. Clément parameters are disabled when "*Several – random generation*" or "*Several – read from file*" is selected.

FIGURE A.2.25
**Data tab Clément parameters**




*Source: Screenshot of COPAM v4.0.*

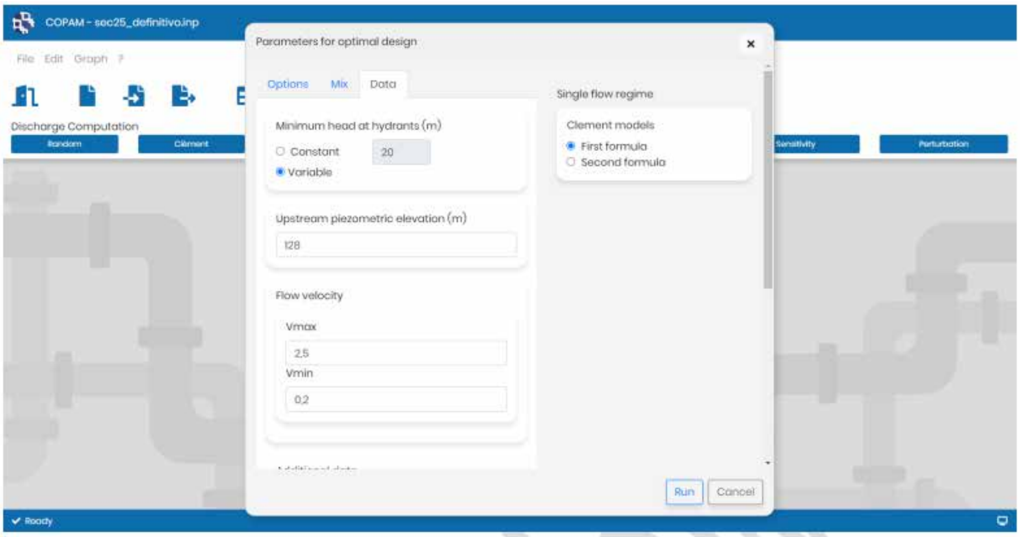
In the Optimization "*Data Tab*" the target value of the "*Upstream piezometric elevation*" is defined (Figure A.2.26).

The "*Minimum head at hydrants*" is also defined. The program allows network computations where the minimum pressure head (Hmin) required for on-farm irrigation is constant or variable.

For constant minimum head, select the "*Constant*" button and enter the Hmin in the box. The constant value of Hmin is automatically assigned to each hydrant regardless of the values of Hmin defined in the "*Hmin Hydrants*" column of the input file.

For variable minimum head, select the "*Variable*" button. The minimum head values at each hydrant will be automatically read from the "*Hmin Hydrants*" column in the data input file.

FIGURE A.2.26
**Optimization Data tab**

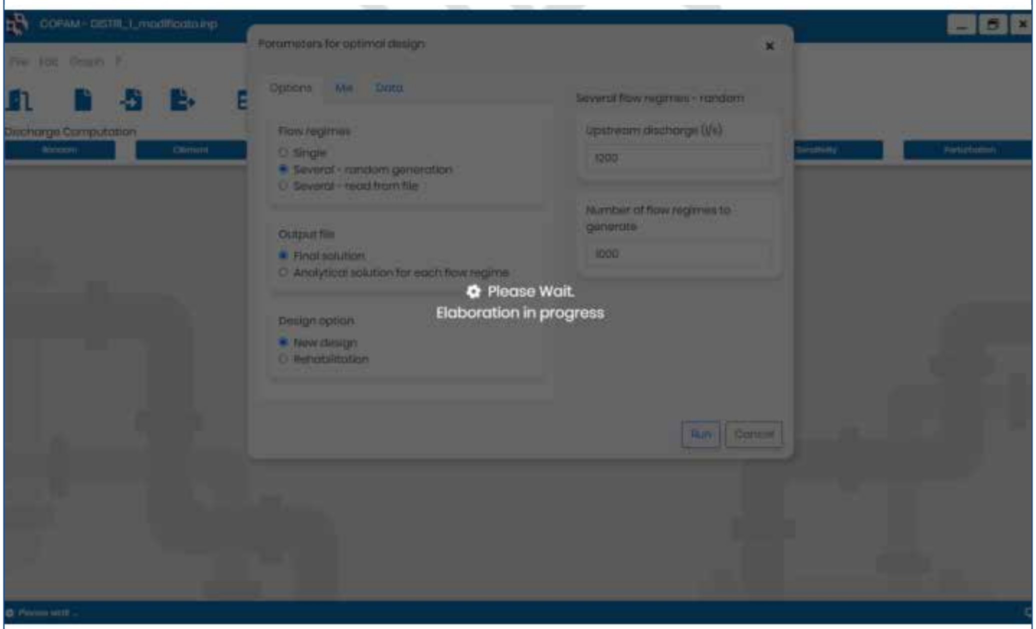



*Source: Screenshot of COPAM v4.0.*

When all inputs parameters are entered, click the "*Run*" button to run the program.

During the model operation, a loading screen will appear (Figure A.2.27).

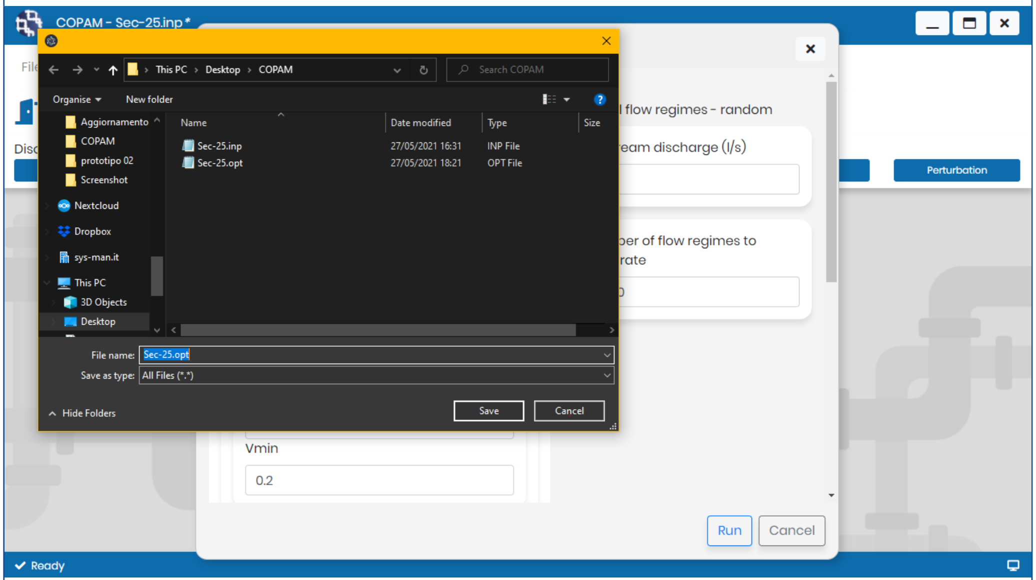
FIGURE A.2.27
**Elaboration in progress screen**




*Source: Screenshot of COPAM v4.0.*

Operating the program generates a file with "*.opt*" extension and the file explorer window is automatically shown (Figure A.2.28). Select the local directory to save the file and assign a new file name (The default file name is the same as the name of the input file and the default directory is the same where the input file is stored).

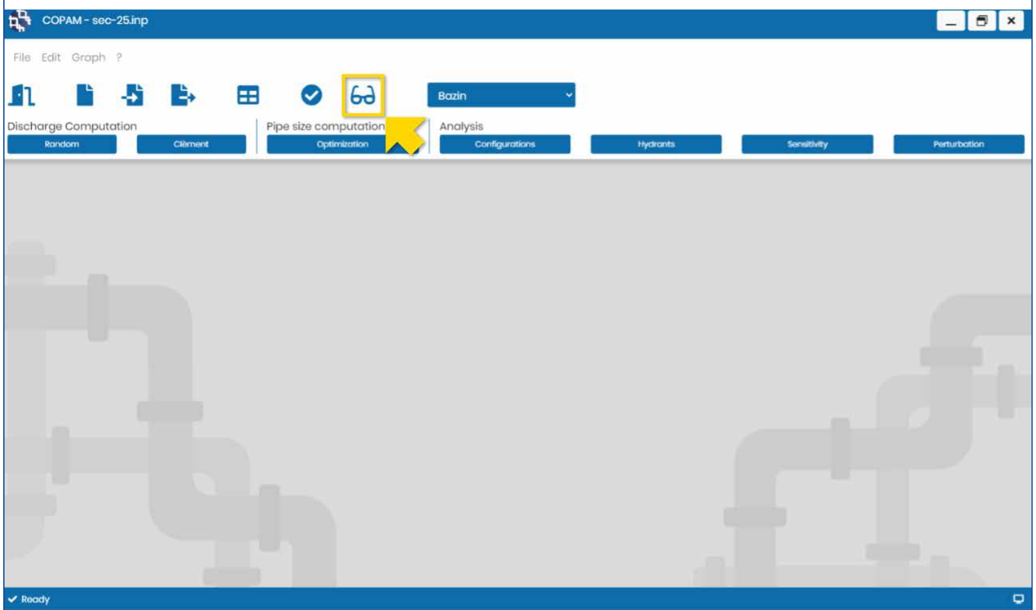
FIGURE A.2.28
**Optimization file explorer window**




*Source: Screenshot of COPAM v4.0.*

The graphical interface of COPAM v4.0 allows easy printing of the outputs from the model. From the Home page, select the glasses icon to visualize the files generated (Figure A.2.29).

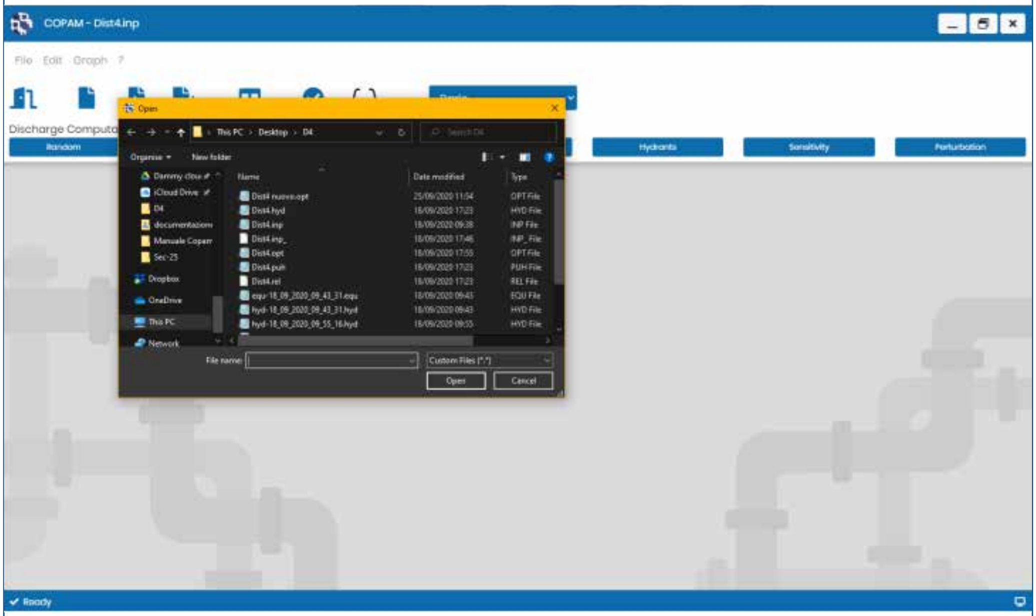
FIGURE A.2.29
**File visualization icon**




*Source: Screenshot of COPAM v4.0.*

Select a file to open (Figure A.2.30)

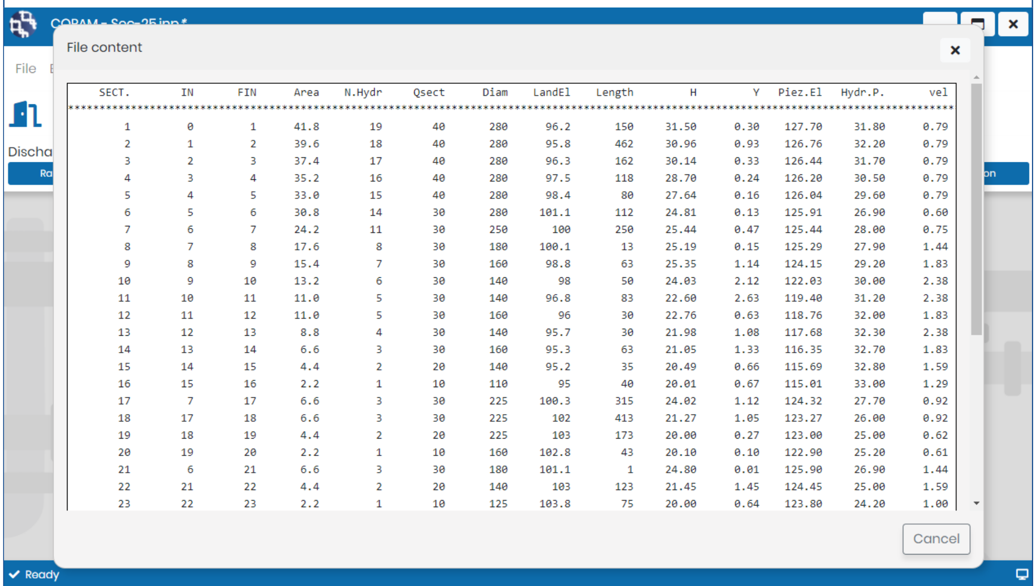
FIGURE A.2.30
**File explorer window**




*Source: Screenshot of COPAM v4.0.*

A dedicated window will automatically appear to view the file content (Figure A.2.31)

FIGURE A.2.31
**File content window**




| SECT. | IN | FIN | Area | N.Hydr | Qsect | Diam | LandEl | Length | H | Y | Piez.El | Hydr.P. | vel |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 41.8 | 19 | 40 | 280 | 96.2 | 150 | 31.50 | 0.30 | 127.70 | 31.80 | 0.79 |
| 2 | 1 | 2 | 39.6 | 18 | 40 | 280 | 95.8 | 462 | 30.96 | 0.93 | 126.76 | 32.20 | 0.79 |
| 3 | 2 | 3 | 37.4 | 17 | 40 | 280 | 96.3 | 162 | 30.14 | 0.33 | 126.44 | 31.70 | 0.79 |
| 4 | 3 | 4 | 35.2 | 16 | 40 | 280 | 97.5 | 118 | 28.70 | 0.24 | 126.20 | 30.50 | 0.79 |
| 5 | 4 | 5 | 33.0 | 15 | 40 | 280 | 98.4 | 80 | 27.64 | 0.16 | 126.04 | 29.60 | 0.79 |
| 6 | 5 | 6 | 30.8 | 14 | 30 | 280 | 101.1 | 112 | 24.81 | 0.13 | 125.91 | 26.90 | 0.60 |
| 7 | 6 | 7 | 24.2 | 11 | 30 | 250 | 100 | 250 | 25.44 | 0.47 | 125.44 | 28.00 | 0.75 |
| 8 | 7 | 8 | 17.6 | 8 | 30 | 180 | 100.1 | 13 | 25.19 | 0.15 | 125.29 | 27.90 | 1.44 |
| 9 | 8 | 9 | 15.4 | 7 | 30 | 160 | 98.8 | 63 | 25.35 | 1.14 | 124.15 | 29.20 | 1.83 |
| 10 | 9 | 10 | 13.2 | 6 | 30 | 140 | 98 | 50 | 24.03 | 2.12 | 122.03 | 30.00 | 2.38 |
| 11 | 10 | 11 | 11.0 | 5 | 30 | 140 | 96.8 | 83 | 22.60 | 2.63 | 119.40 | 31.20 | 2.38 |
| 12 | 11 | 12 | 11.0 | 5 | 30 | 160 | 96 | 30 | 22.76 | 0.63 | 118.76 | 32.00 | 1.83 |
| 13 | 12 | 13 | 8.8 | 4 | 30 | 140 | 95.7 | 30 | 21.98 | 1.08 | 117.68 | 32.30 | 2.38 |
| 14 | 13 | 14 | 6.6 | 3 | 30 | 160 | 95.3 | 63 | 21.05 | 1.33 | 116.35 | 32.70 | 1.83 |
| 15 | 14 | 15 | 4.4 | 2 | 20 | 140 | 95.2 | 35 | 20.49 | 0.66 | 115.69 | 32.80 | 1.59 |
| 16 | 15 | 16 | 2.2 | 1 | 10 | 110 | 95 | 40 | 20.01 | 0.67 | 115.01 | 33.00 | 1.29 |
| 17 | 7 | 17 | 6.6 | 3 | 30 | 225 | 100.3 | 315 | 24.02 | 1.12 | 124.32 | 27.70 | 0.92 |
| 18 | 17 | 18 | 6.6 | 3 | 30 | 225 | 102 | 413 | 21.27 | 1.05 | 123.27 | 26.00 | 0.92 |
| 19 | 18 | 19 | 4.4 | 2 | 20 | 225 | 103 | 173 | 20.00 | 0.27 | 123.00 | 25.00 | 0.62 |
| 20 | 19 | 20 | 2.2 | 1 | 10 | 160 | 102.8 | 43 | 20.10 | 0.10 | 122.90 | 25.20 | 0.61 |
| 21 | 6 | 21 | 6.6 | 3 | 30 | 180 | 101.1 | 1 | 24.80 | 0.01 | 125.90 | 26.90 | 1.44 |
| 22 | 21 | 22 | 4.4 | 2 | 20 | 140 | 103 | 123 | 21.45 | 1.45 | 124.45 | 25.00 | 1.59 |
| 23 | 22 | 23 | 2.2 | 1 | 10 | 125 | 103.8 | 75 | 20.00 | 0.64 | 123.80 | 24.20 | 1.00 |

*Source: Screenshot of COPAM v4.0.*

## A.2.5 Analysis

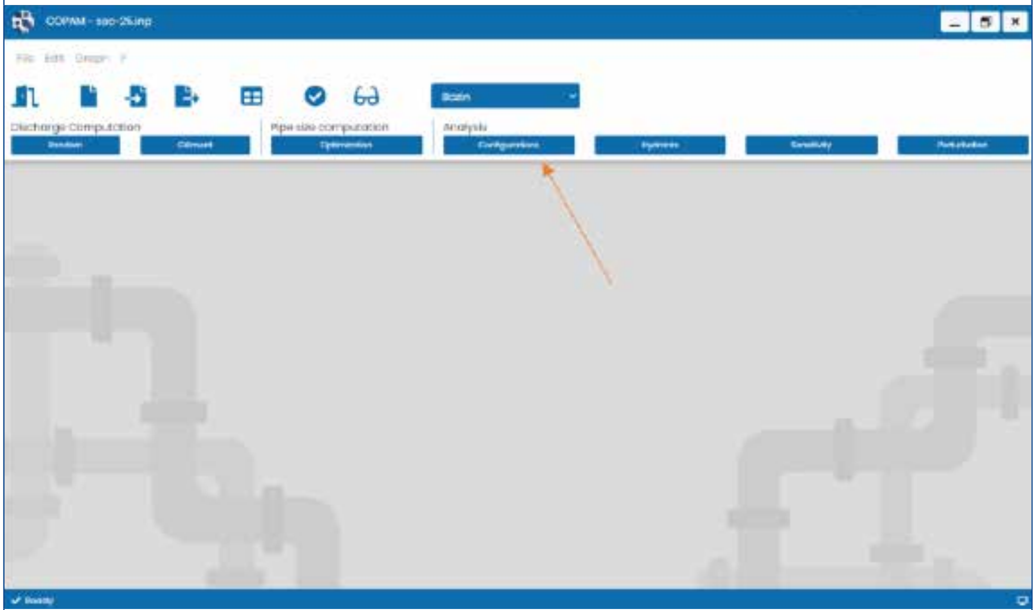
The analysis software provides the following types of analysis:

### A.2.5.1 Configuration (Index characteristic curve)

The indexed characteristic curves model provides information on the global performance of an on-demand irrigation system.

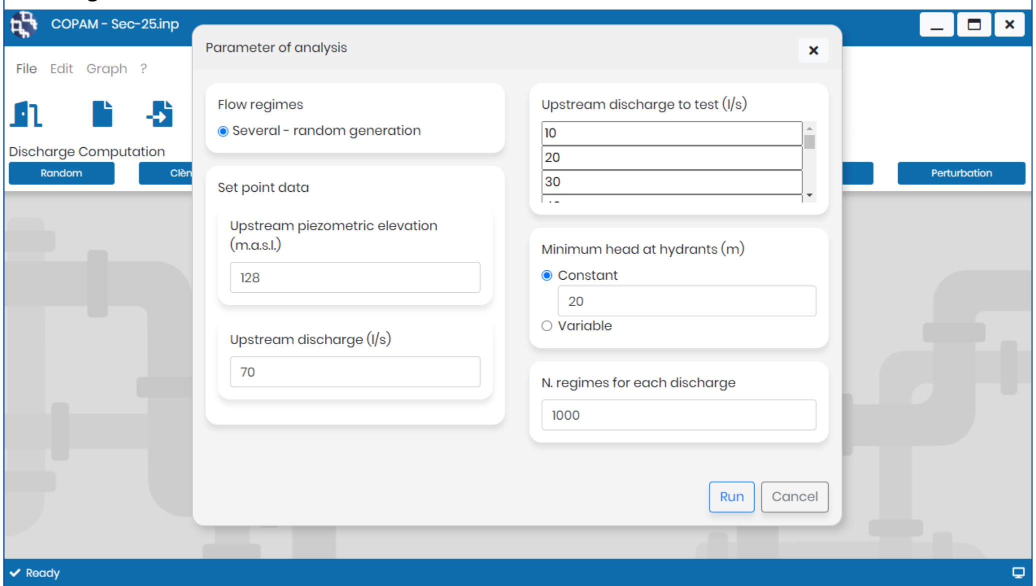
Select "*Configurations*" (Figure A.2.32), and the window "*Parameter of analysis*" will appear (Figure A.2.33).

FIGURE A.2.32
**Configurations model selection**



*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.33
**Configuration model window**



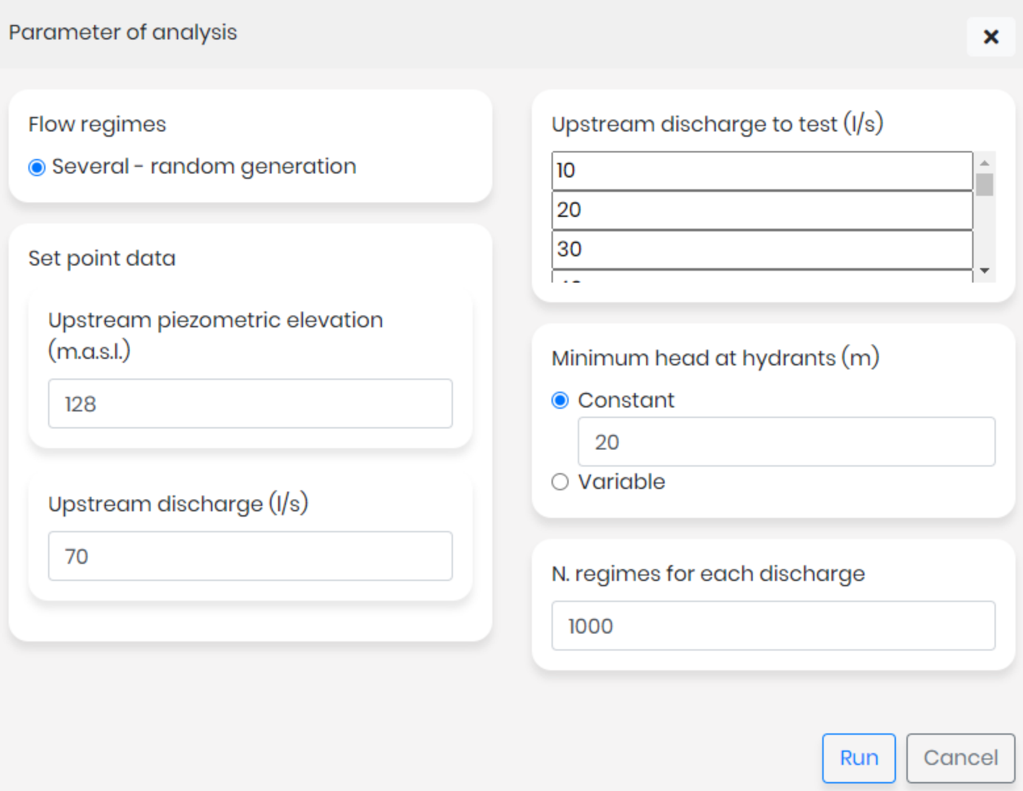

*Source: Screenshot of COPAM v4.0.*

Within the "*Parameter of analysis*" window (Figure A.2.34), only one type of flow regime is available under the "*Flow regimes*":

- *Several –Random Generations:* automatically generates the random flow regimes.

Enter the number of regimes to be generated for each discharge "*Number of regimes to generate for each discharge*" (Figure A.2.34).

FIGURE A.2.34
**Configuration parameter of analysis**




*Source: Screenshot of COPAM v4.0.*

Enter the piezometric elevation at the upstream end of the network and the design upstream discharge in the "*set point data*" frame.

Enter the list of discharges to be tested in "*Upstream discharge to test*."

The program allows network computations where the minimum pressure head (Hmin) required for on-farm irrigation is constant or variable.

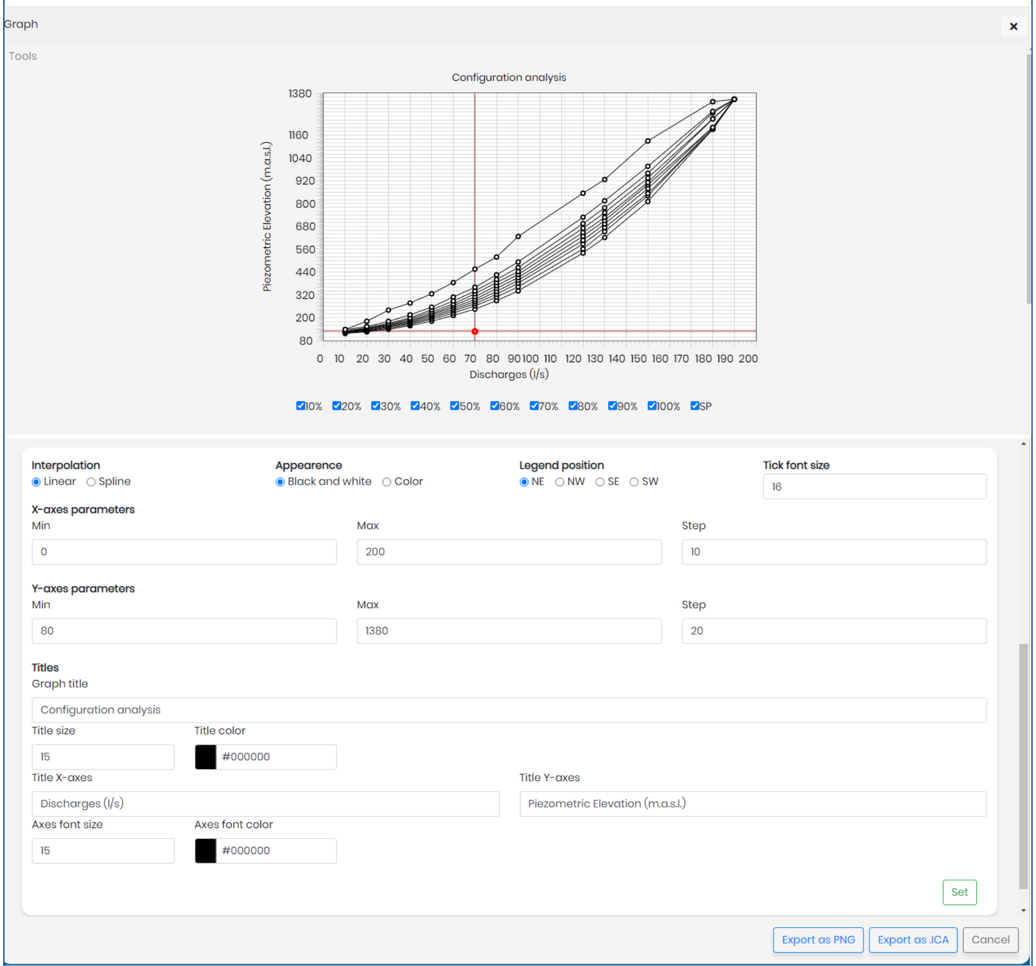
For the constant case, select "*Constant*" and enter the value Hmin. This constant value is automatically assigned to each hydrant regardless of the values in the "*Hmin Hydrants*" column in the input file.

For the variable case, select "*Variable*". The values of the minimum head at each hydrant are automatically read from the "*Hmin Hydrants*" column in the input file.

During the model operation, a loading screen will appear.

When the procedure is complete, the results automatically show in a pop-up window as a "*Graph*" (Figure A.2.35).

FIGURE A.2.35
**Indexed characteristic curve graph**

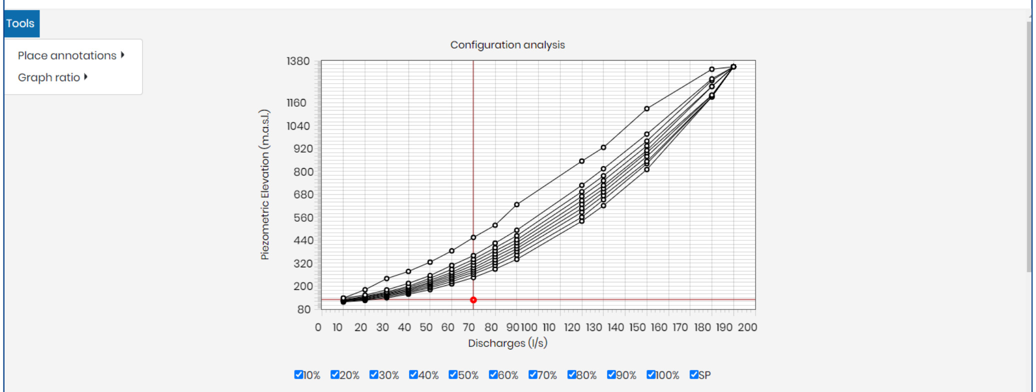



*Source: Screenshot of COPAM v4.0.*

The structure of this window is the same for every graph generated using the COPAM model. The components include the following

1. Tools button: Select this to see the drop-down menu with two options (Figure A.2.36):

FIGURE A.2.36
**Graph tools**

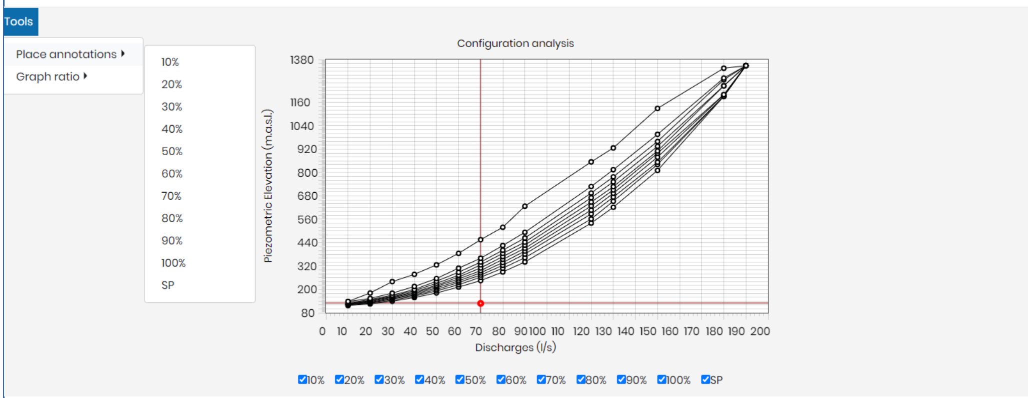



*Source: Screenshot of COPAM v4.0.*

a. Place annotation

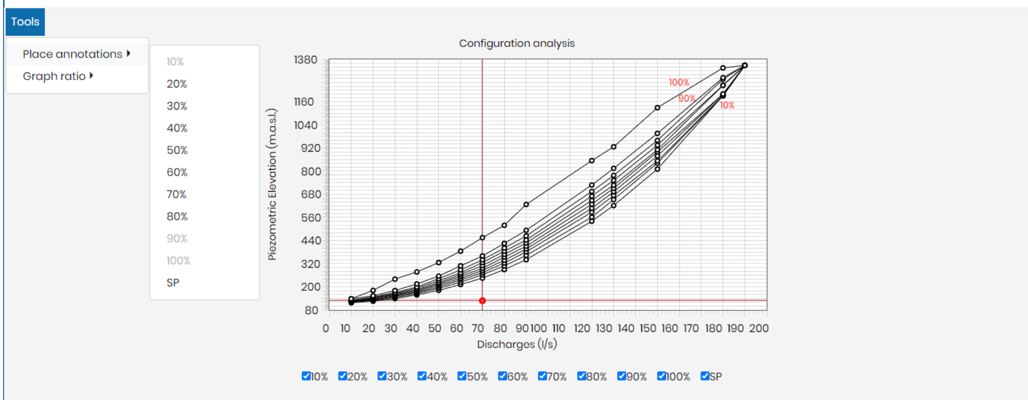
Use *Place annotation* to select a label, and place it on the graph image in the desired position (Figure A.2.37 – Figure A.2.38). The labels placed can also be moved and deleted.

FIGURE A.2.37
**Annotation selection**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.38
**Annotations placed**




*Source: Screenshot of COPAM v4.0.*

b. Graph ratio

Use the *Graph ratio* to change the size and shape of the graph area. This will affect the size of the image exported. A suggested option is to use a 4:3 ratio.

2. Use the checkboxes to define which curves or points are to be shown in the graph.
3. Use "*Export as PNG*" to export the graph image in PNG format and save it in a local folder .through the file explorer window.
4. Use "*Export as .ICA*" to export the text file containing the plotted results and save it in a local folder through the file explorer window.
5. Use interpolation selection to select which type of interpolation to use (Linear or Spline.
6. Use Appearance selection to decide whether to enable the automatic assignment of colours to the plotted elements or black and white. When the colors are assigned, the legend will automatically appear.
7. Use the Legend position to modify the position of the legend.

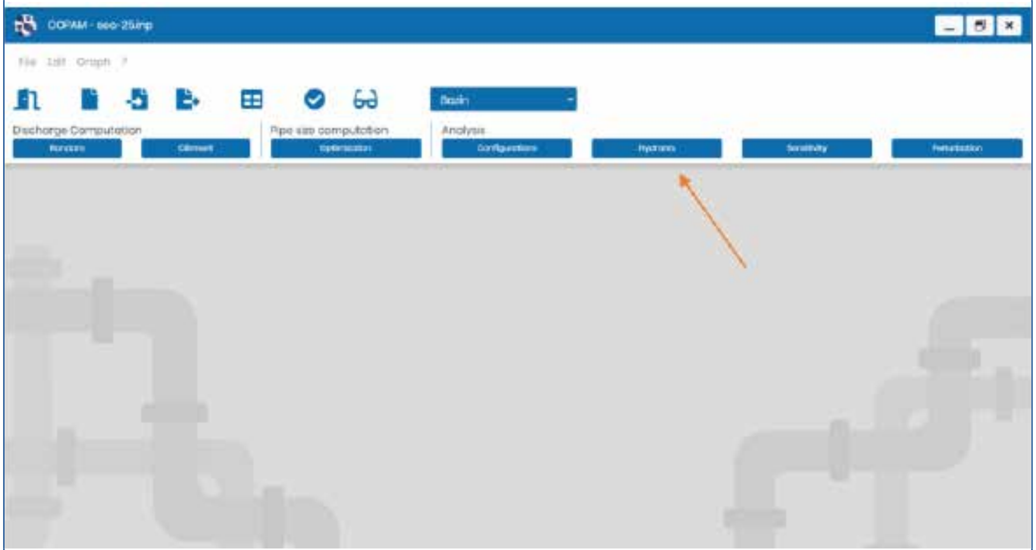
8. Use the Tick font size to modify the size of the axis numbers.
9. Use "*X-axes parameters*" and "*Y-axes parameters*" to customize the chart axes.
10. Use "*Titles*", to change name, size and color of the axes and graph name.
11. Use "*Set*" to confirm all modifications.

### A.2.5.2 Hydrants (AKLA)

This program calculates the percentage of unsatisfied hydrants and the relative pressure as part of the COPAM v4.0 package.

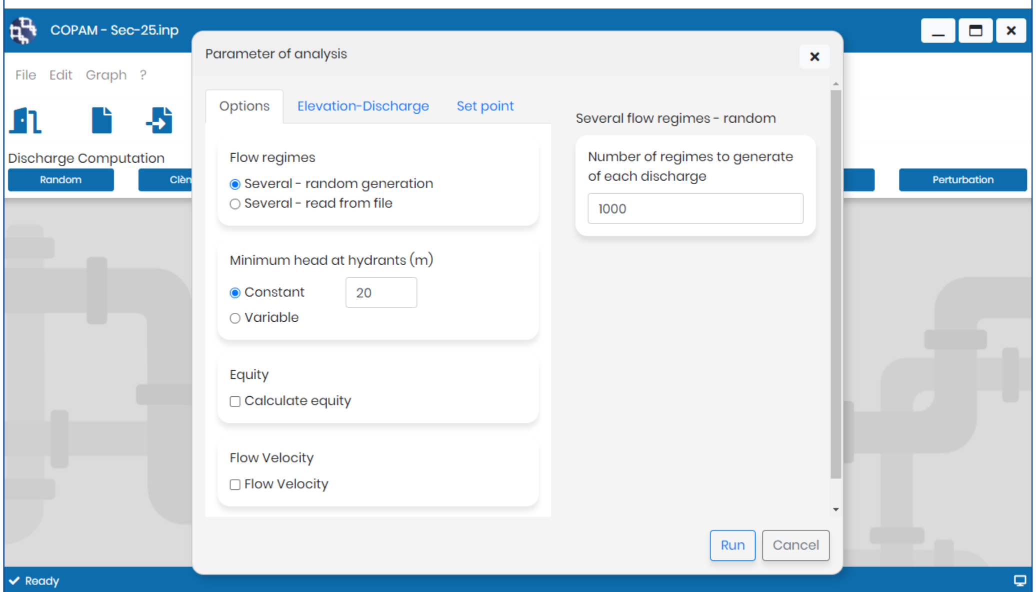
Select "*Hydrants*" (Figure A.2.39) and "*Parameter of analysis*" will appear (Figure A.2.40).

FIGURE A.2.39
**Hydrants model selection**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.40
**Parameter of analysis**



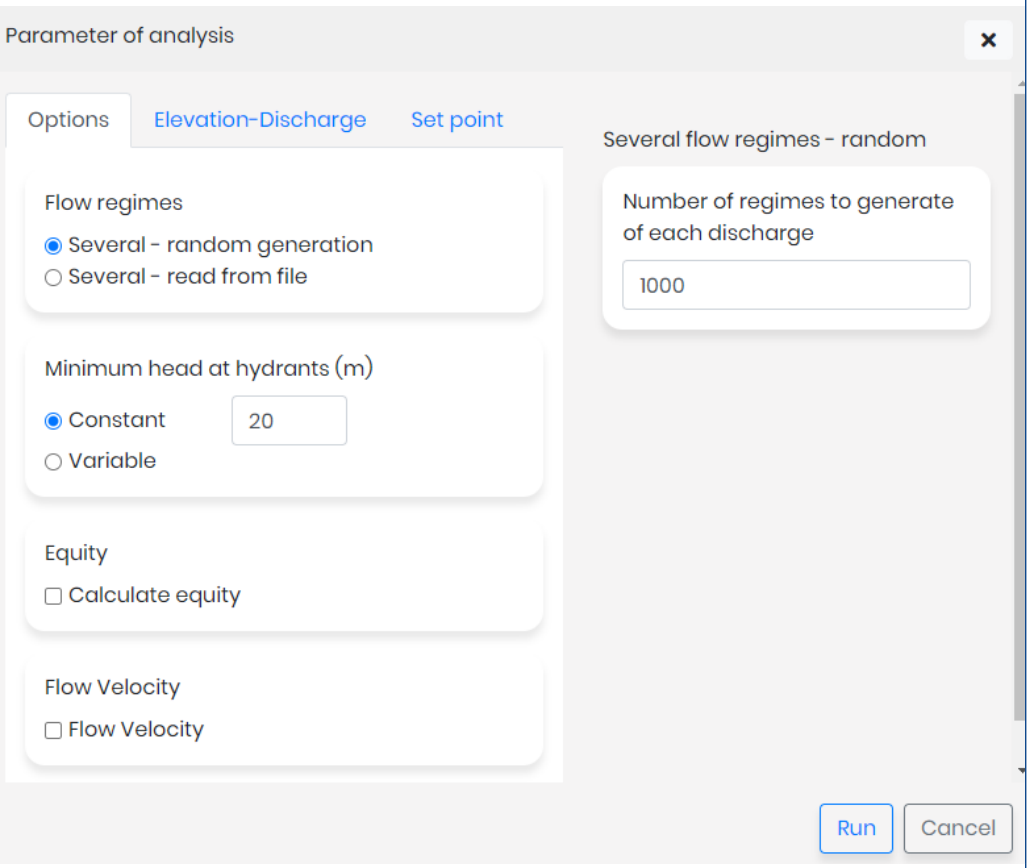

*Source: Screenshot of COPAM v4.0.*

Two flow regimes are available within "*Options*" (Figure A.2.41):

- *Several –Random Generations:* automatically generates the random flow regimes
- *Several – Read from file:* reads the flow regimes from an external file.

For the option "*Several – random generation*" define the number of regimes to generate for each discharge in "Number of regimes to generate for each discharge" (Figure A.2.41).

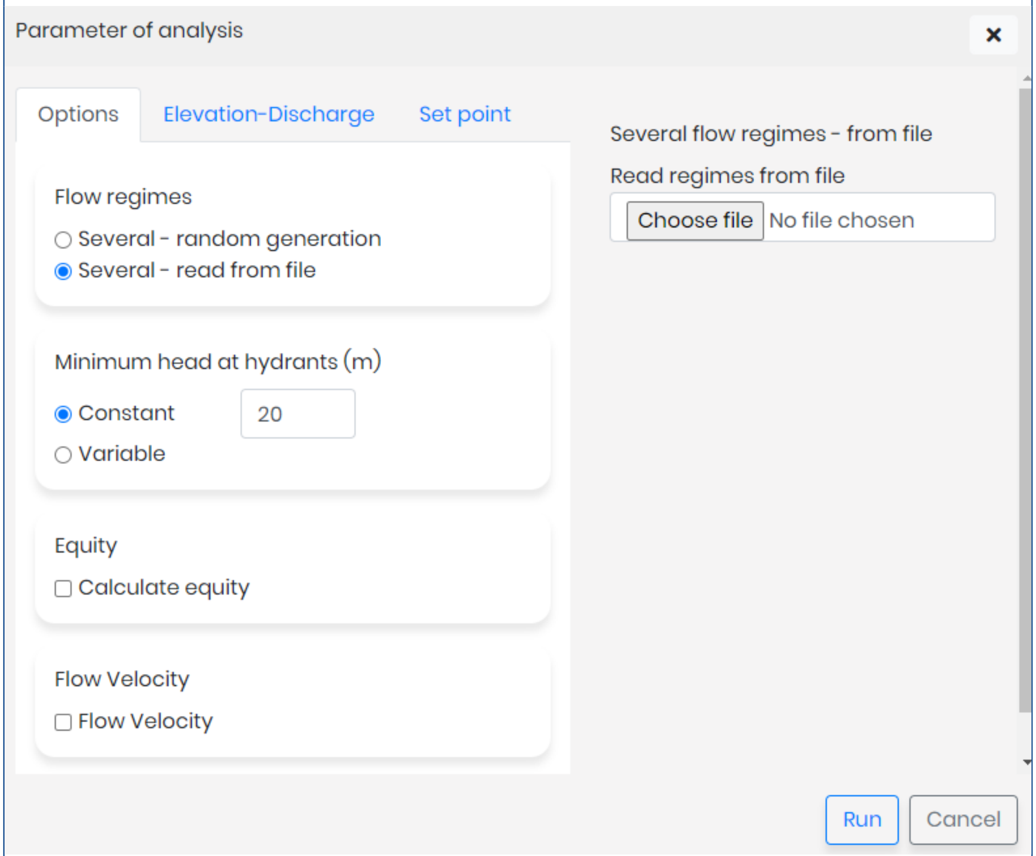
FIGURE A.2.41
**Option Tab control (Several - Random generation)**




*Source: Screenshot of COPAM v4.0.*

For the option "*Several - read from file*" the file containing flow regimes previously generated can be upload. Use "*Choose file*" into the frame "*Read regimes from file*" (Figure A.2.42).

FIGURE A.2.42
**Option Tab control (Several - Read from file)**

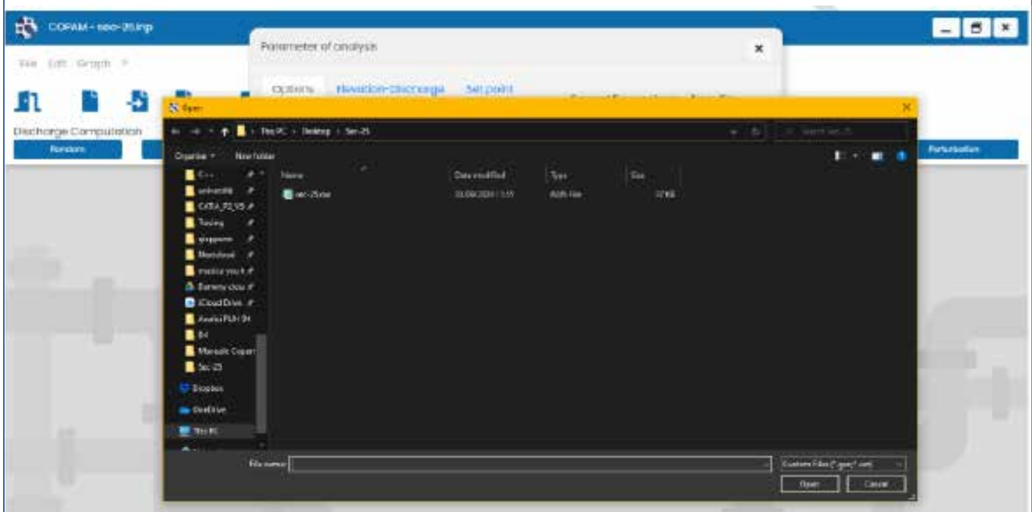



*Source: Screenshot of COPAM v4.0.*

Select "*choose file*," and the file explorer window (Figure A.2.43) will automatically appear. Navigate through the local directories and select the regimes file previously generated with the extension "*.ran*."

Use "*read from file*." Note that the number of flow regimes to be generated is not required because the flow regimes are already stored in the file.

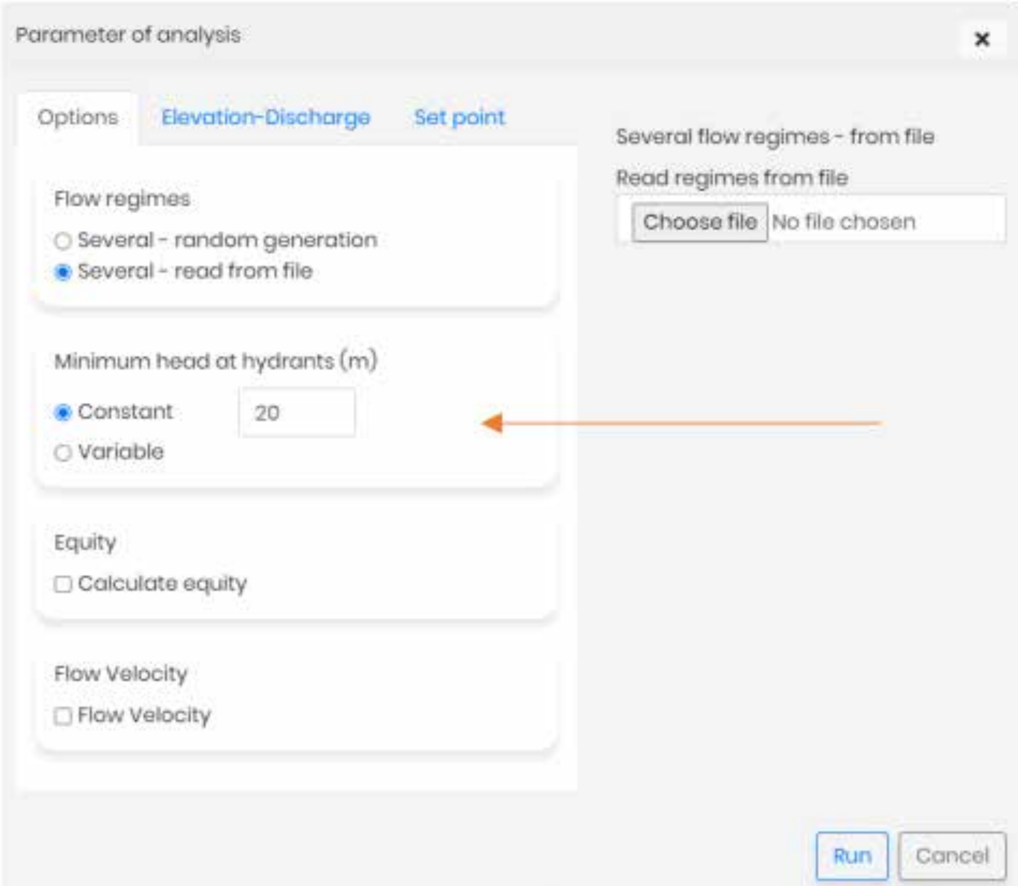
FIGURE A.2.43
**File explorer window**




*Source: Screenshot of COPAM v4.0.*

Use "*Options*" to display "*Minimum head at hydrants*" (Figure A.2.44).

FIGURE A.2.44
**Option Tab control (Minimum head at hydrants)**

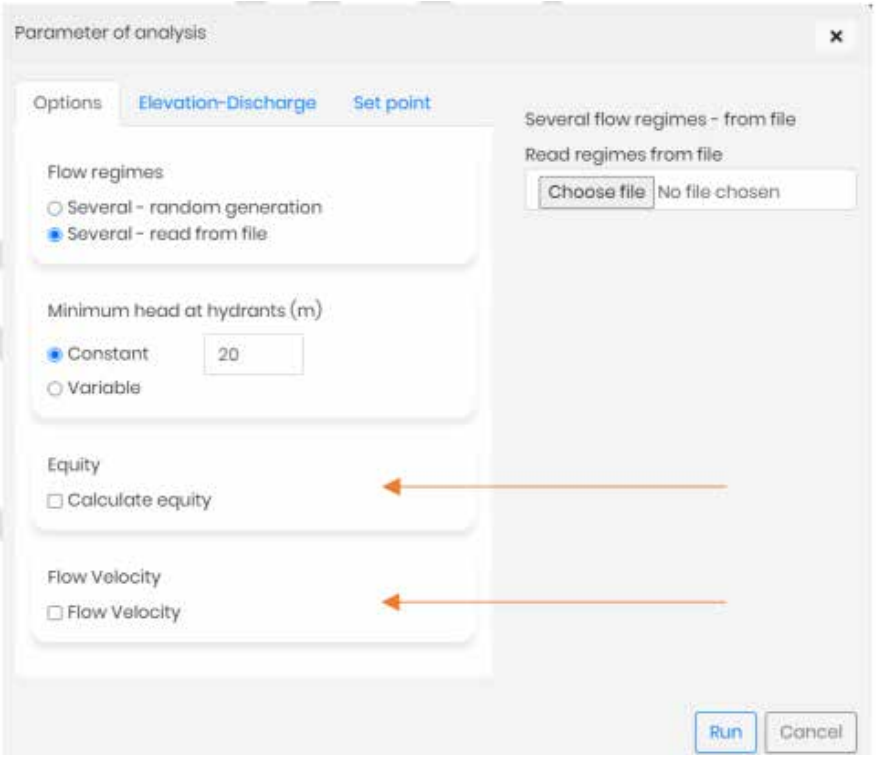



*Source: Screenshot of COPAM v4.0.*

The program allows network computations where the minimum pressure head (Hmin) required for on-farm irrigation is constant or variable.

Use "*Option*" to access two other frames, "*Equity*" and "*Flow Velocity*" (Figure A.2.45).

FIGURE A.2.45
**Option Tab to access "*Equity*" and "*Flow Velocity*"**



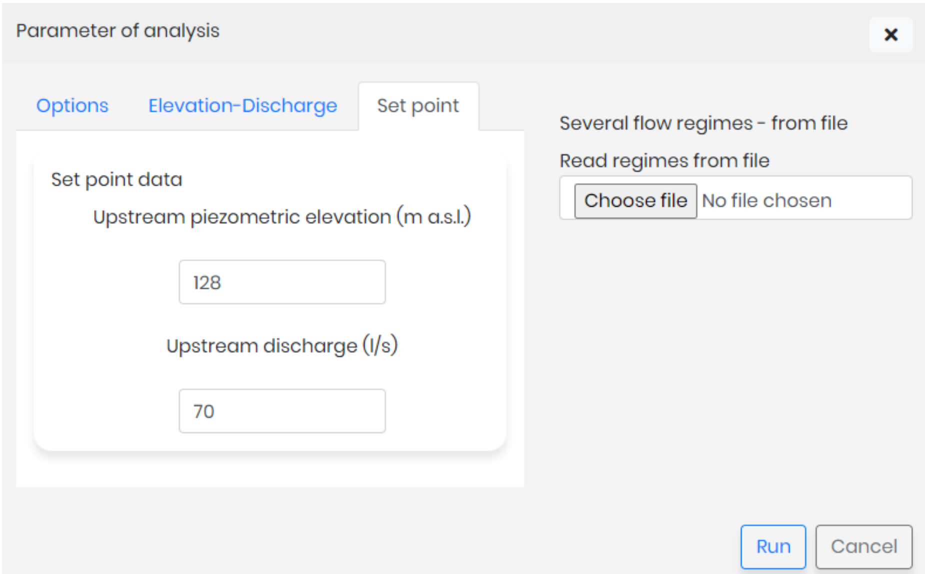

*Source: Screenshot of COPAM v4.0.*

Use "*Calculate equity*" to enable the equity calculation to function.

Use "*Flow Velocity*" to enable the flow velocity calculation in each network section.

Enter the "*Upstream piezometric elevation*" (m a.s.l.) available at the upstream end of the network and the "*Upstream discharge*" (l/s) using the "*set point*" (Figure A.2.46).

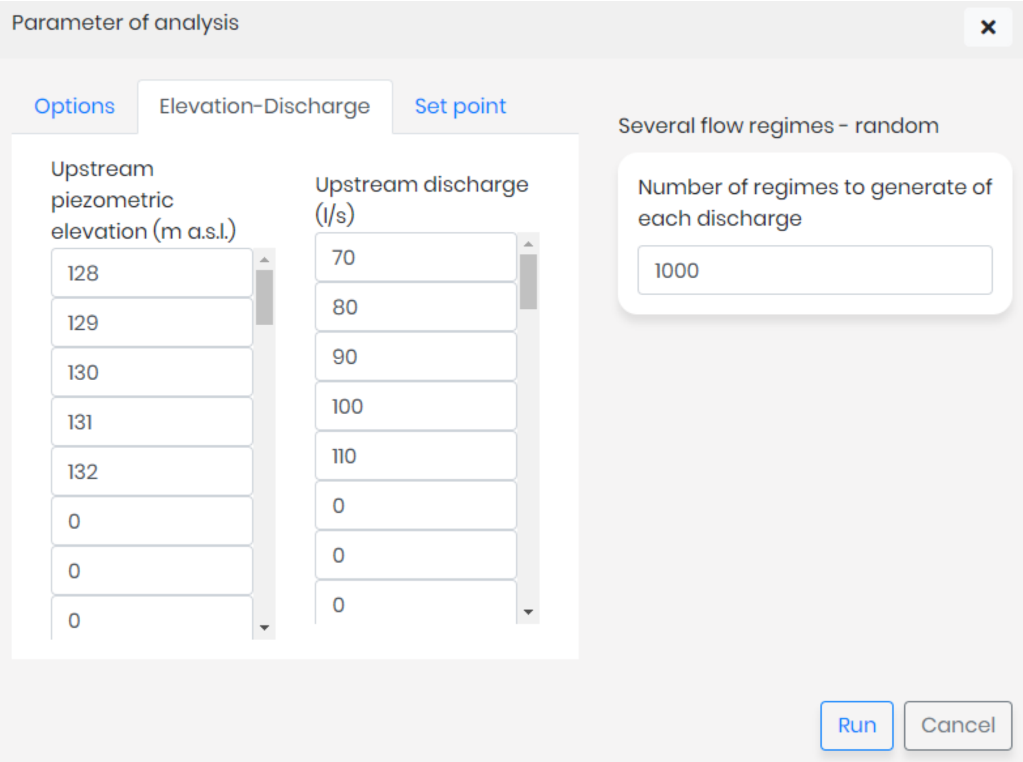
FIGURE A.2.46
**Set point Tab control**




*Source: Screenshot of COPAM v4.0.*

Enter the list of discharges flowing at the upstream end of the network and the list of upstream piezometric elevations to be tested in "*Elevation-Discharge*" (Figure A.2.47).

FIGURE A.2.47
**Elevation-Discharge Tab control**




*Source: Screenshot of COPAM v4.0.*

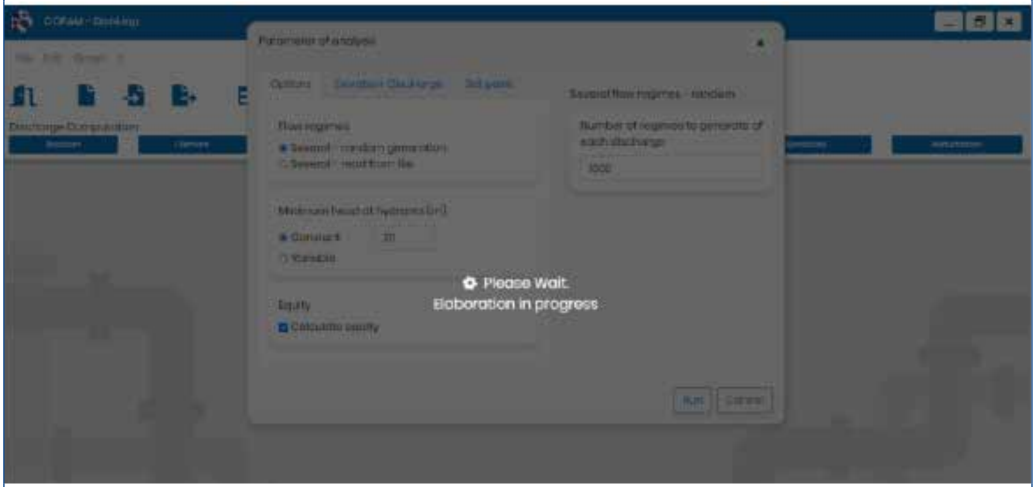
These values allow the percentage of unsatisfied hydrants to be determined when the upstream discharges and piezometric elevations vary.

It is important to include the setpoint data among these values. The relative pressure deficits are only computed for the setpoint values.

To determine the relative pressure deficits for the set point data, only the set point values need to be defined in "*Elevation-discharge*."

Select "*run*" to run the program when all the inputs are in place. A loading screen will appear (Figure A.2.48).

FIGURE A.2.48
**Elaboration in progress screen**



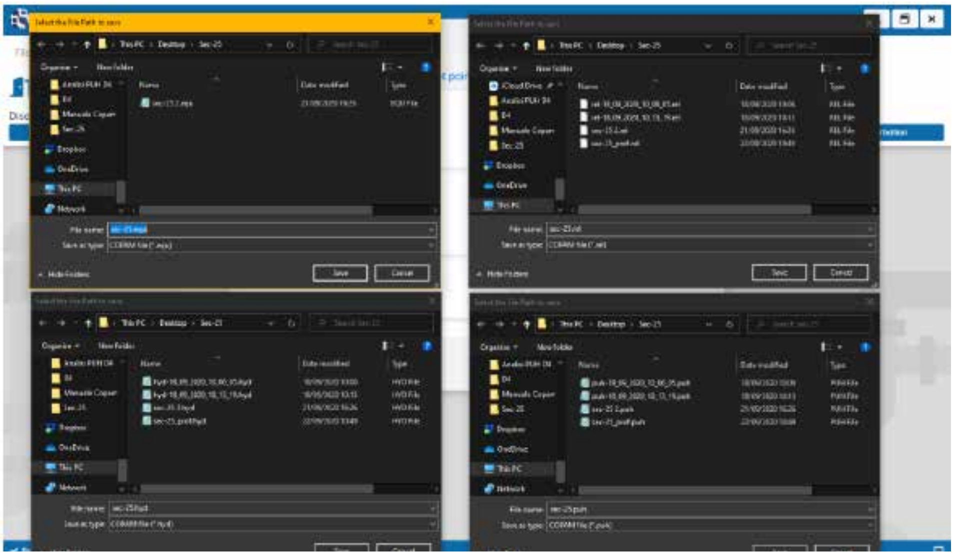

*Source: Screenshot of COPAM v4.0.*

On completing the program run, five files with the following extensions are automatically generated:

- "*Input_file_name.puh*" (Percentage of unsatisfied hydrants results);
- "*Input_file_name.hyd*" (Hydrants deficit results);
- "*Input_file_name.rel*" (Hydrants reliability results);
- "*Input_file_name.equ*" (Network equity results) (Generated if the "*Calculate equity*" checkbox is selected);
- "*Input_file_name.fvl*" (Network Flow Velocity results) (Generated if the "*Flow Velocity*" checkbox is selected).

Five (one for each file generated) file explorer windows are automatically shown (Figure A.2.49). Use the windows to select the local directory to save files.

FIGURE A.2.49
**File explorer windows**



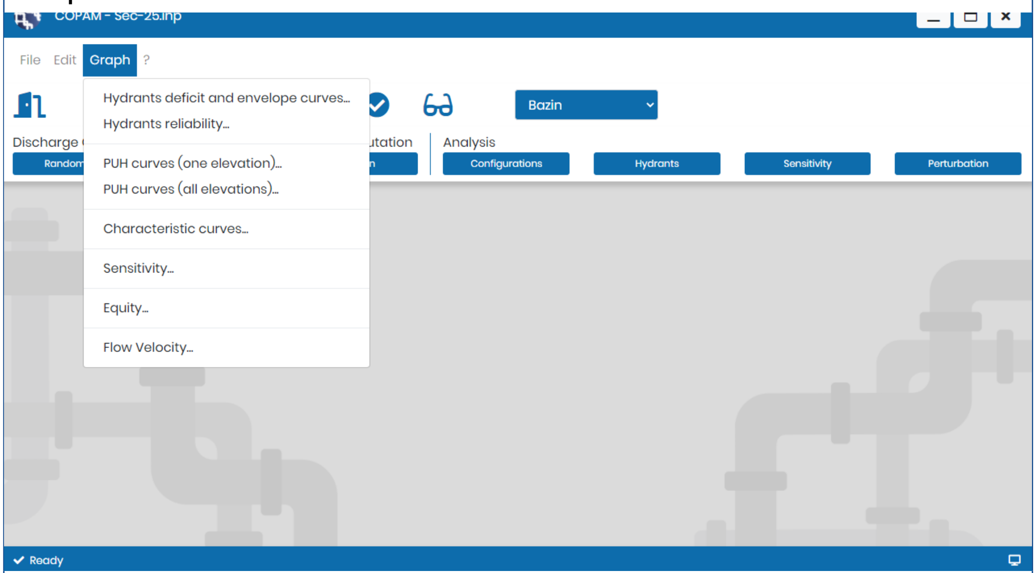
*Source: Screenshot of COPAM v4.0.*

The graphical interface of COPAM v4.0 allows easy printing of the information obtained by the Hydrants model.

Select the “*Graph*” menu bar (Figure A.2.50) to select sub-menu items regarding the results:

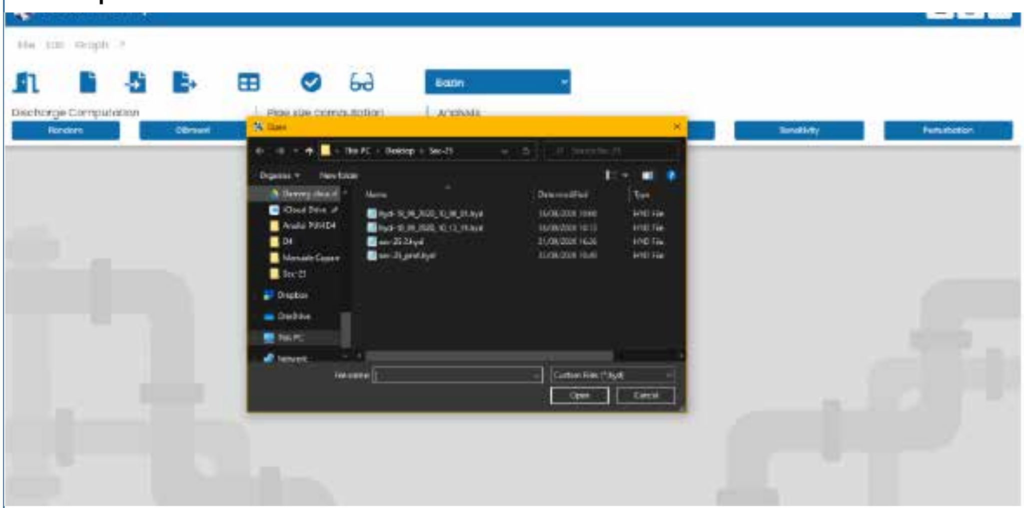
- Hydrants deficit and envelope curves;
- Hydrants reliability;
- PUH curves (one elevation);
- PUH curves (all elevations); and
- Equity.
- Flow Velocity.

FIGURE A.2.50
**Graph menu**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.51
**File explorer window**

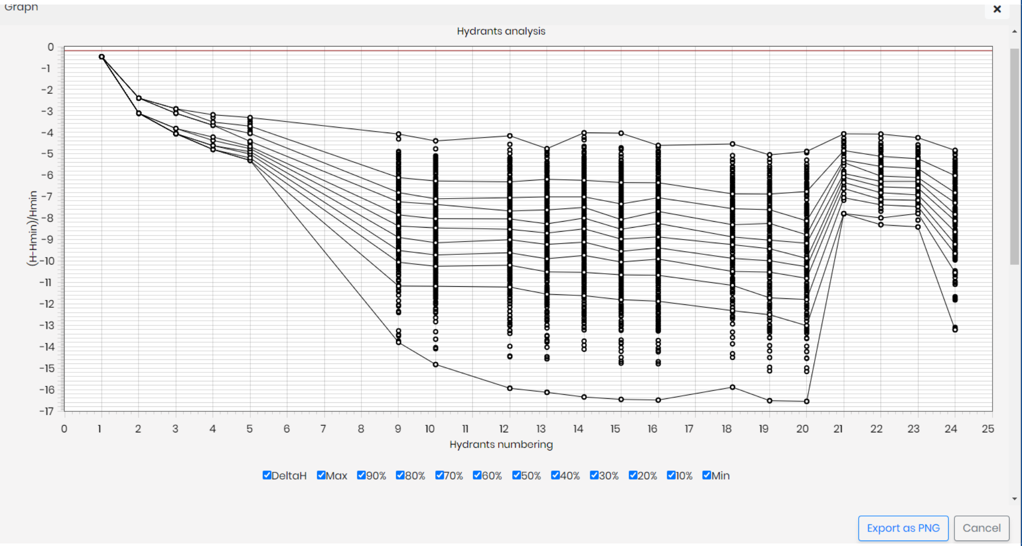


*Source: Screenshot of COPAM v4.0.*

#### *A.2.5.2.1 Hydrants deficit and envelope curves*

Select "*Hydrant deficit and envelope curve*" from the "*Graph*" menu bar and the *.hyd* file to display results (Figure A.2.52).

FIGURE A.2.52
**Hydrant deficit and envelope curve graph**

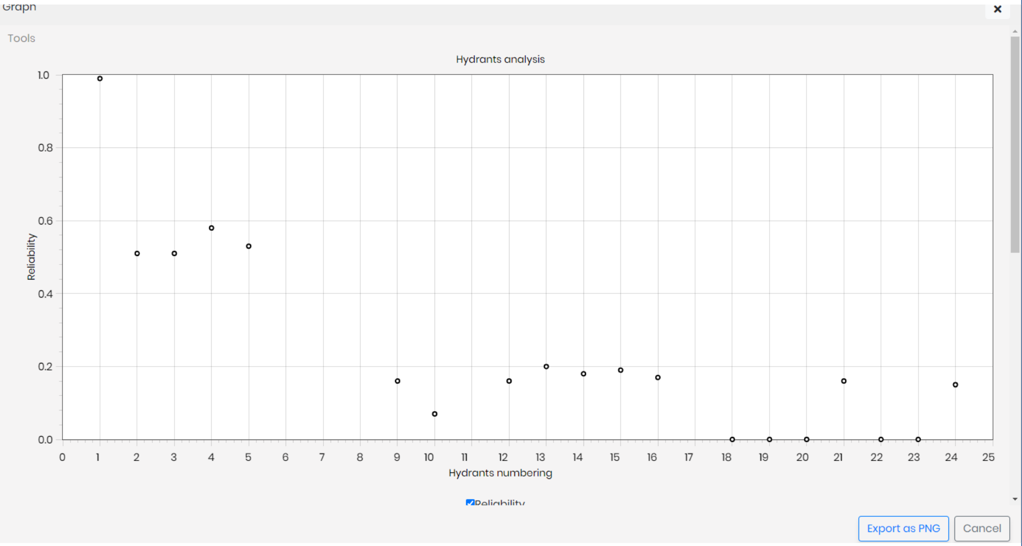



*Source: Authors'own elaboration through COPAM v4.0*

#### *A.2.5.2.2 Hydrants reliability*

Select "*Hydrant reliability*" from the "*Graph*" menu bar and the *.rel* file to display the results (Figure A.2.53).

FIGURE A.2.53
**Hydrants reliability**

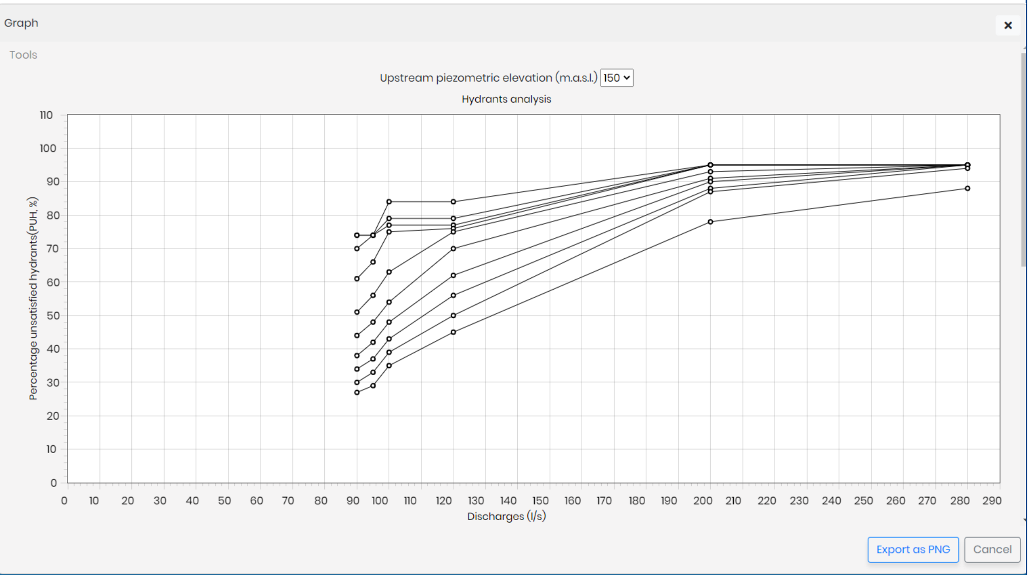



*Source: Authors'own elaboration through COPAM v4.0*

### *A.2.5.2.3 PUH Curves (One Elevation)*

Select "*PUH Curves (One Elevation)*" from the "*Graph*" menu bar and the *.puh* file to display the results (Figure A.2.54).

FIGURE A.2.54
**PUH Curves (One Elevation)**

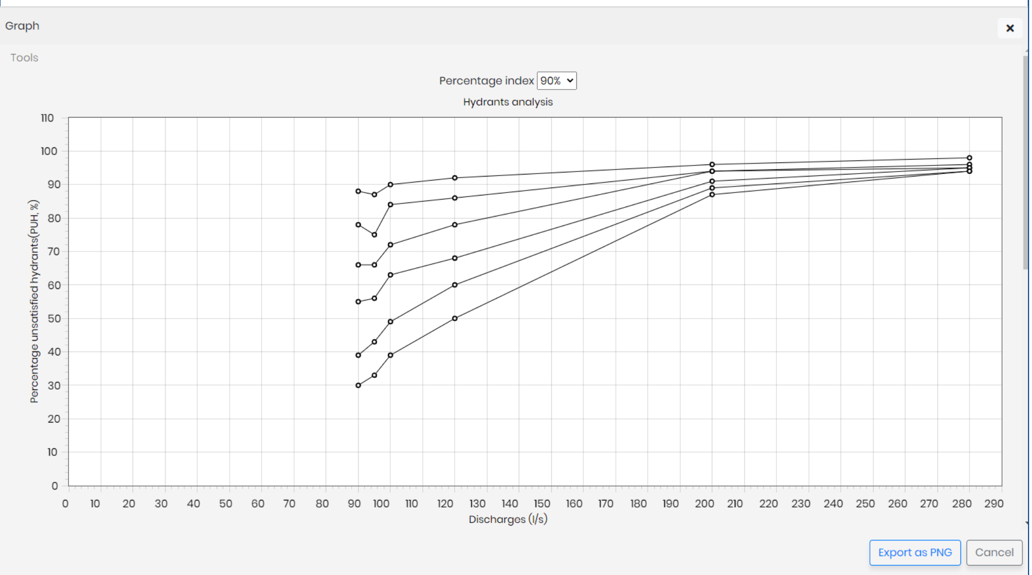



*Source: Authors' own elaboration through COPAM v4.0*

### *A.2.5.2.4 PUH Curves (All elevations)*

Select "*PUH Curves (All elevations)*" from the "*Graph*" menu bar and the *.puh* file to display the results (Figure A.2.55).

FIGURE A.2.55
**PUH Curves (All elevations)**




*Source: Authors' own elaboration through COPAM v4.0*

## Equity

Select "*Equity*" from the "*Graph*" menu bar and then the *.equ* file to display the results (Figure A.2.56).

FIGURE A.2.56
**Equity**

Result of equity

| | | |
|---|---|---|
| 90% | -1.15 | Not Adequate |
| 80% | -0.45 | Not Adequate |
| 70% | -0.11 | Not Adequate |
| 60% | 0.18 | Not Adequate |
| 50% | 0.43 | Not Adequate |
| 40% | 0.61 | Fair |
| 30% | 0.70 | Fair |
| 20% | 0.77 | Fair |
| 10% | 0.93 | Good |

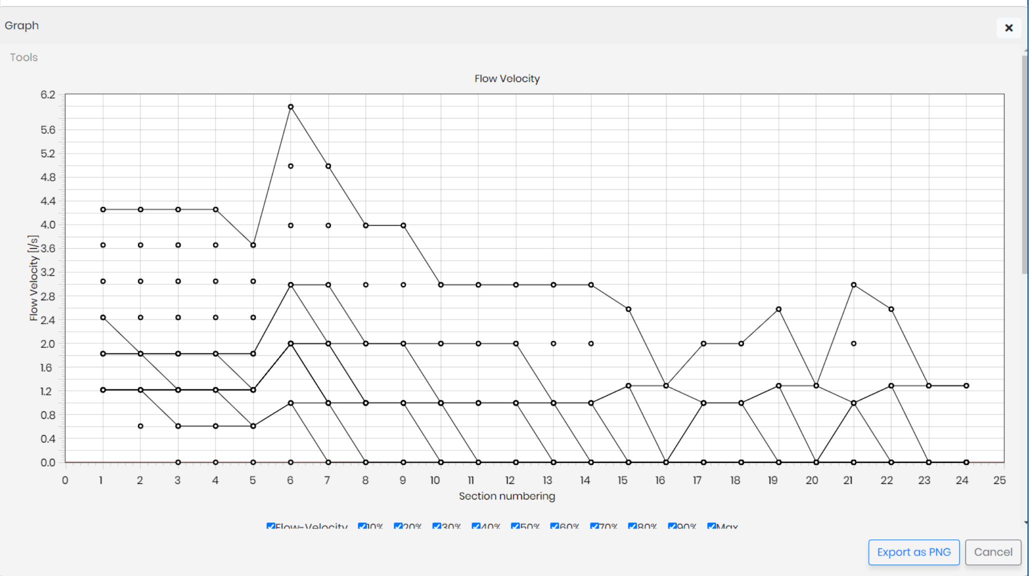
Export Cancel

*Source: Authors' own elaboration through COPAM v4.0*

### *A.2.5.2.5 Flow Velocity*

Select "*Flow Velocity*" from the "*Graph*" menu bar and the *.fvl* file to display the results (Figure A.2.57).

FIGURE A.2.57
**Flow Velocity**



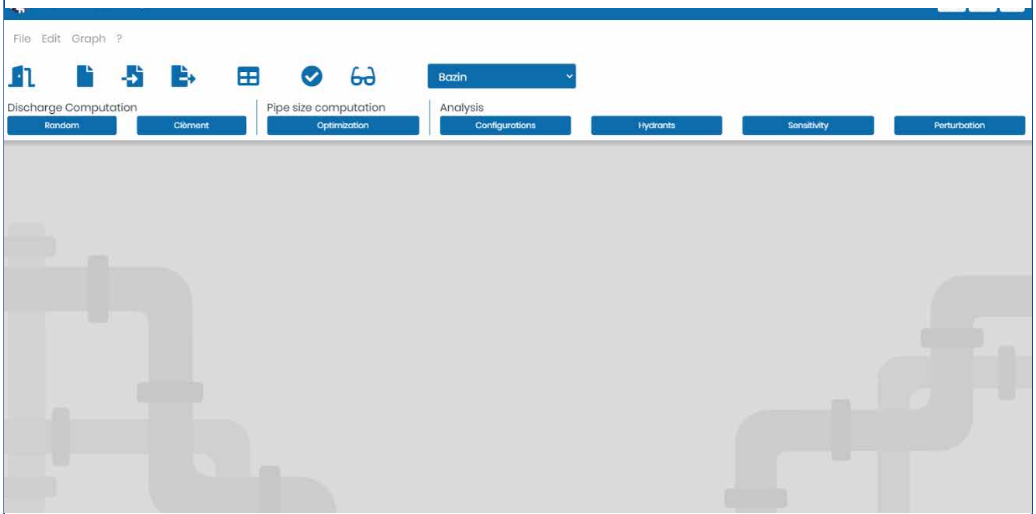

*Source: Authors' own elaboration through COPAM v4.0*

### A.2.5.3 Sensitivity

A program to compute hydrants' sensitivity is integrated into the COPAM v4.0 package.

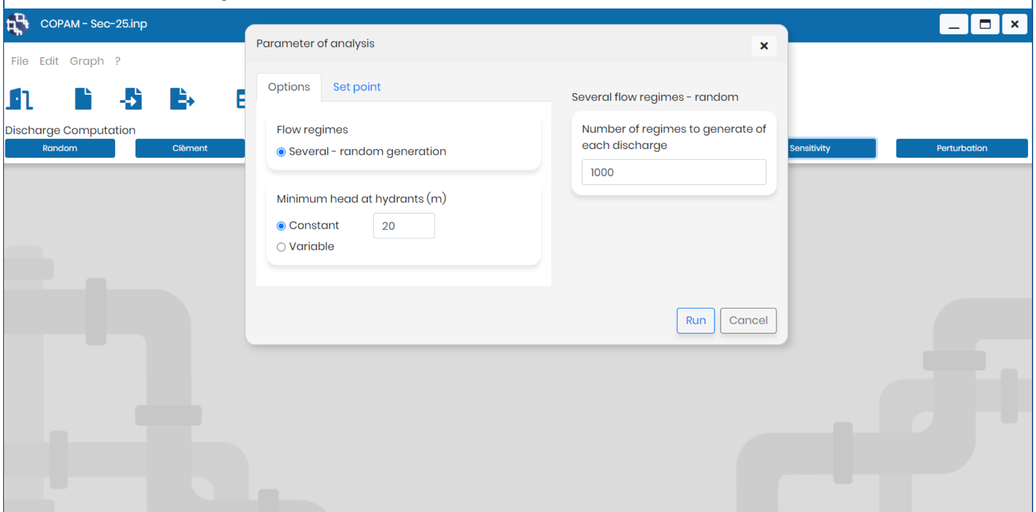
Select "*Sensitivity*" (Figure A.2.58) and the window "*Parameter of analysis*" will appear (Figure A.2.59).

FIGURE A.2.58
**Sensitivity model**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.59
**Parameter of analysis**



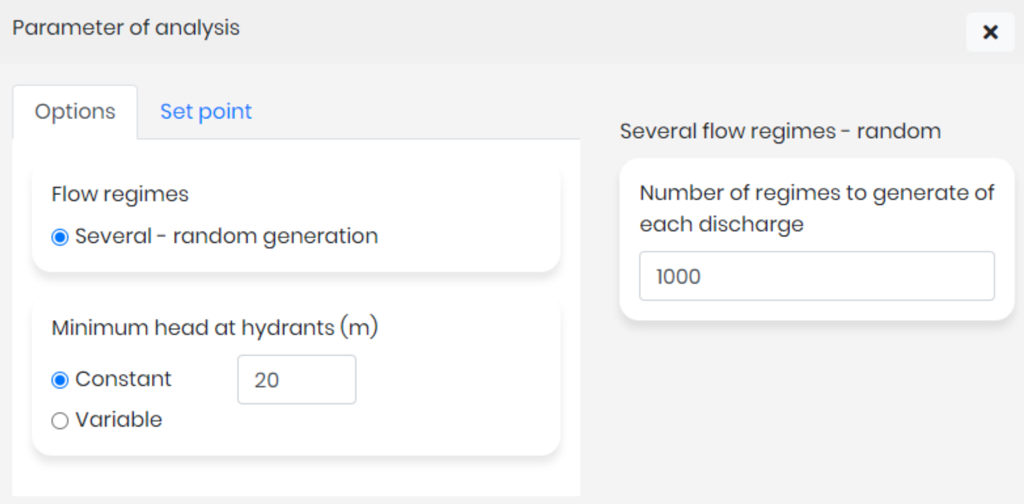

*Source: Screenshot of COPAM v4.0.*

Select "*Options*" (Figure A.2.60), only one type of flow regime is available:

- *Several –Random Generations:* automatically generates the random flow regimes.

Use "*Number of regimes to generate for each discharge*" to define the number of regimes to generate for each discharge (Figure A.2.60).

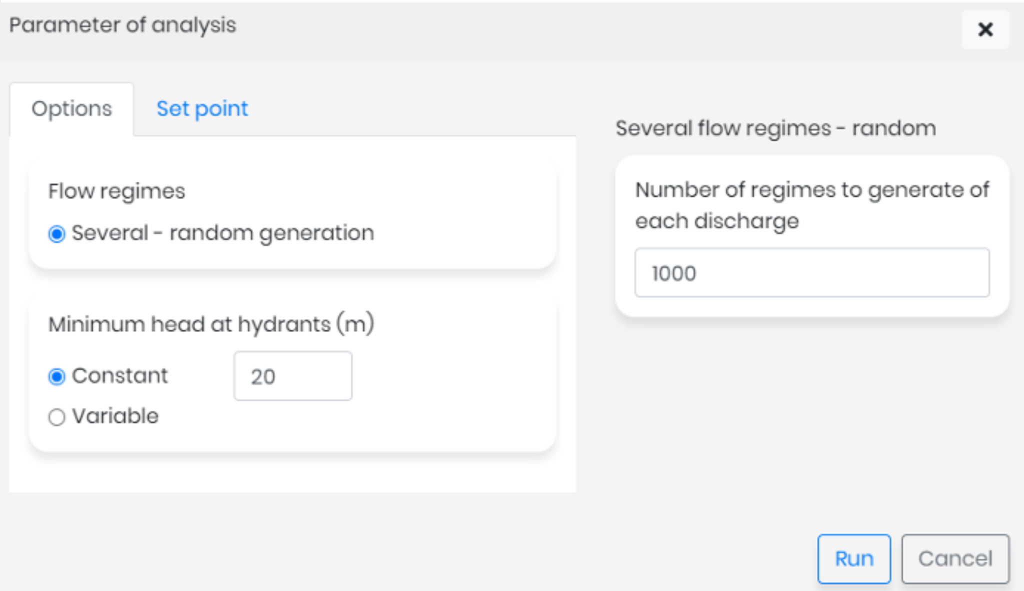
FIGURE A.2.60
**Option Tab control (Several - Random generation)**




*Source: Screenshot of COPAM v4.0.*

Use "*Minimum head at hydrants*" (Figure A.2.61) to define the constant or variable minimum pressure head (Hmin) required for on-farm irrigation.

FIGURE A.2.61
**Option Tab control (minimum head at hydrants)**

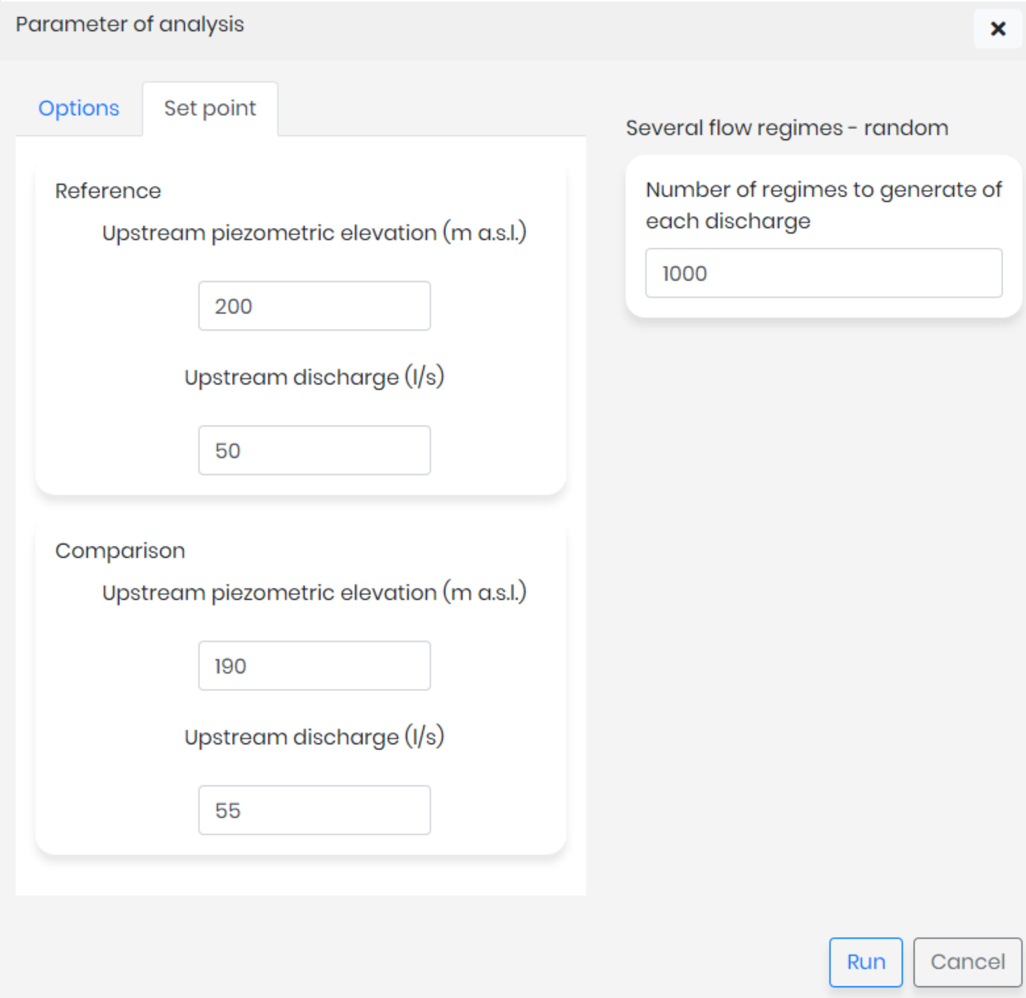



*Source: Screenshot of COPAM v4.0.*

Use "*Set point*" (Figure A.2.62) to set up the reference Set point and the comparison Set point.

The comparison upstream piezometric elevation must be lower than the reference upstream piezometric elevation, whereas the comparison upstream discharge must be greater than the reference upstream discharge.

FIGURE A.2.62
**Option Set point control**

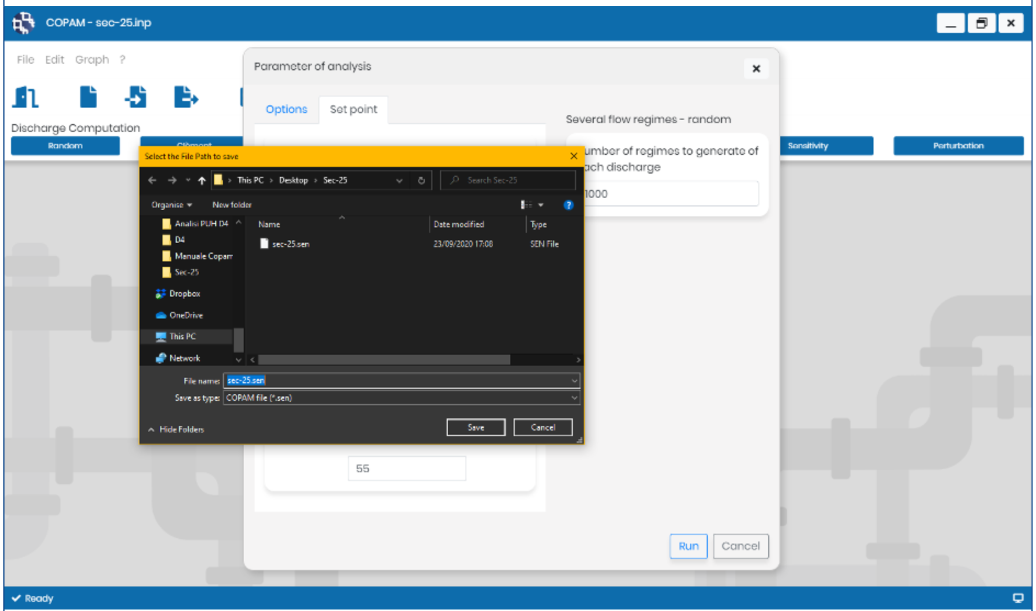



*Source: Screenshot of COPAM v4.0.*

Select "*run*" to run the program, and a loading screen will appear. The program will generate one file with a "*.sen*" extension.

File explorer automatically open (Figure A.2.63) so the file can be saved. The default file name is the same as the name of the input file and the default directory is the same where the input file is stored.

FIGURE A.2.63
**File explorer window**

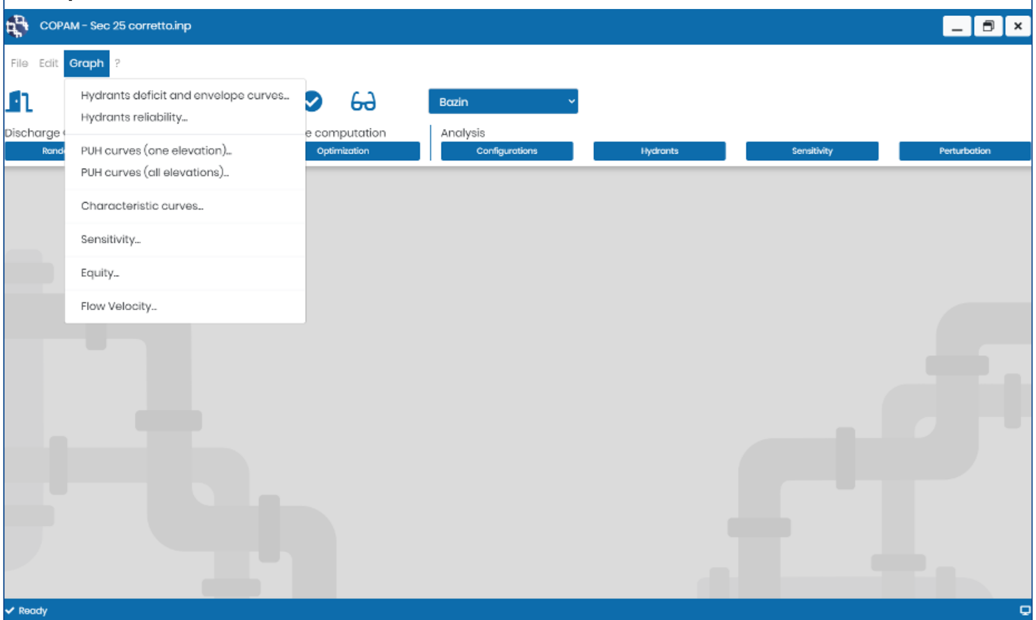



*Source: Screenshot of COPAM v4.0.*

The graphical interface of COPAM v4.0 allows easy printing of the results.

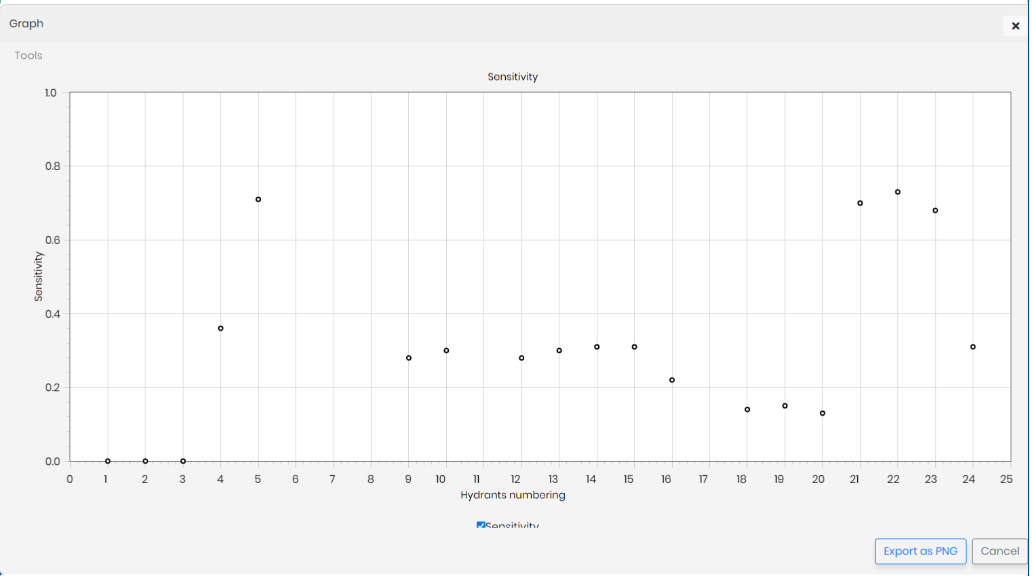
Use the "*Graph*" menu bar (Figure A.2.64) and select the *Sensitivity* sub-menu item, then select the *.sen* file to open the graph window (Figure A.2.65).

FIGURE A.2.64
**Graph menu bar**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.65
**Sensitivity graph**

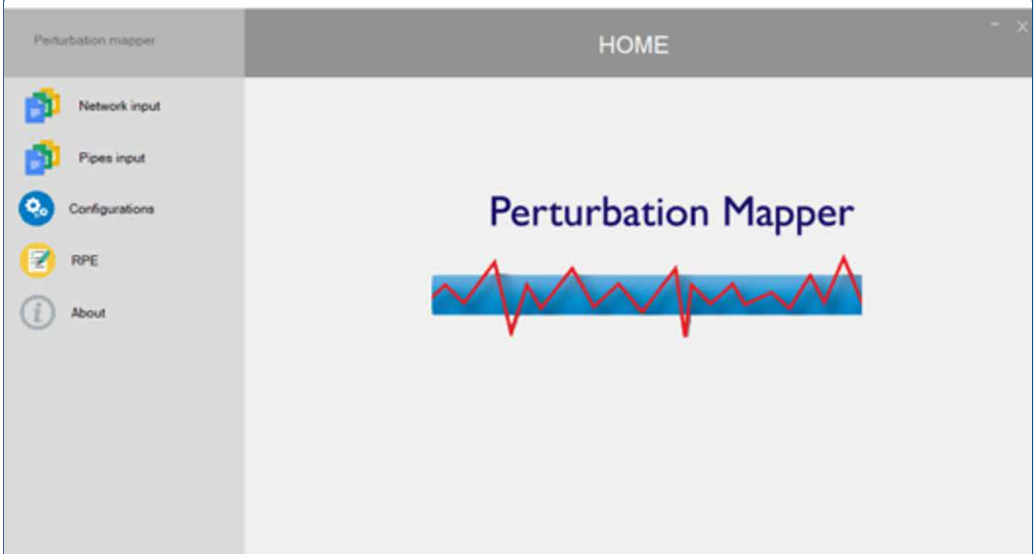



*Source: Authors' own elaboration through COPAM v4.0*

### A.2.5.4. Perturbation

The model for analyzing the perturbation in pressurized irrigation systems is an integral part of COPAM v4.0. Select "*Perturbation*" on the home page to launch the perturbation model (Figure A.2.66).

FIGURE A.2.66
**Home screen of the perturbation model**




*Source: Screenshot of COPAM v4.0.*

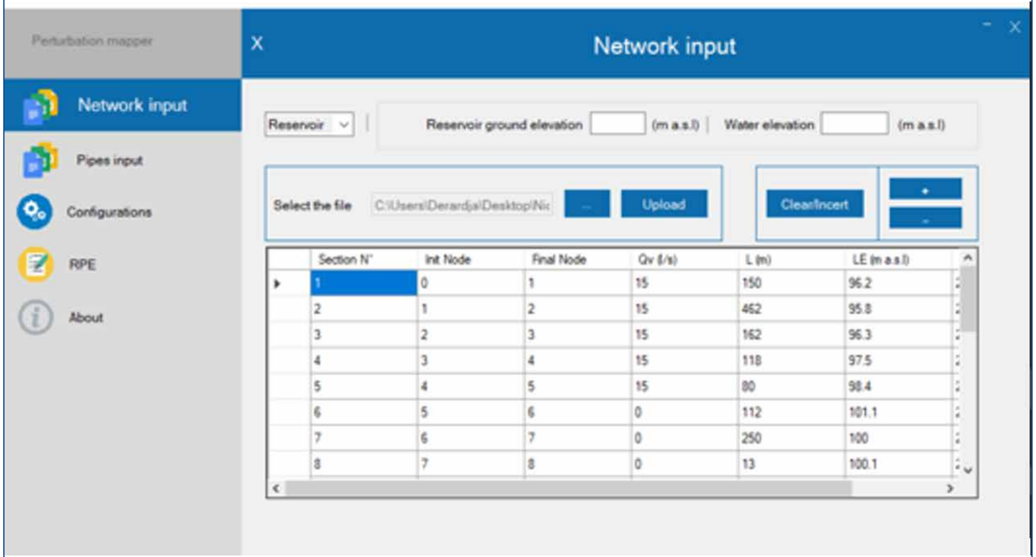
The three input sections are on the left side of the screen. They can be directly uploaded as an input file from COPAM (Figure A.2.67 select the file, and upload) or edited if a new network is to be analysed for unsteady flow conditions.

## The network input

The input data for the network includes:

- the initial and final nodes of each section
- the hydrants discharge (l/s) (at the downstream node)
- sections length (m)
- land elevation of the downstream node (m a.s.l.)
- nominal diameter of the pipe (mm)
- terminal nodes of the branches must have a hydrant
- a maximum of two sections may be derived from each node
- the network is assumed to be of branched type
- each node is positioned by a number. Nodes numbering is important for the correct execution of the model.

FIGURE A.2.67
**Example of the network table with a reservoir at the upstream-end**



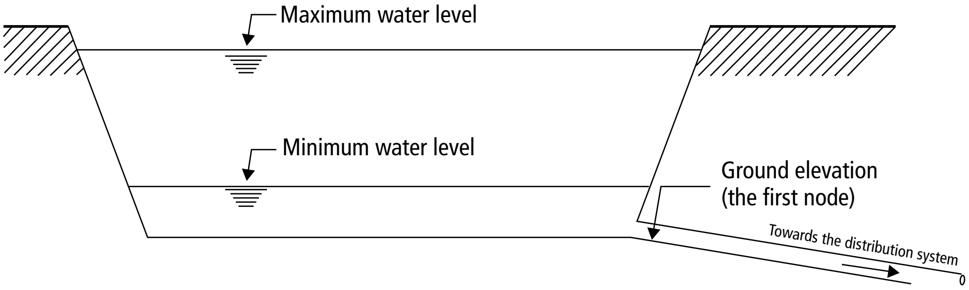

*Source: Screenshot of COPAM v4.0.*

Additional input data are required about the water source. Two options are available:

a. An upstream reservoir (Figure A.2.67) with

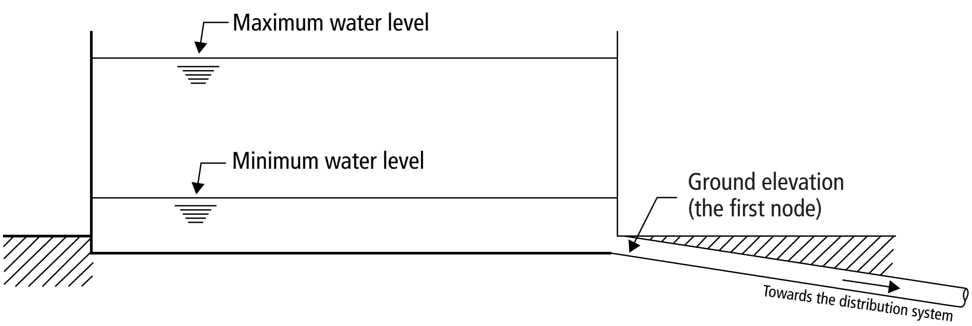
- the water elevation (m a.s.l) corresponds to the elevation of the minimum water level (see Figure A.2.68 and A.2.69);
- the ground elevation (m a.s.l) corresponds to the elevation of the first node (see Figure A.2.68 and A.2.69).

FIGURE A.2.68
**The case of a below-ground reservoir**




*Source: Marchi, E. & Rubatta, A. 1981. Meccanica dei fluidi; Principi ed applicazioni. Torino, Ed. UTET.*

FIGURE A.2.69
**The case of an above-ground reservoir**

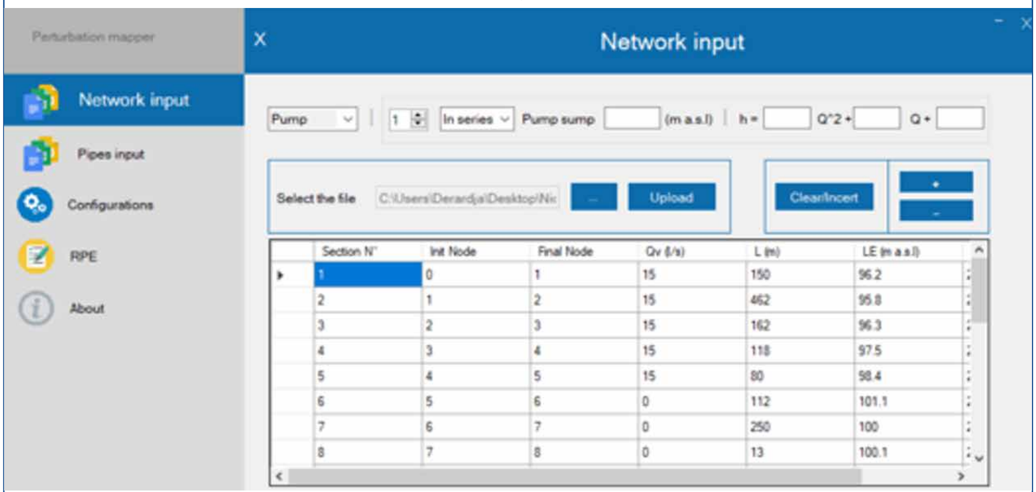



*Source: Marchi, E. & Rubatta, A. 1981. Meccanica dei fluidi; Principi ed applicazioni. Torino, Ed. UTET.*

b. An upstream pumping station (Figure A.2.70), with

- the number of pumps
- the operation mode (in parallel or in series)
- the pump sump (elevation of the suction pipe, m a.s.l)
- different factors for the characteristic curve equations.

FIGURE A.2.70
**Example of the network table with a pumping station at the upstream-end**




*Source: Screenshot of COPAM v4.0.*

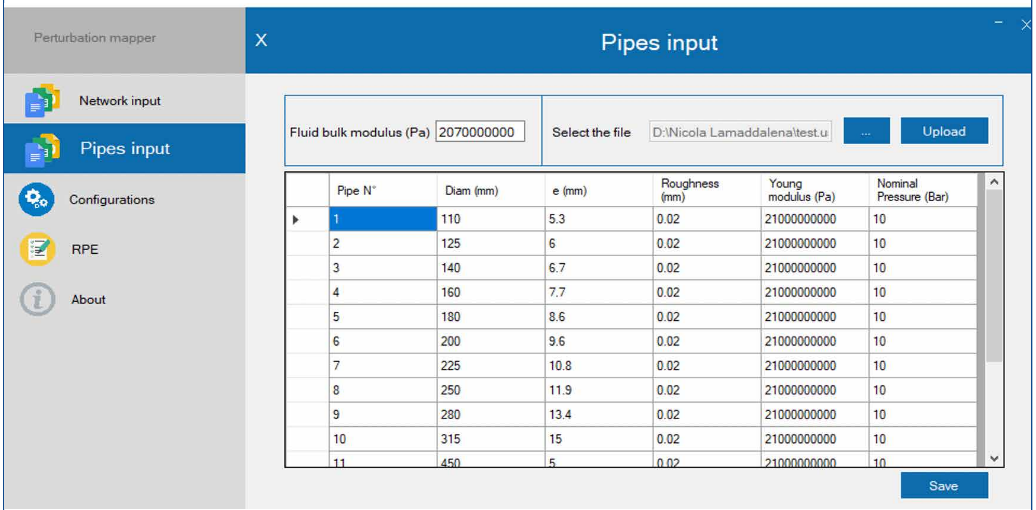
## The pipe characteristics

Additional data are required for steady-state flow calculations and unsteady flow conditions:

- fluid bulk modulus (Pa)
- young modulus of the pipe material (Pa)
- equivalent homogeneous pipe roughness (mm)
- nominal pressure of the pipes (bar).

The equivalent homogeneous roughness of the pipe (instead of the Bazin coefficient) is needed for the unsteady flow calculation. Coefficients are reported in Annex 4. These data appear on the screen in yellow (Figure A.2.71) until it is introduced correctly.

FIGURE A.2.71
**Example of the pipe characteristics table**




| Pipe N° | Diam (mm) | e (mm) | Roughness (mm) | Young modulus (Pa) | Nominal Pressure (Bar) |
|---|---|---|---|---|---|
| 1 | 110 | 5.3 | 0.02 | 21000000000 | 10 |
| 2 | 125 | 6 | 0.02 | 21000000000 | 10 |
| 3 | 140 | 6.7 | 0.02 | 21000000000 | 10 |
| 4 | 160 | 7.7 | 0.02 | 21000000000 | 10 |
| 5 | 180 | 8.6 | 0.02 | 21000000000 | 10 |
| 6 | 200 | 9.6 | 0.02 | 21000000000 | 10 |
| 7 | 225 | 10.8 | 0.02 | 21000000000 | 10 |
| 8 | 250 | 11.9 | 0.02 | 21000000000 | 10 |
| 9 | 280 | 13.4 | 0.02 | 21000000000 | 10 |
| 10 | 315 | 15 | 0.02 | 21000000000 | 10 |
| 11 | 450 | 5 | 0.02 | 21000000000 | 10 |

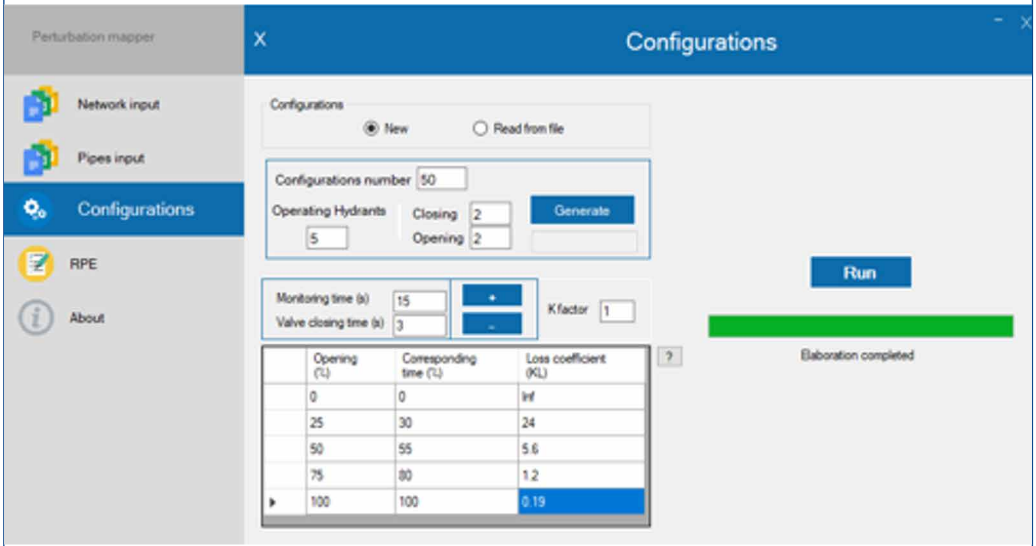
*Source: Screenshot of COPAM v4.0.*

## Different scenarios and valves characteristics

The different scenarios are presented by the generated configurations representing the transition from one steady-state to another steady-state regime. This approach simulates the possible operating conditions describing the farmers' behavior.

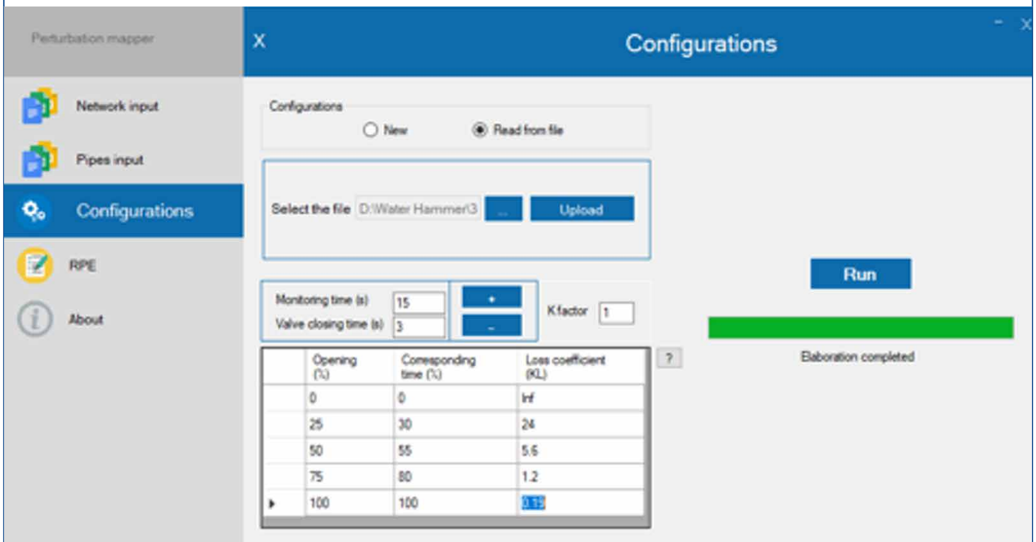
New configurations can be automatically generated or uploaded from a file (Figure A.2.72 and A.2.73).

FIGURE A.2.72
**Example of valves characteristics and generating new configurations**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.73
**Example of valves characteristics and uploading configurations from an existing file**




*Source: Screenshot of COPAM v4.0.*

Information is required about valve closure characteristics (see Chapter 8 section on boundary conditions).

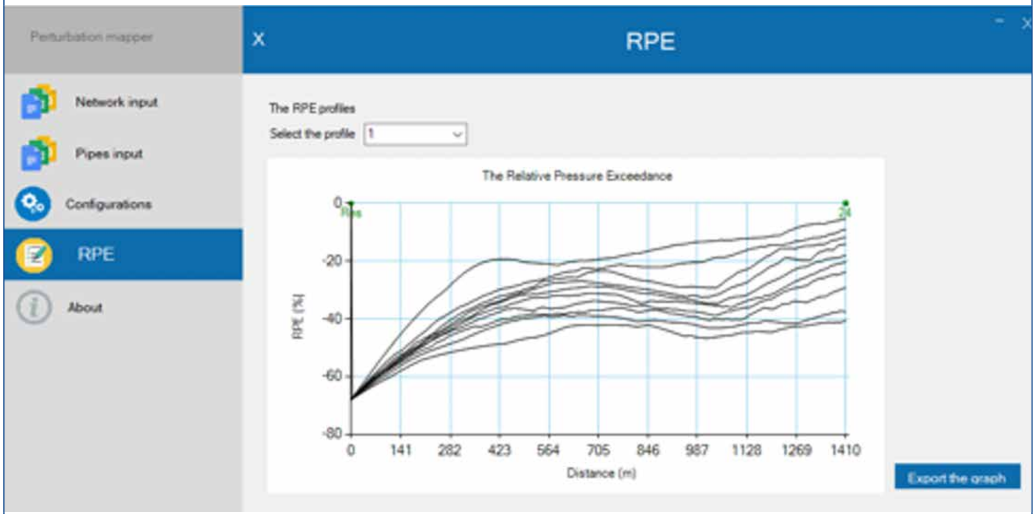
Codes identifying the hydrants operating mode are assigned to each node (0 when there is no hydrant at the node, 1 when the hydrant is closed, 2 when the hydrant is opened, 3 when the hydrant is going to be closed, and 4 when the hydrant is going to be opened).

## RPE profiles (the output section)

The Relative Pressure Exceedance is presented following the different network profiles. A drop-down list on the top left side shows the different profiles. The initial and final node of each profile are shown in green in the graphs.

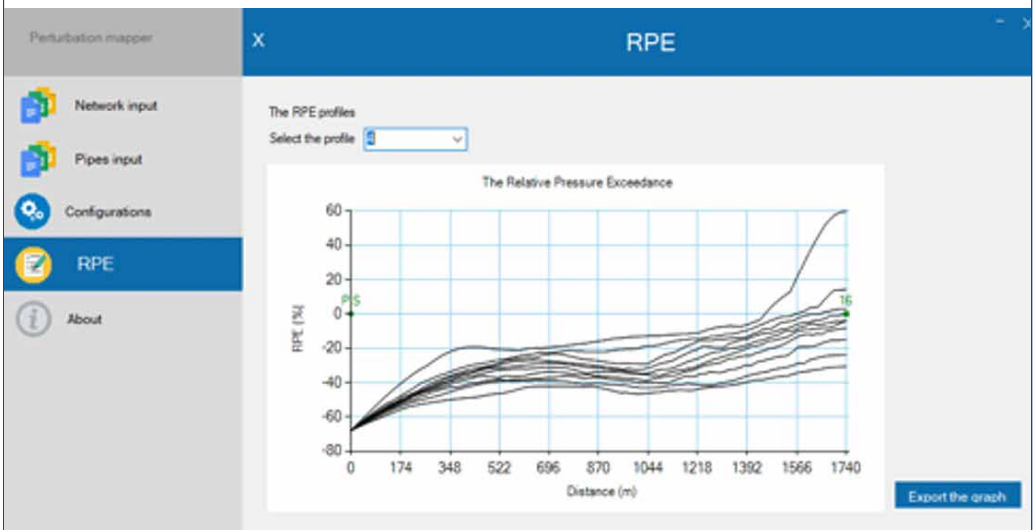
Option for exporting graphs as images is available with different formats (Bitmap, JPEG, PNG, GIF and TIFF) (see Figure A.2.74 and A.2.75).

FIGURE A.2.74
**Example of RPE profile 1**




*Source: Screenshot of COPAM v4.0.*

FIGURE A.2.75
**Example of RPE profile 4**




*Source: Screenshot of COPAM v4.0.*

# A.3. RAP V1 USER'S MANUAL

## A.3.1 About the software

The RAP for pressurized irrigation systems is built on the original work of FAO and the ITRC of California Polytechnic State University (Burt, 2001). RAP and Benchmarking – Explanation and Tools was published in 2001 and revised in 2002 as part of the FAO Irrigation and Drainage Paper 63, Modernizing Irrigation Management, - the MASSCOTE approach, Mapping System and Services for Canal Operation Techniques. The RAP tool was designed in excel spreadsheets, furthermore, explanation manual was appended to the documentation. The original RAP was framed to medium-, large-scale, open-canal systems. RAP for pressurized irrigation system is the revamped version of RAP with adjusted content and computerized user tool.

### A.3.1.1 About the technology

The software consists of a Windows compatible desktop app. The application is the computerized form of the RAP methodology to support users with user-friendly and easy-to-implement interface. The RAP is programmed and packaged as open-source software capable of build native exe file for Windows (x32 and x64).

### A.3.1.2 System requirements

Operating system: Minimum Windows 7 (32 or 64-bit), Recommended Windows 10 (32 or 64-bit)

- Processor: Minimum 1GHz, Recommended 2GHz or more
- RAM: Minimum 1GB, Recommended 4GB or more
- Hard drive: Minimum 100 MB
- Display: Minimum 1280 x 960 resolution
- Java version: Java SE Runtime Environment 8 (update 131 and above)

### A.3.1.3 Installation and Start-up of RAP

Download the exe file from FAO website, create a folder for the RAP software version 1 where you want to store the application and move the file to the folder. Make sure that the folder does not have write-protection. To run the application, JAVA SE Runtime Environment 8 needs to be installed on the computer. At the very first time of launching the application, the application will trigger a pop-up window showing the required JAVA version and navigating the user to the page, where it can be downloaded.

FIGURE A.3.1
**Required update of Java version**


*Source: Screenshot of RAP v1 User's Manual*

After the installation of JAVA updated version, select the icon to run the application from rap.exe file. While, the application loads, a splash screen will appear.

FIGURE A.3.2
**Splash screen**


*Source: Screenshot of RAP v1 User's Manual*

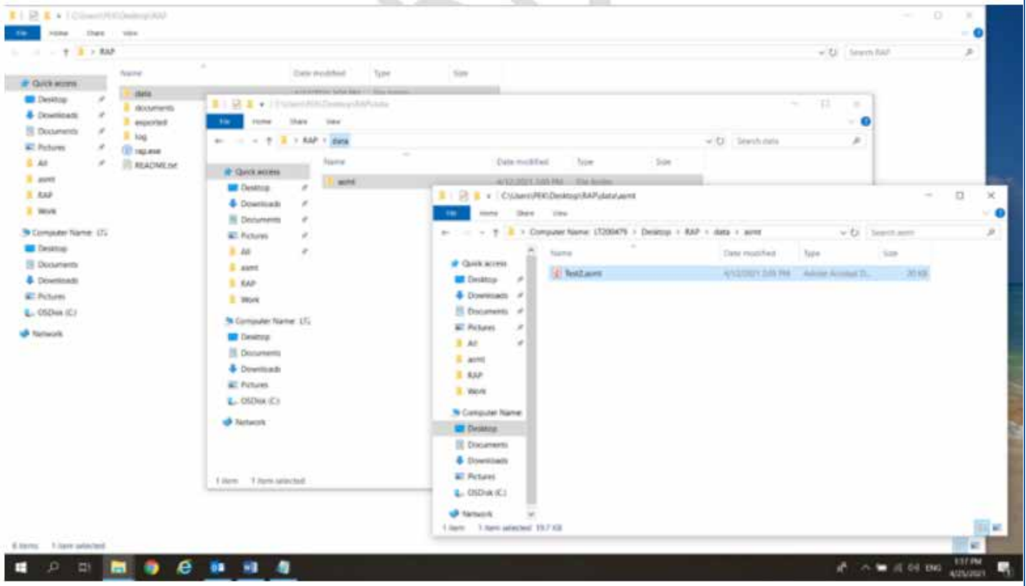
After launching the application, the landing page appears, which contains a summary about the main features of the application. Additionally, there are two buttons on the bottom, either to start a new, or load an existing assessment. These functions are also available from the "*File*" menu in the top menu bar.

FIGURE A.3.3
**Landing page**


*Source: Screenshot of RAP v1 software*

The load file option allows the import of existing assessments. Save and store the assessment as binary file with extension *.asmt* in the automatically created data/asmt subfolder. Files can be loaded only if they are saved in the "*asmt*" sub-folders. Opening .asmt files from other locations is not possible.

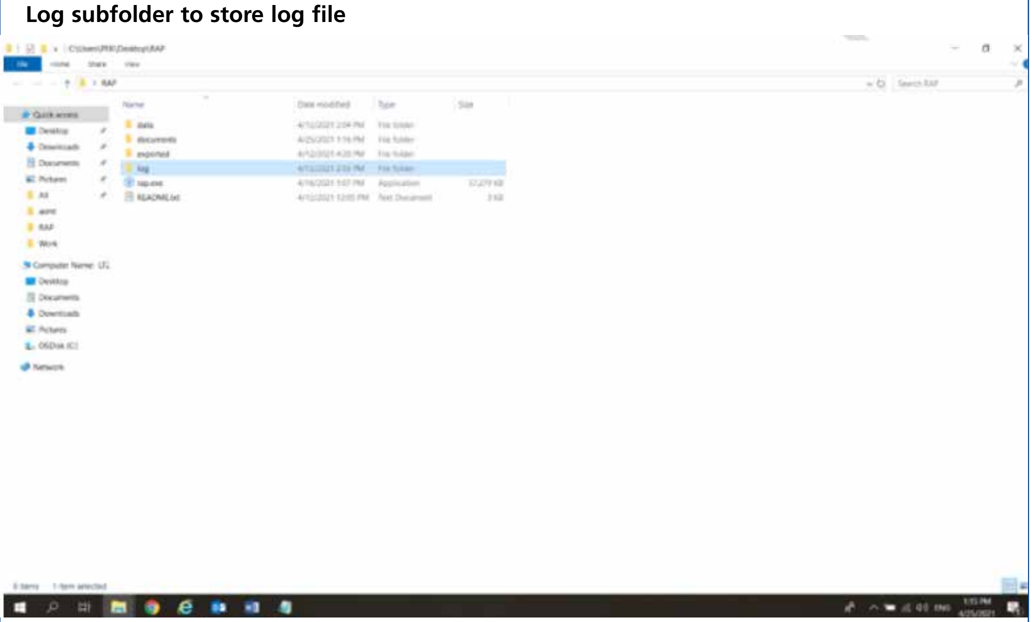
FIGURE A.3.4
**Assessment sub-folder and stored file with .asmt extension**



*Source: Screenshot of RAP v1 software*

The application automatically logs detailed information about its operation while running. The location of the log file is "*log/RapidAppraisalProcedure.log*". This information may become relevant if some malfunction happens when using the application. The user need not be concerned about the log file.

FIGURE A.3.5
**Log subfolder to store log file**



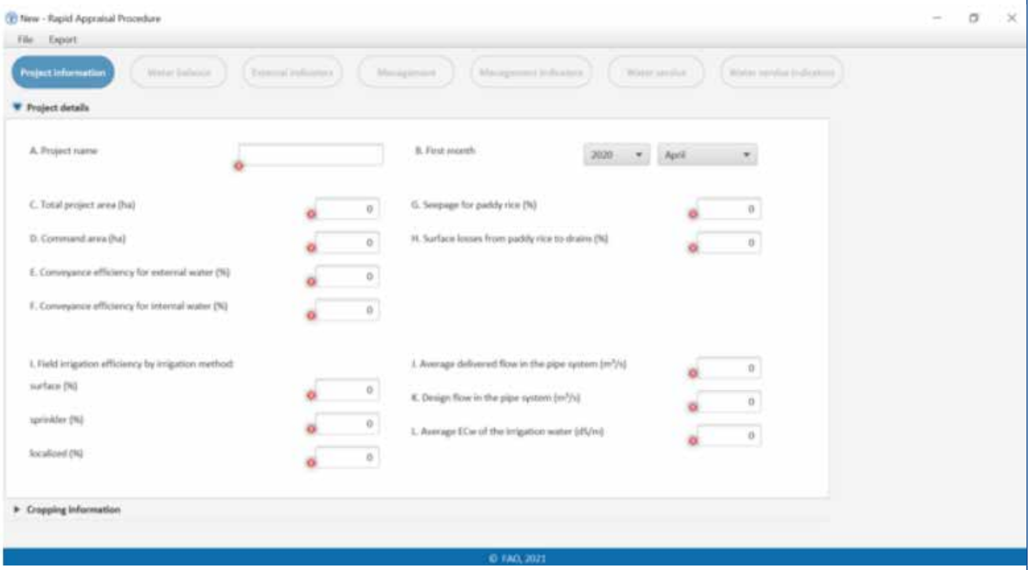
*Source: Screenshot of RAP v1 software*

## A.3.1.4. Main features of the software

### *A.3.1.4.1. User interface*

To edit an assessment the application opens the main view. It consists of 7 tabs: "*Project information*", "*Water Balance*", "*External indicators*", "*Management*", "*Management indicators*", "*Water service*", "*Water service indicators*". The ribbon buttons on the top side can be used to navigate through the chapters of the RAP. These buttons are disabled by default and would be enabled when the validation rules of relevant input data are met.

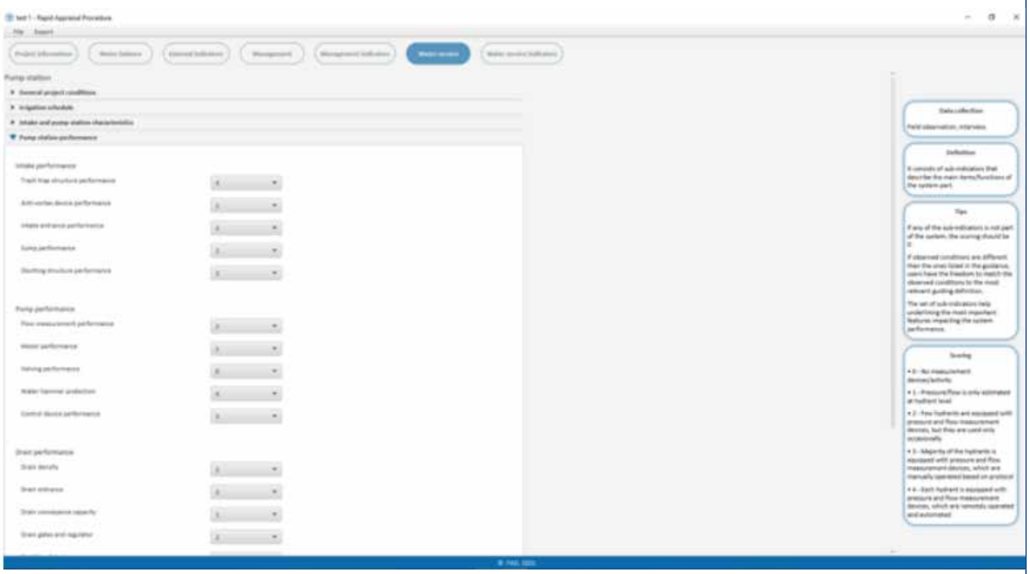
FIGURE A.3.6
**Main view of the software**




*Source: Screenshot of RAP v1 software*

The project information and the input tabs contain standard user interface elements, like text fields, dropdown lists, checkboxes, radio buttons etc. The indicator tabs list the calculated indicator values based on the input data. Closely related indicators are grouped, and certain groups are also visualized to facilitate interpretation of the outcome.

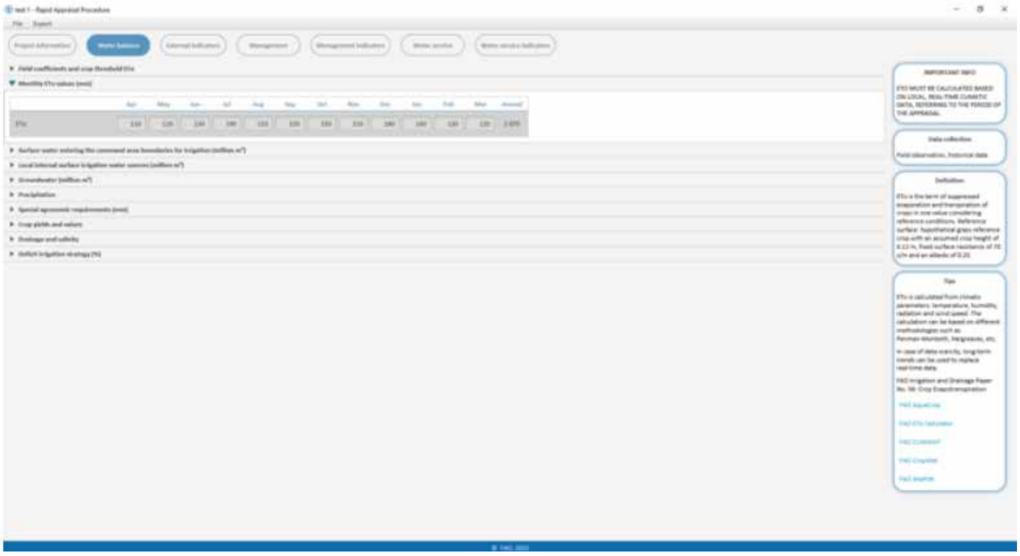
FIGURE A.3.7
**Window of assessment page**



*Source: Screenshot of RAP v1 software*

While navigating through the different elements of the user interface, guiding information appears in the info box on the right side of the window. Depending on the currently selected element, it may include important information, definition, tips, or any specific information related to that element.

FIGURE A.3.8
**Info box for user guidance**

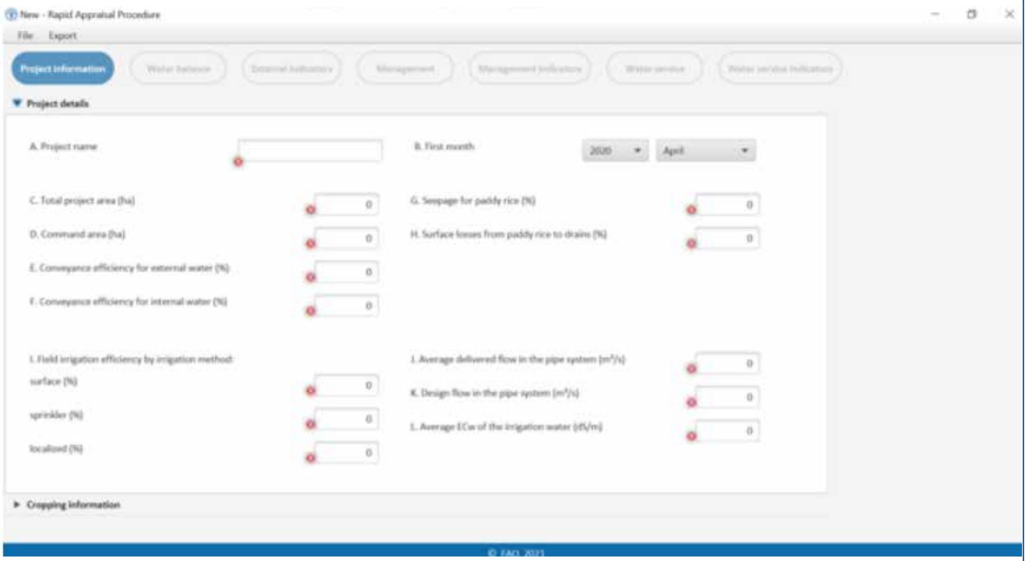


*Source: Screenshot of RAP v1 software*

### *A.3.1.4.2. Input validation*

There are different rules that the input data provided by the user needs to fulfill. The validation rules cover cases like when a field is required, or sum of percentage values must be 100 and so on. If a field is failing to match its defined rules, a symbol  (red dot with cross) is appearing at its bottom-left corner.

FIGURE A.3.9
**View of input validation rules**




*Source: Screenshot of RAP v1 software*

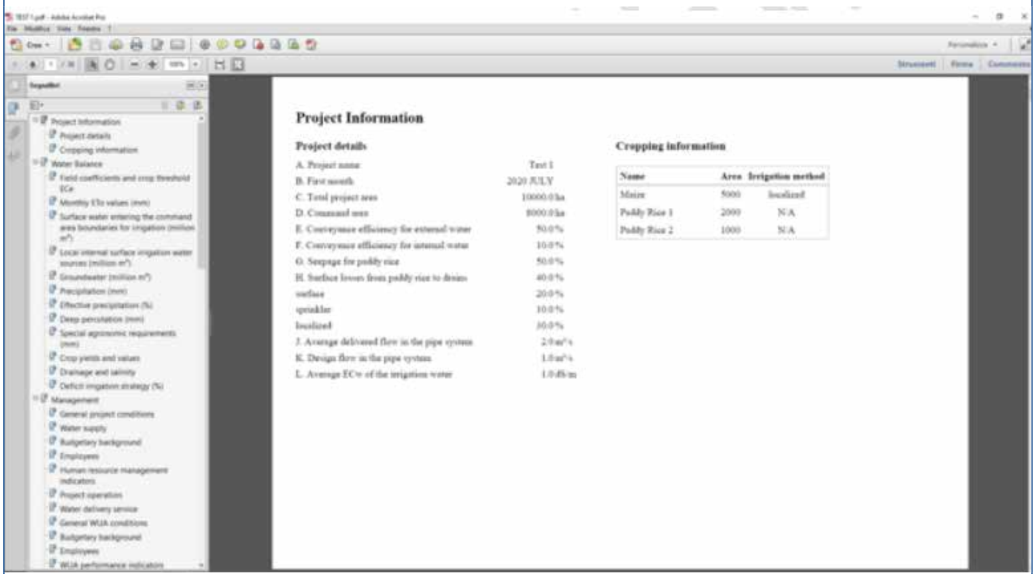
In addition, for text field inputs, it is prevented to enter an invalid or unnatural value. For example, fields containing number of people or percentage accept only integer values. When there are validation errors on a given tab, it may cause other tabs to be inaccessible. To be specific, when new assessment is started, only the project information tab is available. Fulfilling it without error enables the three input tabs, and after each input tab is properly filled, the corresponding indicator tab gets accessible.

#### *A.3.1.4.3. Exporting assessment*

In the "*Export*" menu, there are two options to export assessment data into standard digital formats:

- the "*Export to PDF*" option creates a PDF file with all the input and indicator values, but without the visualization artefacts (charts);
- the "*Export charts to images*" creates a compressed (*.zip) file containing all the charts.

FIGURE A.3.10
**PDF export of the assessment file**




*Source: Authors's own elaboration based on RAP v1 software*

By default, exported files are created in the "*exported*" folder inside the working directory of the application, however the user can choose any other location.

## A.3.2. About the methodology

RAP for pressurized irrigation system is a diagnostic tool for performance assessment related to water resource, institutional management and irrigation service (hardware and software). It aims at identifying the physical bottlenecks hampering the efficient water delivery. The ultimate goal of RAP is to obtain solid baseline assessment of the performance, against which the results of improvement/rehabilitation/modernization can be measured.

### A.3.2.1. Application boundaries

The following parameters describe the application boundaries of RAP for pressurized irrigation system.

1. Irrigation system type: pressurized irrigation system with pipe network from water intakes to final distributaries (hydrants) and drains.
2. Appraisal frame: system-level, not including on-farm irrigation systems.
3. Irrigation system size: small-, medium and large-scale system.
4. Methodology: rapid appraisal to acquire preliminary understanding.
5. Time-horizon: retrospective, covering one-year round operation.
6. Indicative time required: from 1 to 1.5 months (depending on the conditions and complexity of the system, the actual required time can exceed the indicated time frame).
7. Required expertise: solid knowledge related to agricultural engineering, irrigation engineering, water resource management, civil engineering or any related field.
8. Involved stakeholder: 360-degree involvement from end-users, site engineers, experts to management.

### A.3.2.2. General workflow

Three chapters constitute the RAP:

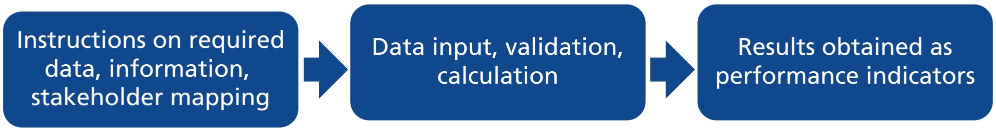
- water balance: appraisal of water resource allocation through water balancing approach between water supply and water demand;
- management (institutional and organizational): assessment of the institutional and organizational mechanism;
- water service: stocktaking of physical water distribution system through the assessment of general characteristics, performance, operation policy, condition and maintenance of physical system components.

The chapters are appraised separately, but some of the questions are overlapping and some of them are transferred from one chapter to another. However, it does not cover more than 10 percent of the questions in overall, thus giving the possibility to conduct both comprehensive and individual analyses of the chapters.

The working mechanism has three major steps:

- The required data and information indicated in the manual must be collected, structured and pre-processed in the right format, unit and scale. Depending on the subject, required information can involve interviews, questionnaires, focus-group discussion, etc. Therefore, the application of RAP requires sufficient time for preparation.
- Data input and result generation is the next step of the exercise. The datasets must be correctly inserted, while the automated functions execute the calculation. The calculated data sheets and obtained results are immediately displayed, can be saved and exported.
- RAP results must be framed into the right context. In order to obtain sound baseline study, the results must be interpreted in proper manner, while both respecting the original definitions and considering the local context.

FIGURE A.3.11
**Flowchart of calculation mechanism**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20 Manual.pdf.*

Related to each chapter:

- users receive basic instructions to the preparation;
- users receive sets of supporting document and applications;
- users receive information and clarification related the definitions of applied methodologies.

## A.3.3. The structure of the manual

The manual is structured as the following:

- Setting the scene: the section provides 'virtual journey' upon arrival to the irrigation scheme together with the recommendations on available tools for preparation.
- RAP chapters: the section is split into the three RAP chapters: water balance, management and water service. Each chapter contains the following sections:
    - Instructions: the section incorporates information related to the required data, preparatory works, involved stakeholders, data units and supporting documents to data acquisition.
    - Input workspace: the section includes clarifications and definitions of the calculation parameter, applied methodologies, data insertion, workflow, possible errors.
    - Definitions: the section includes the definitions of obtained results

The Manual also includes tips to support the assessment. Such tips are developed by case studies and field implementation and included in text boxes.

## A.3.4. Setting the scene

Modern technologies facilitate the acquisition of preliminary information that can support the field work. Global datasets have great potential to obtain data that are not instantly available. A 'virtual journey' in the field is strongly recommended in advance to set the scene for the appraisal. Nevertheless, RAP requires micro-data obtained through field observation, so the datasets from global repositories must be validated in the field.

### A.3.4.1. Geographical location

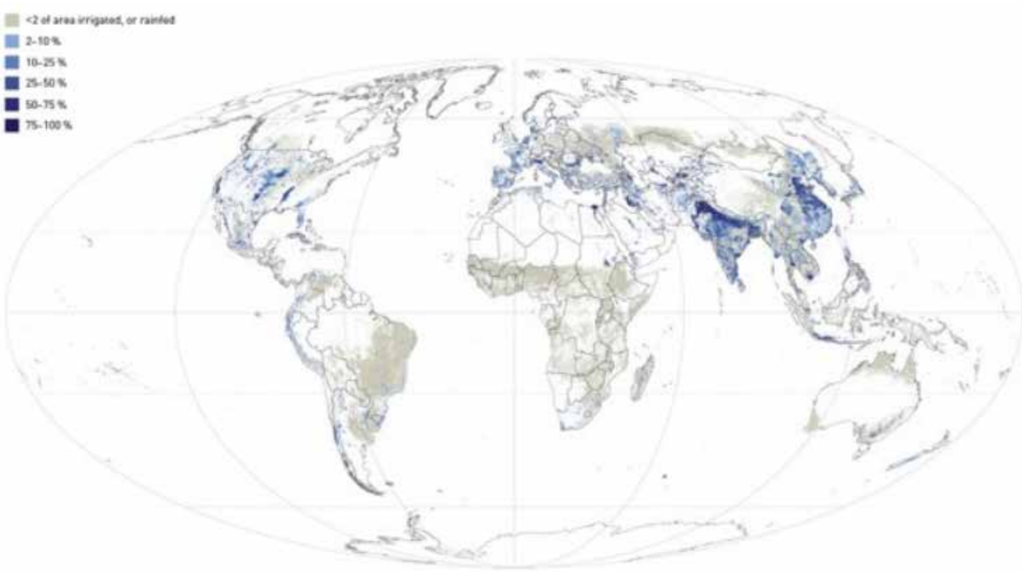
Online maps with high resolution are available, based on which the boundaries and key locations of the irrigation schemes can be identified. Open-access and easy-to-use satellite images are readily available to understand the key geographical features. It is particularly important in a sense that overview about the catchment can provide many clarifications on the water allocation issues, e.g. water resource endowment, topographical constraints.

#### *A.3.4.1.1. Example*

Google Earth is one of the most frequently used application suitable to a variety of devices. The application allows to insert paths, polygons, markers and layers. Furthermore, it has function on measuring distances, and calculating elevation.

Global Map of Irrigated Area (GMIA) by FAO is a regularly updated map displaying the area equipped for irrigation in the percentage of the total area on a raster (FAO, 2021a) . The GMIA involves add-in maps featuring the area equipped for irrigation and actually used for irrigation and the percentages of the area equipped for irrigation from groundwater, surface water or non-conventional sources of water. The maps are compiled from the combination of sub-national irrigation statistics with geospatial information on the position and extent of irrigation schemes. The digital information helps pre-assess the degree of equipped area, as well as the major water sources and actual use of irrigation systems.

FIGURE A.3.12
**Area equipped for irrigation as percentage of land area**




*Source: Food and Agriculture Organization of the United Nations (FAO). 2021a. Global Map of Irrigated Area (GMIA) [online]. http://www.fao.org/aquastat/en/geospatialinformation/global-maps-irrigated-areas/latest-version/.*

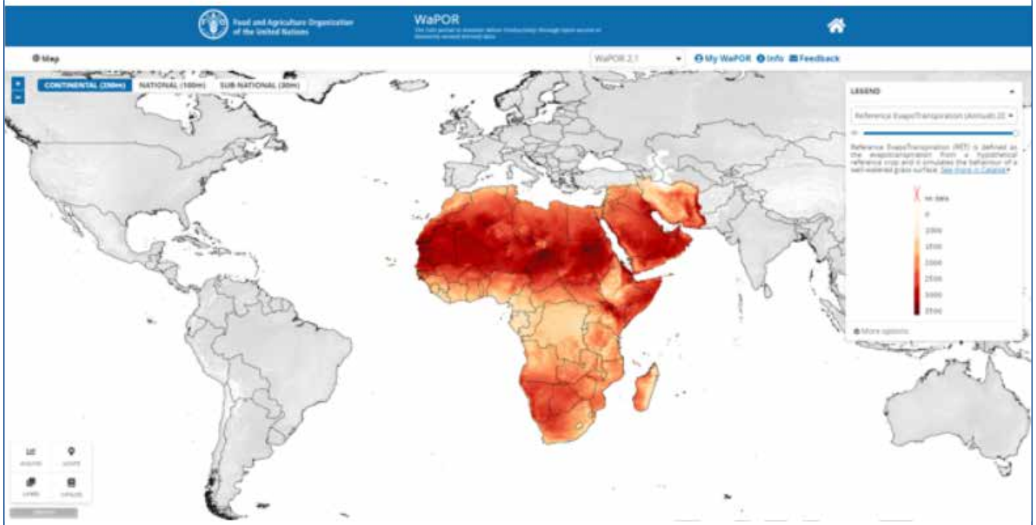
### A.3.4.2. Climate, vegetation and agricultural water use

Monitoring of surrounding environment can be done through highly-versatile GIS-based tools. Remote-sensing tools are often available right at sub-national level to provide readily available information regarding to climatic, hydrological, land use and agricultural parameters.

#### *A.3.4.2.1. Example*

FAO's portal to monitor Water Productivity through Open-access of Remotely sensed data (WAPOR) opens new opportunities in data acquisitions through the application of global datasets (FAO, 2021b). It assists countries in monitoring water productivity while providing a set of information related to climate (precipitation, evapotranspiration), vegetation (land cover), biomass production and water productivity. The maps are available in 250, 100 and 30 m spatial resolution, and can be exported in raster files.

FIGURE A.3.13
**WaPOR - FAO portal: Annual reference evapotranspiration**




*Source: Food and Agriculture Organization of the United Nations (FAO). 2021a. Global Map of Irrigated Area (GMIA) [online]. http://www.fao.org/aquastat/en/geospatialinformation/global-maps-irrigated-areas/latest-version/.*

AQUASTAT is the most comprehensive global repository of water related data. The datasets are compiled by experts and frequently updated. AQUASTAT includes data at national-level, which can be utilized to contextualize the irrigation sector and irrigation performance (FAO, 2021c).

FIGURE A.3.14
**AQUASTAT dataset**


*Source: FAO. 2021c. AQUASTAT - FAO's Global Information System on Water and Agriculture [online]. http://www.fao.org/aquastat/statistics/query/index.html;jsessionid=8F91EF0E411552F0E351E433543EEBD5.*

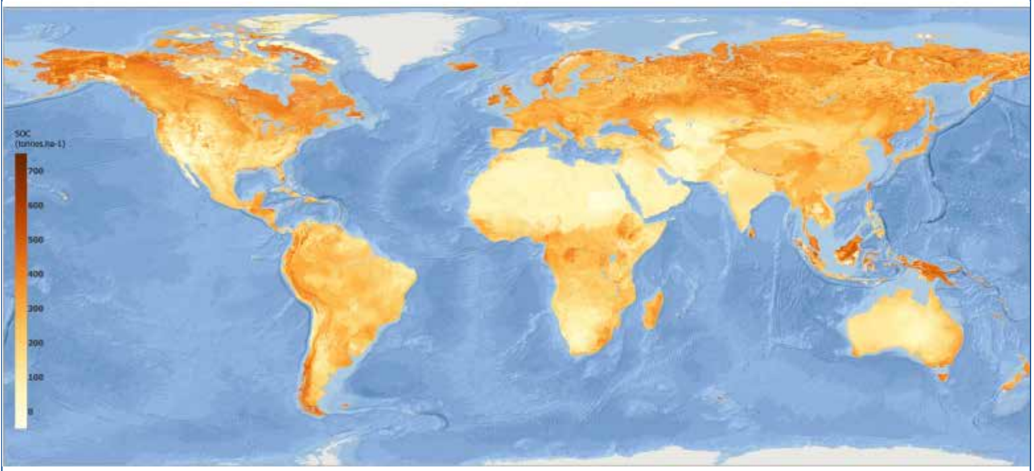
## A.3.4.3. Soil data

Irrigation water demand largely depends on land resources. Therefore, information related land and soil is highly desirable to reach accurate estimates related to deep percolation, effective precipitation, root zone depth etc. Although soil analysis requires field work, global statistics are available to obtain information on main characteristics.

### *A.3.4.3.1. Example*

FAO provides diverse sets of soil maps including Global Soil Organic Carbon Map, FAO/UNESCO Soil Map of the World, Harmonized world soil database, Regional and National Soil Maps and Databases that contains open-access data for users (FAO, 2022b).

FIGURE A.3.15
**Global Soil Organic Carbon Map, GLOSIS – GSOCmap**




*Source: FAO. 2022b. Global Soil Organic Carbon Map – GSOCmap v.1.6. Technical report. Rome. https://doi.org/10.4060/cb9015en.*

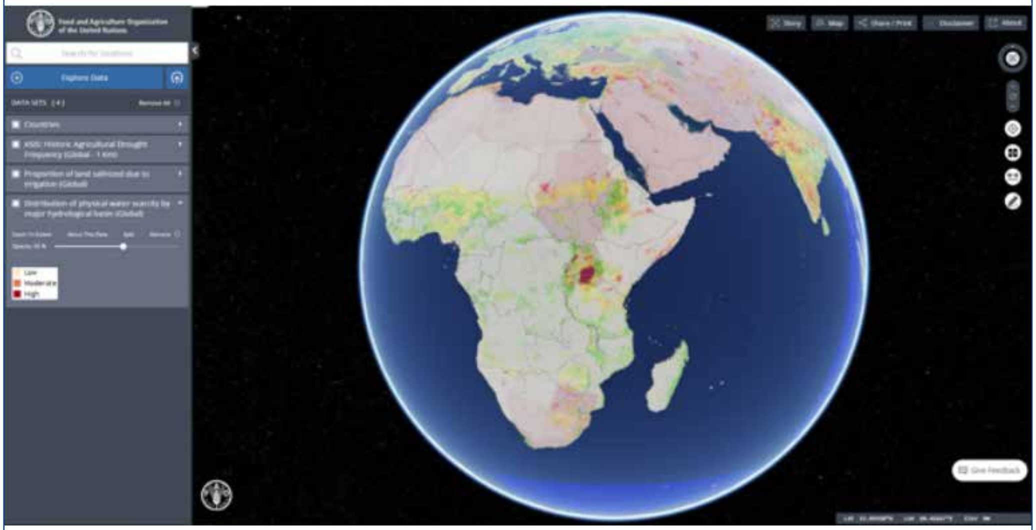
## A.3.4.4. Global repositories to characterize agriculture and water management

Integrated global repositories are extremely valuable tools to collect further information in order to characterize the national or sub-national agriculture, water resources and irrigation sectors. National cropping pattern, cropping and harvesting calendar, food prices, registered lands, cadastral parcels, irrigated area ratio, water resource, aridity etc. can be accessed from national and international sources to acquire a rapid overview and retrieve relevant information

### *A.3.4.4.1. Example*

FAO Hand-in-Hand Geospatial Platform is designed to host the global datasets and statistics generated by FAO in different fields of sciences (FAO, 2021e). The online platform provides open access to all datasets fostered by FAO, such as "*Crops*", "*Land*", "*Water*" and "*Climate*" tabs can directly support the RAP implementation.

FIGURE A.3.16
**Hand-in-Hand GIS platform snapshot**



*Source: FAO. 2021e. Hand-in-Hand Geospatial Platform [online]. http://www.fao.org/hihgeospatial-platform/en/.*

### A.3.4.5. Synthesis

Together this initial data collection exercise has multiple function: data acquisition, data validation, data replacement. If in-situ measurements or observations are not available at the time of the appraisal, open-access sources can be used to construct bulk information. Such datasets should be also used to properly frame the baseline assessment and understand the prevailing trends in the irrigation scheme. However, the original scope and scale of RAP is to obtain micro-analysis. Therefore, local data and information have absolute priority throughout the appraisal.

## A.3.5. Appraisal

### A.3.5.1. Project information

The project information tab involves the basic information about the irrigation system. It is set to determine the overall boundaries of the irrigation scheme and the basic agricultural information. The tab has two main section:

1. Project details: the overall information about the irrigation scheme include the area, irrigation type, agricultural year and efficiencies of the infrastructure.
2. Cropping information: the cropping pattern is defined per crop type, production area per crop type and irrigation method per crop.

FIGURE A.3.17
**Main view of project information window**

*Source: Screenshot of RAP v1 software.*

The project information determines the basic features, therefore the data inserted into the following chapter must correspond to this. The boundaries of the command area must be defined carefully. A command area can be determined based on different approaches, and the assessment must remain consistent with command areas.

BOX A.3.1
**The command area selection**

The boundaries of irrigation schemes are often not straightforward. An irrigation scheme can be defined by hydrological, agricultural or administrative boundaries. It is important to be clear with the boundaries in advance. The RAP allows the identification of boundaries via water intakes belonging to the scheme or administration. However, the chapters must be filled accordingly. If the boundaries are based on the hydrological boundaries, the command area might include more management entities or shared management entity. If the boundaries are based on the administrative boundaries, multiple agricultural area can be aggregated and assessed. In case of large area, it is recommended to divide the area to sub-systems and conduct the assessment per sub-system. This will allow for a more accurate assessment and the comparison of performance across sub-systems.

Source: Authors' own elaboration based on RAP v1 User's Manual.

#### *A.3.5.1.1. Data input and calculation scheme*

The input data should be filled step-by-step starting from project information. Any missing value can hamper the correct calculation. The stepwise guide below provides information on the stepwise data requirement.

### Project details:

*Project name:* user defines the name of the project, preferably the name of the irrigation scheme

*First Month:* the first month of irrigation system use or cropping within the year. E.g. if the cropping starts in March, the first month of the water year will be March.

- It usually refers to the beginning of the year-round agricultural season;
- user defines the water/agricultural year when the appraisal is conducted;
- water/agricultural year does not necessarily start with January;
- one year can include a double season.

*Total project area (ha):*

- the total area of the irrigation scheme, including the non-cropped areas, such as inspection roads, yards, infrastructure, etc.;
- arable lands without irrigation facilities must also be calculated in the total project area.

*The command area (ha): the area with irrigation facilities.*

- Command area is the net cropped and irrigation area available in a year;
- in case of double cropping (multiple seasons in one calendar year), the area cropped should be calculated only once (e.g., if the arable land is 100 ha but cropped twice per year, the command area will be 100 ha).

*Conveyance efficiency for external water (percentage):*

- external water is the water conveyed to the project area from outside of its hydrological boundaries;
- it is the ratio of delivered external water over external supplied water in percentage;
- the ratio expresses the water loss during transportation. E.g. leaking pipe, water loss at the joints or offtakes etc.;
- conveyance efficiency concerns the infrastructure from water intake until offtakes (deliveries) on the farm.

*Conveyance efficiency for internal project water (percentage):*

- internal project water is the water pumped from wells located with in the hydrological boundaries of the project;
- it is the ratio of delivered internal water over internal supplied water in percentage;
- the ratio expresses the water loss during transportation. E.g. leaking pipe, water loss at the joints or offtakes etc.;
- conveyance efficiency concerns the infrastructure from water intake until offtakes (deliveries) on the farm

*Seepage for paddy rice (percentage):*

- ratio of water applied over water infiltration from the paddies into the soil;
- the ratio expresses the average loss of water from paddies due to seepage.;
- the seepage information should be filled only if the cropping pattern includes paddy rice, seepage from paddies could be estimated using the drainage type lysimeter.

*Surface losses from paddy rice to drains (percentage):*

- ratio of water lost as runoff or evaporation from the paddies;
- the ratio expresses the average water loss by runoff and/or evaporation;
- the surface loss should be filled only if the cropping pattern includes paddy rice.

*Field irrigation efficiency by irrigation method (percentage):*

- ratio of water that can be used by the crop over water delivered to the field, in other words the efficiency of the different on-farm irrigation techniques;
- the ratio expresses the water amount utilized by the crop, including the water loss of deep percolation, runoff, evaporation and other water losses on the field;
- the ratio must be estimated per irrigation technique. Usually, surface irrigation has the lowest efficiency, while localized techniques such as drip has higher field irrigation efficiency;
- the estimates have substantial impact on the crop water requirement. 1) The water loss calculated from the efficiency is considered additional water requirement. Therefore, the less efficient the method, the more extra water requirement. 2) The leaching requirement is calculated as per irrigation method. The leaching requirement of high-frequency irrigation methods differs from the low-frequency methods. Therefore, the accurate estimate of the irrigation efficiency is of utmost importance;
- existing irrigation techniques must be estimated and the field must be filled.

*Average delivered flow ($m^3/s$):*

- the average discharge conveyed through the conveyance system (pipes) during a usual irrigation event;
- averaged delivered flow can differ from the design discharge defined by the designer.

*Design flow in the pipe system ($m^3/s$):*

- the design or maximum discharged defined during the design and implementation phase of irrigation system and that the pumping station can supply.

*Average electrical conductivity (ECw) of the irrigation water (dS/m):*

- average value of electrical conductivity of irrigation water during typical irrigation event;
- the value must be determined in due time of irrigation. If historical data is available, the most typical value must be selected during the most frequent irrigation/cropping period;
- the calculation assumes good to excellent quality of water. It is not likely that ECw of irrigation water is higher than the threshold of crop tolerance. This must be taken into consideration while defining ECw.

## Cropping information:

*Cropping information:*

- the cropping pattern of the area over the year;
- Each crop type and variety must be filled individually. For example, if more crop varieties are produced over the year, each of them must be indicated separately;
- the irrigation method must be indicated to each crop, except paddy rice.
- if the same crop is produced in double-cropping in the same year, the crop must be added per season.

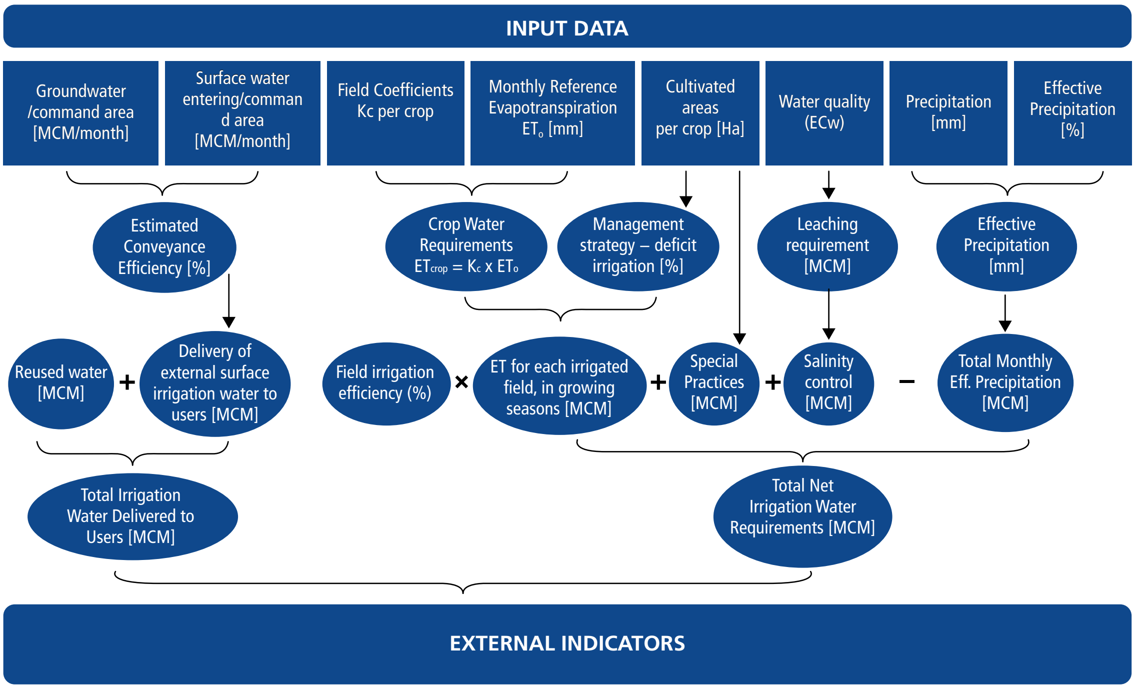
### A.3.5.2. Water balance

The water balance chapter aims at matching the bulk water supply and bulk water demand at system level:

3. Water supply: the surface- and groundwater resources are categorized under "*external*" and "*internal*" water resources, depending whether the water enters the command area from outside or it is sourced directly within the command area. Water reuse is considered as additional internal water supply (recirculated). The water supply is corrected with conveyance efficiencies.
4. Water demand: water demand is calculated in sequence. ET-based crop water requirement is scaled at command area level, and effective precipitation is subtracted from the net water requirement of command area. In case of deficit irrigation, the crop water requirement can be altered based on the deficit irrigation strategy. Additional water demand is calculated by considering the salinity control and special irrigation practices. The total net irrigation water requirement is corrected by the field irrigation efficiency, depending on the type of on-farm irrigation system.

The main external indicators of the water balance chapter include the obtained ratio of water supply and water demand. Depending on both cases of oversupply and water scarcity, the ratio shows the magnitude of the imbalance between water sources and required water demand.

FIGURE A.3.18
**Flowchart of indicator calculation in water balance chapter**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20Manual.pdf.*

### *A.3.5.2.1. Preparation of the input file*

The Water balance chapter builds on one-year-round data related to agriculture, agricultural water, conveyance system and climate. It is recommended to request the available information prior to the field visit. The chapter requires secondary data collection, literature review, historical data and field observation.

TABLE A.3.1
**Data input support of Water balance chapter**

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| **Agriculture** | | | | |
| cropping pattern of the area | ha | year | - | historical data |
| cultivated area size per crop | ha | monthly | - | historical data |
| crop coefficient (Kc) | - | monthly | • FAO Irrigation and Drainage Paper No. 56: Crop Evapotranspiration<br>• FAO Irrigation and drainage paper 66: Crop yield response to water | literature review, historical data, field observation |
| salt tolerance threshold (ECe) | dS/m | year | • FAO Irrigation and Drainage Paper 29: Water quality for agriculture | literature review, historical data |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| special water requirement of the crop | mm | monthly | • FAO Irrigation and drainage paper 66: Crop yield response to water | literature review, historical data, field observation |
| crop yield | tons | season | - | historical data, field observation |
| crop value | local currency | season | - | secondary data, historical data, field observation |
| regulated deficit irrigation strategy | percentage | monthly | - | historical data, field observation |
| irrigation water pumped into the command area | million m³ | monthly | - | historical data, field observation |
| other irrigation water entering the command area | million m³ | monthly | - | historical data, field observation |
| direct farmer usage of surface water inside the command area (recirculated water) | million m³ | monthly | - | historical data, field observation |
| project authority usage of surface water inside command area -(recirculated water) | million m³ | million m³ | - | historical data, field observation |
| groundwater pumped by farmers inside the command area | million m³ | monthly | - | historical data, field observation |
| groundwater pumped by project authorities inside the command area | million m³ | monthly | - | historical data, field observation |
| groundwater pumped from the aquifer remaining outside the command area | million m³ | monthly | - | historical data, field observation |
| groundwater pumped outside the command area brought into | million m³ | monthly | - | historical data, field observation |
| salinity of the irrigation water | dS/m | monthly | - | historical data, field observation |
| salinity of the drainage | dS/m | monthly | - | historical data, field observation |
| annual depth to the shallow water table | m | year | - | historical data, field observation |
| change in shallow water table | m | year | - | historical data, field observation |
| Chemical Oxygen Demand (COD) of the irrigation water | mgm/L | year | - | historical data, field observation |
| Chemical Oxygen Demand (COD) of the drain water | mgm/L | year | - | historical data, field observation |
| Biological load (BOD) of the irrigation water | mgm/L | year | - | historical data, field observation |
| Biological load (BOD) of the drain water | mgm/L | year | - | historical data, field observation |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| **Climate** | | | | |
| reference evapotranspiration (ETo) of the command area | mm | monthly | • FAO Irrigation and Drainage Paper No. 56: Crop Evapotranspiration<br>• FAO AquaCrop: http://www.fao.org/land-water/databases-and-software/aquacrop/en/<br>• FAO ETo Calculator: http://www.fao.org/land-water/databases-and-software/eto-calculator/en/<br>• FAO CLIMWAT: http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat<br>• FAO CropWat: http://www.fao.org/land-water/databases-and-software/cropwat/en/<br>• FAO WaPOR: http://www.fao.org/land-water/databases-and-software/wapor/en/ | literature review, secondary data, historical data, field observation |
| precipitation | mm | monthly | • FAO CLIMWAT: http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat<br>• FAO WaPOR: http://www.fao.org/land-water/databases-and-software/wapor/en/ | literature review, secondary data, historical data, field observation |
| rate of effective precipitation (eff.precip) | | monthly | • FAO Irrigation and Drainage Paper No. 25: Effective rainfall in irrigated agriculture | literature review, historical data, field observation |
| deep percolation of precipitation | mm | monthly | • FAO Irrigation and Drainage Paper No. 45: Guidelines for designing and evaluating surface irrigation systems<br>• FAO: Irrigation Water Management: Irrigation Water Needs. Training manual no. 3 | literature review, historical data, field observation |
| **Conveyance system** | | | | |
| estimated conveyance efficiency for external water | percentage | year | • FAO Irrigation Water Management Training manual: Irrigation Scheduling | field observation |
| estimated conveyance efficiency for internal percentag e year FAO Irrigation Water Management Training manual: field observation project well water | percentage | year | • FAO Irrigation Water Management Training manual: Irrigation Scheduling | field observation |
| estimated seepage for paddy rice | percentage | year | • FAO Irrigation Water Management Training manual: Irrigation Scheduling | field observation |
| estimated surface losses from paddy rice to drains | percentage | year | • FAO Irrigation Water Management Training manual: Irrigation Scheduling | literature review, historical data, field observation |
| estimated field irrigation efficiency for other crops (surface, sprinkler, localized) | percentage | year | • FAO Irrigation Water Management Training manual: Irrigation Scheduling | literature review, historical data, field observation |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| average delivered flow in the pipe system | m³/s | year | Design, plans, master plans, technical drawings, manufacturer recommendations | Field observation, interview |
| design flow in the pipe system | m³/s | m³/s | Design, plans, master plans, technical drawings, manufacturer recommendations | Field observation, interview |
| external water deep percolating during conveyance | percentage | year | FAO Irrigation Water Management Training manual: Irrigation Scheduling | Historical data, field observation |
| delivered water deep percolating on-farm | percentage | year | FAO Irrigation Water Management Training manual: Irrigation Scheduling | Historical data, field observation |

#### A.3.5.2.2 Involved stakeholders

The section is data-intense, therefore, it requires preparation prior to the field visit. The majority of the questions can be filled by historical data collected from the scheme. However, if historical data is not available, expert benchmarking within field visit is required to estimate the values.

- The following stakeholders are recommended to be involved:
- project office and scheme management;
- national authority storing relevant data;
- site engineers;
- WUA, irrigation association, farmers' organization etc.

#### A.3.5.2.3 Requested time

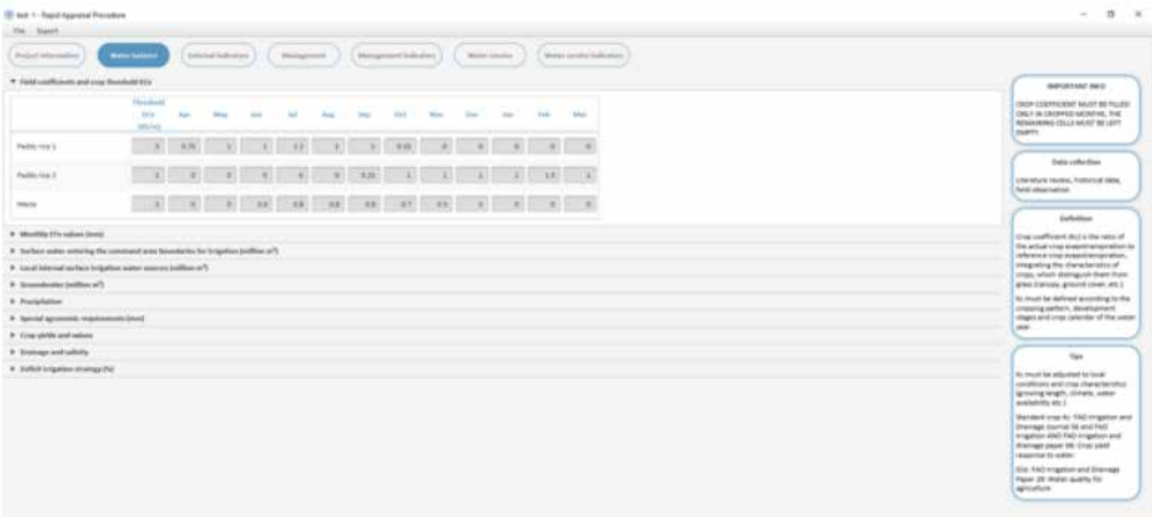
The preparatory works require more-or-less 2 weeks, depending on the scheme size, data availability and complexity of the scheme. If data cannot be obtained within the indicated timeframe, expert benchmarking methods and observation can complement the missing data.

#### A.3.5.2.3 Data input and calculation scheme

*Crop Coefficient and crop threshold:*

- crop coefficient must be filled only in cropped months, the remaining cells must be left empty;
- crop coefficient (Kc) is the ratio of the actual crop evapotranspiration to reference crop evapotranspiration, integrating the characteristics of crops, which distinguish them from grass (canopy, ground cover, etc.);
- Kc must be defined according to the cropping pattern, development stages and crop calendar of the water year;
- Kc must be adjusted to local conditions and crop characteristics (growing length, climate, water availability etc.);
- threshold of crop salt tolerance to soil salinity (ECe) is the average soil salinity tolerated by the crop and measured as soil saturation extract.

FIGURE A.3.19
**Main view of crop coefficient table**



*Source: Screenshot of RAP v1 software.*

*Monthly reference evapotranspiration values (mm):*

- the reference evapotranspiration (ETo) is the term of suppressed evaporation and transpiration of crops in one value considering reference conditions. The reference surface is hypothetical grass reference crop with an assumed crop height of 0.12 m, fixed surface resistance of 70 s/m and an albedo of 0.23;
- ETo is calculated from climatic parameters: temperature, humidity, radiation and wind speed. The calculation can be based on different methodologies such as Penman-Monteith, Hargreaves, etc.;
- ETo must be calculated based on local climatic data, referring to the period of the appraisal;
- in case of data scarcity, long-term trends can be used to replace the appraisal year data.

*Surface water entering the command area boundaries for irrigation (million $m^3$):*

- the total monthly volume of surface water entering the scheme;
- this refers only to the irrigation water imported into the scheme;
- only the water coming from outside of the irrigation scheme must appear in this table. Such categorization indicates the dependency on external/internal irrigation water source;
- the table is split into varieties of water sourced from outside of the scheme: Irrigation water pumped into the command area from the main surface water source, Other irrigation water entering the command area from an external source.

*Local internal surface irrigation water sources (million $m^3$):*

- the total monthly volume of local internal surface irrigation water.
- only the water coming from inside of the irrigation scheme must appear in this table. Such categorization indicates the dependency on external/internal irrigation water source.
- the table requires only the volumes related to irrigation water. If the water is stored internally, but not utilized for irrigation water, it should not be considered.

For example, reservoir in the command area without conveying water from it should not be calculated as water source.

- the table is split into varieties of local internal surface irrigation water: direct farmer usage of surface water inside the command area, Project authority usage of surface water inside command area

*Groundwater data (million m³):*

- the total monthly volume of groundwater for irrigation;
- the table is split into varieties of groundwater: groundwater pumped by farmers inside the command area, groundwater pumped by the Project Authorities inside the command area, Groundwater pumped from the aquifer remaining outside the command area, Groundwater pumped outside the command area brought into the command area.
- if groundwater abstraction is informal, the amount of withdrawn water should not be indicated here, as it would distort the perception about the sufficiency of irrigation water;
- the table requires the volumes related only to irrigation water.

BOX A.3.2
**Discharge measurement**

Many irrigation schemes do not apply discharge monitoring. Consequently, discharge history is not available at the time of the appraisal. However, the flow in pressurized irrigation systems is more predictable than in open-canal systems. It is recommended conducting discharge measurement campaign, whereas flow measurement devices are installed both in the pump station and on selected hydrants. Discharge measurement must be conducted both at water intake (pump station) and distribution level (hydrant). Discharge measurement in the pump station must be conducted in a typical irrigation day, when the water level of the water sources is around the average. Consultation with the pump operators helps understand the frequency and duration of irrigation events, thus the estimation of the water supply. Evidence shows if more hydrant operates at the same time and the irrigation schedule is not adjusted to the system configuration, the discharge received is unequal amongst the hydrants. Therefore, it is important to profile the irrigation practices (number of simultaneously operating hydrants, position of hydrants, time of irrigation etc.) and conduct random measurements simultaneously.

*Source: Authors' own elaboration.*

*Precipitation (mm):*

- the precipitation refers to the overall precipitation in the command area, referring to the period of the appraisal;
- if precipitation data is not available, the data can be replaced with average long-term trends;
- precipitation value must be filled in each month within and out of the crop calendar;
- effective precipitation (percentage) is the rate of precipitation that actually reaches the root zone. This is the available amount of precipitation for the plant, expressed in percentage;

- it is not recommended to calculate effective precipitation if the daily rainfall is less than 5 mm. Below 5 mm, the estimated effective precipitation should be 0;
- if it is assumed that the amount of precipitation in the month before cropping is sufficient to maintain the soil moisture, the effective precipitation of last month can be manually added to the first month of the cropping. However, it requires proper calculation to equal the ratio of the next month;
- deep percolation of precipitation (mm) is the amount of precipitation that deep percolates from the root zone into deeper layers. This part of the precipitation is not effective, because it is no longer available to the plant.;
- deep percolation cannot exceed the precipitation minus the effective precipitation together with runoff (calculated from field irrigation efficiency);
- your estimate of external water that deep percolates during conveyance is the water loss from conveyance structure. For example, the deep percolation from unlined canals can lead to significant water loss. The estimate cannot exceed the total amount of water loss calculated from estimated conveyance efficiency for external water (Project information). For example, if your estimation of conveyance efficiency for external water is 80 percentage, this value cannot exceed the indicated 20percentage water loss (100 – estimated conveyance efficiency for external water);
- your estimate of delivered water that deep percolates on-farm is the water loss on the farm due to irrigation inefficiency. The estimate cannot exceed the proportional estimated field irrigation efficiency to cropped area size and the indicated and the proportional seepage for paddy rice to the cropped area size.

*Special Agronomic Requirements (mm):*

- the special agronomic requirement refers to any additional irrigation water need beyond the crop water requirement. Such special requirement can be the pre-wetting of soil to prepare seedbeds, pre-irrigation of paddies, etc.;
- special agronomic requirement must be inserted only in the corresponding months, when the additional water need appears.

*Crop Yields and Values:*

- typical yield is the average yield productivity of crop in tons/ha;
- farmgate selling price refers to the average trigger price received by farmers for 1 ton of harvested crop.

*Drainage and Salinity information:*

- the table includes variety of water quality-related information, whereas average salinity of the irrigation water is already defined in the project information section;
- the average salinity of the drainage outflow from command area (dS/m) requires time-series of salinity measurement. It is recommended to conduct measurement during or right after irrigation event;
- the average annual depth to the shallow water table (m) requires information about the level of groundwater table or subsurface water. This information has utmost importance to understand the possible cause of salinity, therefore, it should be monitored throughout the year in terms of both frequency and duration;
- the change in the shallow water table depth over the last 5 years, (-) decrease, (+) increase (m) is the deviation from the average depth to both positive and negative

depth. If the shallow groundwater table frequently reaches the root zone, it can cause salinity, therefore, it should be monitored throughout the year in terms of both frequency and duration;

- the amount of oxygen equivalents consumed in the chemical oxidation of organic matter. It is an indicator of organic matter of the water. The chemical oxygen demand of the irrigation water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information must be carefully evaluated;
- the amount of oxygen equivalents consumed in the chemical oxidation of organic matter. It is an indicator of organic matter of the water. The chemical oxygen demand of the drainage water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information must be carefully evaluated;
- the amount of oxygen consumed by microorganism to decompose organic matter. The biological oxygen demand of the irrigation water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information must be carefully evaluated;
- the amount of oxygen consumed by microorganism to decompose organic matter. The biological oxygen demand of the drainage water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information must be carefully evaluated.

*Deficit irrigation strategy (percentage):*

- deficit (or regulated deficit) irrigation is a method to optimize crop water productivity by applying irrigation water during certain growth stages. Deficit irrigation means that the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season;
- some of the irrigation scheme hit by water scarcity applied regulated deficit irrigation, whereas crops are exposed to certain level of water stress temporally or throughout the season, which do not entail any/significant yield loss;
- in case of deficit irrigation, only a certain level of crop water requirement is satisfied. The percentage, frequency and duration of regulated deficit irrigation is defined by the management;
- the table requires the rate of satisfied water requirement in percentage. Only those months must be filled, through which the management applies deficit irrigation.

BOX A.3.3

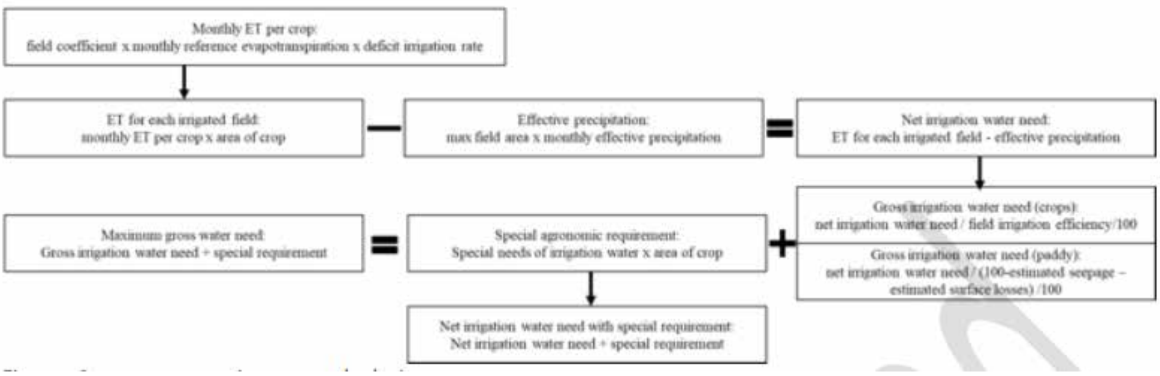
**Deficit irrigation strategy**

Deficit irrigation strategy must always be considered as a management strategy. To create such an irrigation plan, the management must know the crop water requirement and understand the yield response to water stress. The regulated deficit must be driven by the demand side and not by the supply side. If management does not know the crop water requirement, thus the water deficit occurs by insufficient knowledge and poor irrigation practices, it cannot be considered a deficit irrigation strategy.

*Source: Authors' own elaboration.*

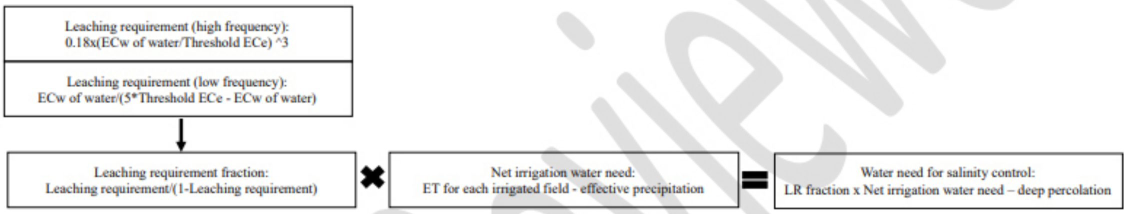
The following stepwise calculation schemes explain how interim and final results are obtained. The charts include the considered equations in workflow.

**Crop water requirement calculation**



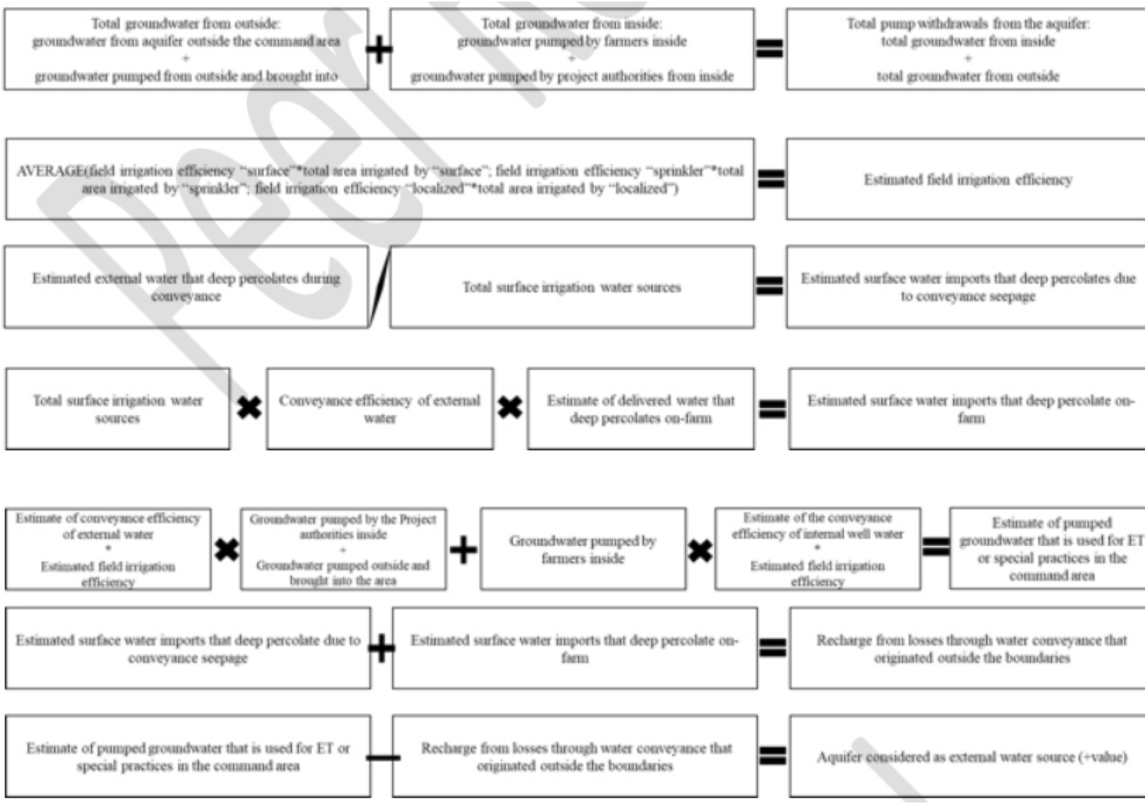

*Source: Authors' own elaboration based on RAP v1 User's manual.*

**Water need for salinity control**



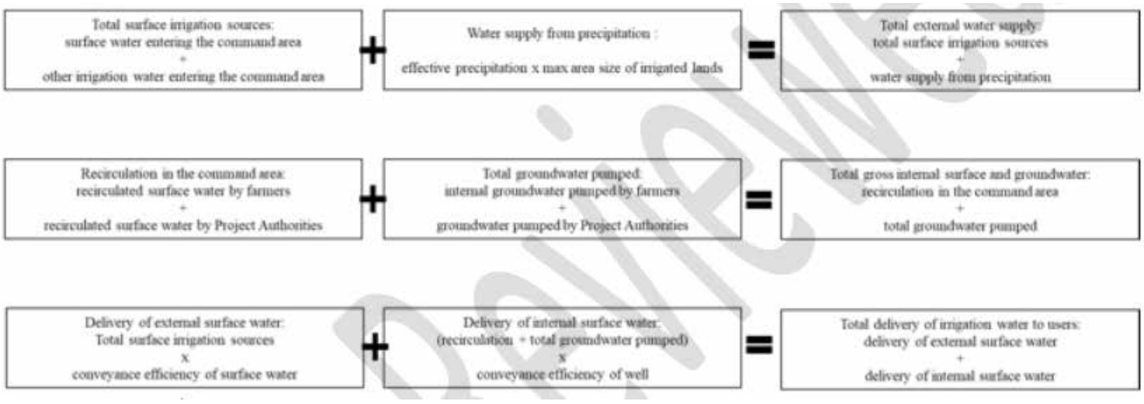

*Source: Authors' own elaboration based on RAP v1 User's manual.*

**Groundwater storage and recharge**




*Source: Authors' own elaboration based on RAP v1 User's manual.*

**Water supply**

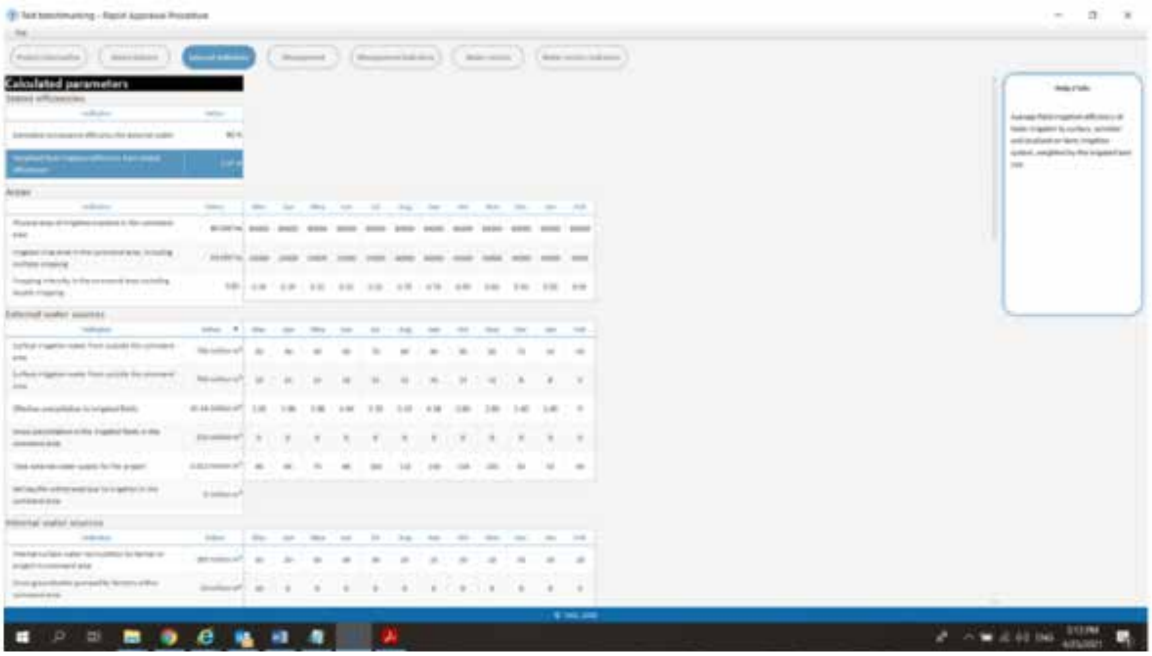



*Source: Authors' own elaboration based on RAP v1 User's manual.*

## A.3.5.3. Water balance and external indicators

The results of Water Balance chapter are summarized in the External indicators. The External indicators express the hydrological performance. If the minimum obligatory information are filled in the input page, the External Indicators button is activated and results are displayed.

FIGURE A.3.20
**Main view of the External indicators window**




*Source: Screenshot of RAP v1 software*

The External Indicator page includes the summary of calculated parameters, the external indicators and environmental indicators. The calculated parameters are the sub-results and summary of input values. The external indicators are the performance indicators, based on which the appraisal can be interpreted. The environmental indicators are the transferred values from the input sheets, which should be interpreted based on the national requirements, local particularities and the vulnerability to changes in water quality.

TABLE A.3.2
**Calculated parameters of External indicators**

| Indicator | Units | Definition |
|---|---|---|
| | | **Calculated parameters** |
| estimated conveyance efficiency for external water | percentage | • Transferred value from "Data input and calculation scheme":<br>• ratio of delivered external water over external supplied water in percentage;<br>• the ratio expresses the water loss during transportation, e.g. Leaking pipe or leakage at joints are considered water loss;<br>• conveyance efficiency is applied to the infrastructure from water intake until offtakes (deliveries) on the farm. |
| weighted field irrigation efficiency from stated efficiencies | percentage | Transferred value from "Data input and calculation scheme":<br>• average field irrigation efficiency of fields irrigated by surface, sprinkler and localized on-farm irrigation system, weighted by the irrigated land size. |
| physical area of irrigated cropland in the command area | ha | Transferred value from "Data input and calculation scheme":<br>• command area is the net cropped and irrigation area available in a year, regardless the number of crops produced in sequence;<br>• in case of double cropping (multiple seasons in one calendar year), the command area should not be calculated twice. |
| irrigated crop area in the command area, including multiple cropping | ha | Transferred value from "Data input and calculation scheme":<br>• cropped area size including double cropping;<br>• in case of land is used in multiple seasons, the accumulated land size is displayed, e.g. if 200 ha land is cropped two times per year, the irrigated crop area is 400 ha in the year. |
| cropping intensity in the command area including double cropping | percentage | The ratio of irrigated crop area and physical area of irrigation cropland. It shows the utilization rate of the area, the higher the intensity the more utilized the area. Cropping intensity can be increased by double-cropping or intercropping:<br>• if 100 percent of available command area is cropped and/or double-cropped, the value is to be =>100 percent;<br>• if less than 100 percent of available command area is cropped and double-cropped areas still do not make up the 100 percent of the available command area, the value is to be =<100 percent. |
| surface irrigation water from outside the command area | million $m^3$ | The indicator expresses the gross precipitation received by the command area equipped with irrigation facilities, calculated as the following:<br>A*B<br>A: Total precipitation<br>B: Command area with irrigation facilities |
| effective precipitation to irrigated fields | million $m^3$ | The indicator expresses the effective part of precipitation in the cropped area. This indicator is different from the gross precipitation in the irrigated fields, because it measures only the effective precipitation in the cropped area. Cropped area does not necessarily correspond to the command area, as farmers can decide to set aside a portion of land. The indicator considers only the potential fraction of precipitation utilized by the crops in the water year, calculated as the following:<br>A*B<br>A: Maximum field area of crops<br>B: Effective precipitation |
| net aquifer withdrawal due to irrigation in the command area | million $m^3$ | The indicator expresses the difference between pumped groundwater used for irrigation and recharge from water conveyance losses. The aquifer recharge from conveyance loss is expected to be low, as pipes have normally very low water loss. However, if earth reservoir or water tank exist in the irrigation scheme, it can result substantial recharge. The indicator is calculated only if the groundwater recharge is sufficient to supply water for irrigation, calculated as the following:<br>A – B<br>IF(A>B) → A-B; otherwise=0<br>A: Estimate of pumped groundwater used for ET or special practices<br>B. Recharge from losses through water conveyance outside the boundaries |

| Required data | Unit | Time-step |
|---|---|---|
| total external water supply for the project | million $m^3$ | The indicator expresses the total amount of water from outside of the irrigation scheme, and the gross precipitation in the area, calculated as the following:<br>A+B+C<br>A: Surface irrigation water from outside the command area<br>B: Gross precipitation in the irrigated fields in the command area<br>C: Net Aquifer withdrawal due to the irrigation in the command area |
| total external irrigation supply for the project | million $m^3$ | The indicator expresses the total amount of irrigation water from outside of the irrigation scheme. Unlike the total external water supply, this indicator does not include the precipitation, so it indicated the sufficiency of water supply without rain, calculated as the following:<br>A+B<br>A: Surface irrigation water from outside the command area<br>B: Net Aquifer withdrawal due to the irrigation in the command area |
| internal surface water recirculation by farmer or project in command area | million $m^3$ | The indicator expresses the total recirculated water by farmers and project authorities, calculated as the following:<br>A+B<br>A: Direct farmer usage of surface water inside the command area/recirculated<br>B: Project Authority usage of surface water inside command area/recirculated |
| internal surface water recirculation by farmer or project in command area | million $m^3$ | The indicator expresses the total recirculated water by farmers and project authorities, calculated as the following:<br>A+B<br>A: Direct farmer usage of surface water inside the command area/recirculated<br>B: Project Authority usage of surface water inside command area/recirculated |
| gross groundwater pumped by farmers within command area | million $m^3$ | Transferred value from "Data input and calculation scheme". It is equal to the groundwater pumped by farmers inside the command area. |
| groundwater pumped by project authorities and applied to the command area | million $m^3$ | Transferred value from "Data input and calculation scheme". It is equal to the groundwater pumped by the project authorities inside the command area. |
| total groundwater pumped and dedicated to the command area | million $m^3$ | The indicator expresses the total groundwater pumped by farmers and project authorities, calculated as the following:<br>A+B<br>A: Gross groundwater pumped by farmers within command area<br>B: Groundwater pumped by project authorities and applied to the command area |
| groundwater pumped by project authorities and applied to the command area, minus net groundwater withdrawal | million $m^3$ | he indicator expresses the difference of total groundwater pumped by project authorities and net aquifer contribution, calculated as the following:<br>A – B<br>A: Groundwater pumped by project authorities and applied to the command area<br>B: Net aquifer withdrawal due to irrigation in the command area |
| estimated total gross internal surface water and groundwater | percentage | Transferred value from "Data input and calculation scheme":<br>• this estimated ratio of delivered internal water over internal supplied water in percentage;<br>• the ratio expresses the water loss during transportation. E.g. leaking pipe or offtakes are considered as water loss;<br>• conveyance efficiency concerns the infrastructure from water intake until offtakes (deliveries) on the farm. |

| Required data | Unit | Time-step |
|---|---|---|
| gross total annual volume of project authority irrigation supply | million $m^3$ | The indicator expresses the total amount of external and internal water supplied – but not yet delivered – by the project authority to the users including surface water, groundwater and recirculated water, calculated as the following:<br>A+B+C<br>A: Groundwater pumped by project authorities and applied to the command area, minus net groundwater withdrawal<br>B: Surface irrigation water from outside the command area<br>C: Project Authority usage of surface water inside command area |
| delivery of external surface irrigation water to users - using stated conveyance efficiency | million $m^3$ | The indicator expresses the delivered external water amount to users through correcting total supplied external water by conveyance efficiency, calculated as the following:<br>A*B<br>A: Surface irrigation water from outside the command area<br>B: Conveyance efficiency for external water |
| all other irrigation water to users | million $m^3$ | he indicator expresses all other delivered irrigation water to users including internal water and groundwater (recirculated and groundwater) corrected by conveyance efficiency for internal water, calculated as the following:<br>A+B+(C*D)+(E*F)+(G*D)<br>A: Gross groundwater pumped by farmers within command area<br>B: Direct farmer usage of surface water inside the command area<br>C: Project Authority usage of surface water inside command area<br>D: Conveyance efficiency for internal recirculation<br>E: Groundwater pumped from outside the command area<br>F: Conveyance efficiency for external water<br>G: Groundwater pumped inside the command area |
| total irrigation water deliveries to users, reduced for conveyance efficiencies | million $m^3$ | The indicator expresses total delivered irrigation water including external and internal water sources excluding conveyance losses, calculated as the following:<br>A+B<br>A: Delivery of external surface irrigation water to users corrected by conveyance efficiency<br>B: All other irrigation water to users |
| total irrigation water (internal plus external) as intermediate value | million $m^3$ | The indicator expresses total irrigation water supply external and internal water sources, calculated as the following:<br>A+B<br>A: Estimated total gross internal surface water and groundwater<br>B: Total external irrigation supply for the project |
| overall conveyance efficiency of project authority delivered water | percentage | The indicator expresses the aggregated conveyance efficiency of both external and internal water at system level |
| average delivered flow in the pipe system | $m^3/s$ | Transferred value from “Data input and calculation scheme”:<br>• the average discharge conveyed through the conveyance system during an average irrigation event;<br>• averaged delivered flow can differ from the design discharge defined by the designer. |
| design flow in the pipe system | $m^3/s$ | Transferred value from “Data input and calculation scheme”:<br>• the design discharged defined during the design and implementation phase of irrigation system. |
| ETc of irrigated fields in the command area | million $m^3$ | The indicator expresses the total ETc-based irrigation requirement of the cropped command area, not considering effective precipitation. |
| ETc of irrigation water in the command area | million $m^3$ | The indicator expresses the total ETc-based irrigation requirement of the cropped command area reduced by the effective precipitation. |
| irrigation water needed for salinity control | million $m^3$ | The indicator expresses the total irrigation water need for leaching requirement to control salinity based on salinity of irrigation water and threshold of crop salt tolerance in the cropped command area. |

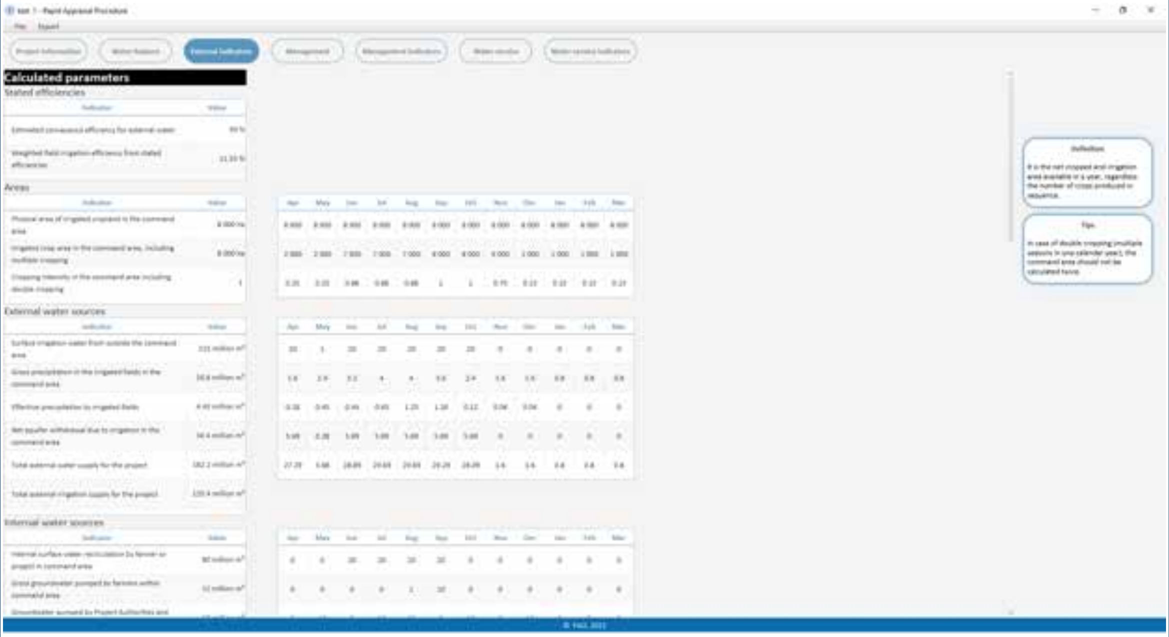
| Required data | Unit | Time-step |
|---|---|---|
| irrigation water needed for special practices | million $m^3$ | The indicator expresses the total irrigation water need for special practices in the cropped command area. |
| total net irrigation water requirements | million $m^3$ | The indicator expresses the total irrigation water need reduced by the effective precipitation, calculated as the following:<br>A+B+C<br>A: ET of irrigation water in the command area<br>B: Irrigation water needed for salinity control<br>C: Irrigation water needed for special practices |
| | | **External Indicators** |
| peak net irrigation requirement for field, including any special requirements | $m^3/s$ | The indicator expresses the required aggregated discharge in peak water requirement in the cropped command area. |
| design discharge of irrigation water flows per hectare | l/s | The indicator expresses the required discharge in peak water requirement per hectare. |
| relative water supply for the irrigated part of the command area (RWS) | none | Ratio of total external water supply of the project over total net irrigation water requirement. The net irrigation water requirement includes ET-based water requirement, water requirement for special practices and water requirement for salinity control, reduced by effective precipitation |
| annual command area irrigation efficiency (ACAIE) | percentage | Rate of total net irrigation water requirement (including ET-based water requirement, water requirement for special practices and water requirement for salinity control, reduced by effective precipitation) over surface irrigation water from outside the command area and net aquifer withdrawal:<br>• the indicator matches the effective water supply from outside the command area and the net irrigation requirement. However, this indicator is not reduced by the conveyance losses. Therefore, it can be considered a baseline value for optimal conveyance conditions;<br>• the larger the deviation from 100 percent the larger the imbalance. Values close to 100 percent indicates the better performance. |
| field irrigation efficiency (FIE) | percentage | Rate of total net irrigation water requirement (including ET-based water requirement, water requirement for special practices and water requirement for salinity control, reduced by effective precipitation) and total delivered water (external and internal surface and groundwater resources corrected by conveyance efficiency):<br>• the indicator expresses the sufficiency of delivered water amount to meet net irrigation water requirement that is reduced by effective precipitation;<br>• the indicator is dynamic. If water oversupply occurs, the total net irrigation water requirement is measured over the total delivered water. If water scarcity occurs, the total delivered water is measured over total net irrigation water requirement. Negative sign (-) indicates water scarcity, while positive value indicates water oversupply or overall balance (100percentage);<br>• the larger the deviation from 100 percent the larger the imbalance. Values close to 100 percent indicates the better performance. |
| relative actual flow (RAF) | None | The ratio of average delivered flow in the pipe system over the required discharge for in case of peak net irrigation requirement for field:<br>• the ratio shows the balance between maximum required discharge and average supplied discharge in case of continuous flow;<br>• the ratio matches the requirement with the actual supply, thus pinpointing the sufficiency of average discharge to meet required discharge;<br>• this ratio is a benchmarking value to be compared with Relative System Capacity (RAF). It shows the difference between actual and design flow. The larger the difference, the larger the decline in performance. |

| Required data | Unit | Time-step |
|---|---|---|
| relative system capacity (RSC) | None | • The ratio design flow in the pipe system over the required discharge for in case of peak net irrigation requirement for field:<br>• the ratio shows the balance between maximum required discharge and design discharge in case of continuous flow;<br>• the ratio matches the requirement with the design capacity, thus pinpointing the potential capacity gaps of the default system design. |
| peak gross irrigation requirement, including all inefficiencies | $m^3/s$ | The indicator expresses the required aggregated discharge including the expected conveyance losses. |
| total annual value of agricultural production (TAVAP) | USD | • The indicator expresses the total generated revenue of agricultural production in the command area in the given year. |
| unit annual value of agricultural production (UAVAP) | USD/ ha | • The indicator expresses the average revenue generation per hectare in the given year. |
| | | **Environmental indicators** |
| average salinity of the irrigation supply | dS/m | Transferred value from "Data input and calculation scheme":<br>• average value of electrical conductivity of irrigation water during typical irrigation event;<br>• the value must be determined in due time of irrigation. If historical data is available, the most typical value must be selected during the most frequent irrigation/cropping period;<br>• the calculation assumes good to excellent quality of water. It is not likely that ECw of irrigation water is higher than the threshold of crop tolerance. This must be taken into consideration while defining ECw;<br>• the indicator must be assessed in the context of the crop salt tolerance, the water supply amount, the climate and soil type. |
| average salinity of the drainage water | mgm/ liter | Transferred value from "Data input and calculation scheme":<br>• the Biological Oxygen Demand of the irrigation water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information has utmost importance;<br>• the BOD value must be assessed in the context of the national regulations on water quality. |
| average BOD of the drainage water (biological) | mgm/ liter | Transferred value from "Data input and calculation scheme":<br>• the Biological Oxygen Demand of the drainage water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information has utmost importance;<br>• the BOD value must be assessed in the context of the national regulations on water quality. |
| average COD of the irrigation supply (chemical) | mgm/ liter | Transferred value from "Data input and calculation scheme":<br>• the Chemical Oxygen Demand of the irrigation water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information has utmost importance;<br>• the COD value must be assessed in the context of the national regulations on water quality. |
| average COD of the drainage water (chemical) | mgm/ liter | Transferred value from "Data input and calculation scheme":<br>• the Chemical Oxygen Demand of the drainage water requires water quality measurement. In particular, if the irrigation scheme applies reused water, the information has utmost importance;<br>• the COD value must be assessed in the context of the national regulations on water quality. |
| average depth to the shallow water table | m | Transferred value from "Data input and calculation scheme":<br>• the Average annual depth to the shallow water table (m) requires information about the level of groundwater table or subsurface water. This information has utmost importance to understand the possible cause of salinity, therefore, it should be monitored throughout the year in terms of both frequency and duration. |

| Required data | Unit | Time-step |
|---|---|---|
| change in shallow water table depth over last 5 years | m | Transferred value from "Data input and calculation scheme":<br>• the Change in the shallow water table depth over the last 5 years, (-) decrease, (+) increase (m) is the deviation from the average depth to both positive and negative depth. If the shallow groundwater table frequently reaches the rootzone, it can cause salinity, therefore, it should be monitored throughout the year in terms of both frequency and duration. |

Analysis of aggregated annual indicators would be misleading as off-season water supply compensates the water deficit in critical vegetation period. To better understand and appraise the indicators, the results are displayed in monthly breakdown.

FIGURE A.3.21
**View of disaggregated results of the External indicators**




*Source: Screenshot of RAP v1 software*

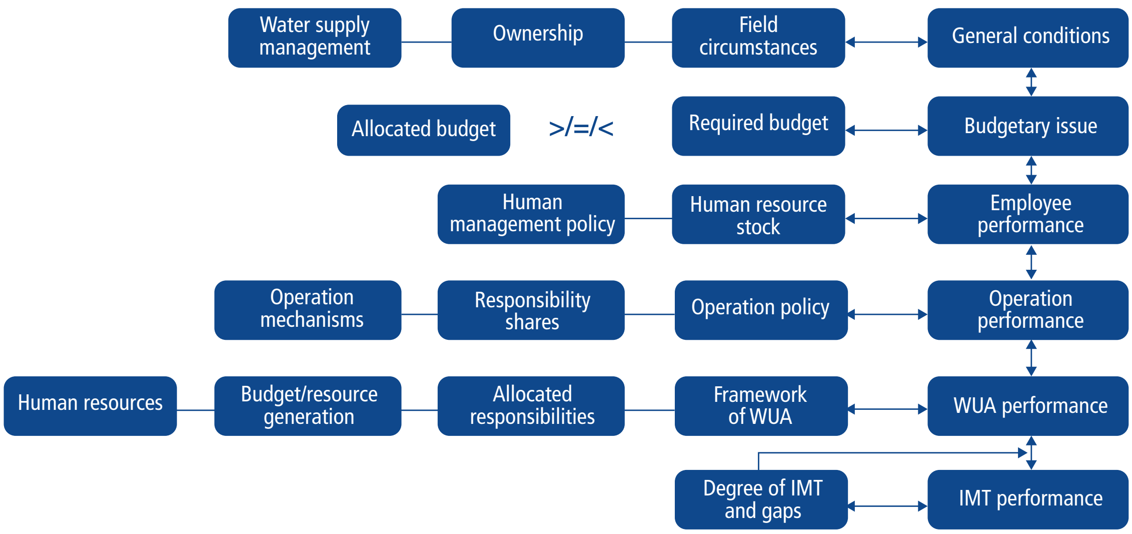
### A.3.5.4 Management

The management chapter aims at introducing the institutional setting of the irrigation scheme layered into two interdependent management levels:

1. Project management: the sub-chapter refers to the authority level of public investment in irrigation system construction, implementation, development and operation and maintenance. Usually, project management is assigned to state authorities that are responsible for overall management of the "project", whereas project indicates the establishment, operation and maintenance, and development of public irrigation scheme.
2. WUA: the sub-chapter refers to the co-management of the irrigation system, whereas farmers or farmers' representatives are involved into management. The WUA is considered as autonomous authority but working closely with or complementing the project authority.

The chapter structure differs from the Water Balance chapter, as it provides a "catchall" list of different management perspectives. The list of input data serves as systematic stocktaking of relevant information describing and characterizing the efficiency of institutional management.

FIGURE A.3.22
**Flowchart of the Management chapter**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20Manual.pdf.*

### *A.3.5.4.1 Preparation of the input file*

The management chapter builds on the characteristics and information related institutional managements including general institutional settings, budgetary issues, employment, operation performance, WUA performance and degree of irrigation management transfer. It is recommended to share the data requirement and survey with relevant institutions in advance. This can facilitate the data collection before arriving to the management office. The chapter requires secondary data collection, screening official records, interviews and expert observation.

TABLE A.3.3
**Data input support of Management chapter**

| Required data | Unit | Time-step | Data source/ Supporting institute | Methodology |
|---|---|---|---|---|
| | | **General Project Conditions/Management** | | |
| average net farm size | ha | annual average | project office | secondary data, field observation, interview |
| number of water users | - | annual average | project office | secondary data, field observation, interview |
| typical field size | ha | annual average | project office | secondary data, field observation, interview |
| number of offtakes (hydrants) that are physically operated by paid employees | - | - | project office | secondary data, field observation, interview |

| Required data | Unit | Time-step | Data source/ Supporting institute | Methodology |
|---|---|---|---|---|
| land consolidation exists on percentage of the project area | percentage | - | project office | secondary data, field observation, interview |
| share of drinking water in pumped water supplies in the project area | percentage | - | project office | secondary data, field observation, interview |
| ownership of land | percentage | - | project office | secondary data, field observation, interview |
| field irrigation description | percentage | - | - | field observation |
| | | **Water supply/Management** | | |
| water source | - | - | project office | secondary data, field observation, interview |
| live Storage Capacity of reservoir | million $m^3$ | annual | project office | secondary data, field observation, interview |
| times per year when majority of system is shut down without water | - | annual | project office | secondary data, field observation, interview |
| typical total annual duration of pressurized system shutdown | days | annual average | project office | secondary data, field observation, interview |
| volume of gross irrigation water officially allocated to the project | million $m^3$ | annual | project office | secondary data, field observation, interview |
| maximum flow rate officially allocated to the project | $m^3/s$ | - | project office | secondary data, field observation, interview |
| | | **Budgetary background/Management** | | |
| land ownership | - | - | project office | secondary data, interview |
| annual actual budget | local currency/ year | 5 years average | project office | secondary data, interview |
| budget sources | percentage | 5 years average | project office | secondary data, interview |
| annual required budget | local currency/ year | 5 years average | project office | secondary data, interview |
| | | **Employees/Management** | | |
| number of employees | - | annual average | project office | secondary data, interview |
| average years a typical professional employee works for the project | - | annual average | project office | secondary data, interview |
| operation staff number in the field | - | annual average | project office | secondary data, interview |
| salaries | local currency/ year | 5 years average | project office | secondary data, interview |
| visitor's estimate of the adequacy of the actual dollars and in-kind services that is available (from all sources) to sustain adequate O&M with the present mode of operation | percentage | - | - | field observation |

| Required data | Unit | Time-step | Data source/ Supporting institute | Methodology |
|---|---|---|---|---|
| | | **Human resource management indicators** | | |
| frequency and adequacy of training of operators and middle managers | score | - | - | field observation |
| availability of written performance rules | score | - | - | field observation |
| power of employees to make decisions | score | - | - | field observation |
| ability of the project to dismiss employees with cause | score | - | - | field observation |
| rewards for exemplary service | score | - | - | field observation |
| | | **Project operation** | | |
| umbrella water user association | score | - | - | field observation, interview |
| annual operation Policies | - | - | project office | secondary data, field observation, interview |
| daily operation policies | - | - | project office | secondary data, field observation, interview |
| how are flow changes in the pipe system computed and adjusted? | - | - | project office | secondary data, field observation, interview |
| what daily or weekly instructions for field persons does the office give? | - | - | project office | secondary data, field observation, interview |
| Computers (either central or on-site) used for operation | score | - | - | field observation |
| computers used for billing and record management | score | - | - | field observation |
| | | **Water delivery service** | | |
| stated water delivery service that pump station provides to the pipe system (public authority perspective) | score | - | project office | interview |
| stated water delivery service provided for sub-pipelines operated by a paid employee (public authority perspective) | score | - | project office | interview |
| stated water delivery service received by individual units - fields and farms (public authority perspective) | score | - | project office | interview |
| | | **General WUA conditions** | | |
| project area for which WUA meet the following descriptions | percentage | - | WUA, project office | secondary data, interview |
| WUA area | ha | - | WUA, project office | secondary data, interview |

| Required data | Unit | Time-step | Data source/ Supporting institute | Methodology |
|---|---|---|---|---|
| WUA age | years | - | WUA, project office | secondary data, interview |
| functions of a typical WUA | - | - | WUA, project office | secondary data, interview |
| are there written rules in the WUA regarding proper behavior of farmers and employees? | - | - | WUA, project office | field observation, interview |
| number of fines levied by a typical active WUA in the past year | - | - | WUA, project office | field observation, interview |
| governing board of WUA | - | - | WUA, project office | field observation, interview |
| | | **General WUA conditions** | | |
| annual actual budget | local currency/ year | 5 years average | WUA, project office | secondary data, interview |
| budget sources | percentage | - | WUA, project office | secondary data, interview |
| annual required budget | local currency/ year | 5 years average | WUA, project office | secondary data, interview |
| water charges | - | - | WUA, project office | secondary data, interview |
| fee collection efficiency | percentage | - | WUA, project office | secondary data, interview |
| what group collects the water charges? | - | - | WUA, project office | secondary data, interview |
| basis of water charge and amount of the charge | - | - | WUA, project office | secondary data, interview |
| type of volumetric water charge (volumetric slabs based tariff) | - | - | WUA, project office | secondary data, interview |
| special charge for private well usage | - | - | WUA, project office | secondary data, interview |
| annual value of in-kind services or contributions by water users | local currency/ year | 5 years average | WUA, project office | secondary data, interview |
| frequency of in-kind services | - | - | WUA, project office | secondary data, interview |
| farmers participation in in-kind services | percentage | - | WUA, project office | secondary data, interview, field observation |
| | | **Employees** | | |
| number of employees | - | annual average | WUA, project office | secondary data, interview, field observation |
| average years a typical professional employee works for the project (anticipated) | years | annual average | WUA, project office | secondary data, interview, field observation |
| how many of the operation staff actually work in the field? | - | annual average | WUA, project office | secondary data, interview, field observation |
| salaries | local currency/ year | 5 years average | WUA, project office | secondary data, interview |

| Required data | Unit | Time-step | Data source/ Supporting institute | Methodology |
|---|---|---|---|---|
| | | WUA performance indicators | | |
| actual ability of the strong water user associations to influence real-time water deliveries | score | - | WUA | interview |
| ability of the WUA to rely on effective outside help for enforcement of its rules | score | - | WUA | interview |
| legal basis for the WUA | score | - | WUA | interview |
| financial strength of WUA | score | - | WUA | interview |
| | | Level of Irrigation Management Transfer | | |
| responsibility share of O&M activities | - | - | WUA, farmers | interview, field observation |

#### *A.3.5.4.2 Involved stakeholders*

The chapter can be completed by preliminary investigation and field visit. The majority of the questions rely on secondary data, interview and field visit. The following stakeholders are recommended to be involved:

- project office and scheme management;
- responsible public authority;
- WUA, irrigation associations, farmers' organization etc.

#### *A.3.5.4.3 Requested time*

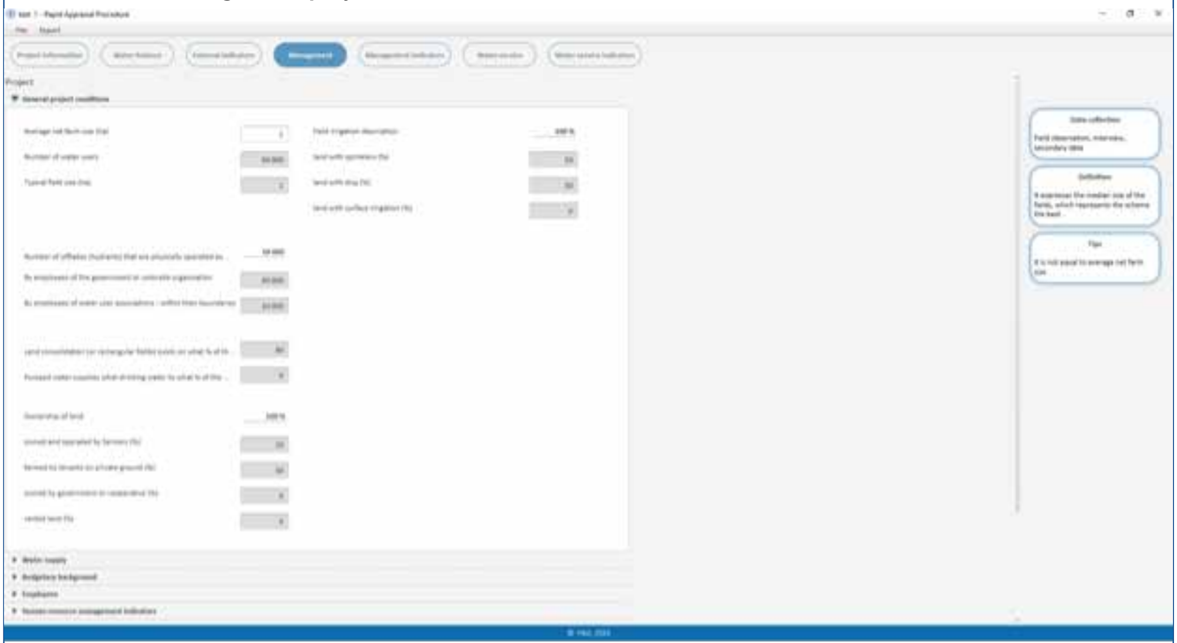
The work can be conducted directly, involving project office, WUA or other relevant authorities. The task should be implemented within not more than one week.

#### *A.3.5.4.4 Data input and calculation scheme*

Recommendations: the input data should be used as structured stocktaking of different parameters about management performance. Therefore, it is recommended to analyse the indicators together with the input data during write-up.

## General project conditions:

FIGURE A.3.23
**Main view of the general project conditions section**



*Source: Screenshot of RAP v1 software*

*Average net farm size (ha):* the net farm size refers to the size of cropped land per land user or any specific characterization of farm under the same management unit (i.e. farmer, household, farmers' collective, etc.)

*Number of water users:* total number of water users in the scheme, limited to agricultural water users.

*Typical field size (ha):* this is not equal to average net farm size. Typical size means the median size of the fields. The size that represents the scheme the best.

*Number of offtakes that are physically operated by paid employees – by employees of the government or umbrella organizations:* offtake refers to the distribution equipment operated under the authority of employees of government/umbrella organizations. For example, if authorities are responsible to divert water from main pipe to branches i.e. through butterfly valves, only these offtakes should be calculated. If authorities are responsible to operate final offtakes, such as hydrants, those should be calculated.

*Number of offtakes that are physically operated by paid employees – by employees of the WUA:* offtake refers to the distribution equipment operated under the authority of employees of WUA. For example, if WUA is responsible to divert water from main pipe to branches i.e. through butterfly valves, only these offtakes should be calculated. If WUA is responsible to operate final offtakes, such as hydrants, those should be calculated.

*Land consolidation existing on certain percentage of the project area:* the ratio of land size over total land area that has undergone any kind of consolidation to rationalize agricultural production.

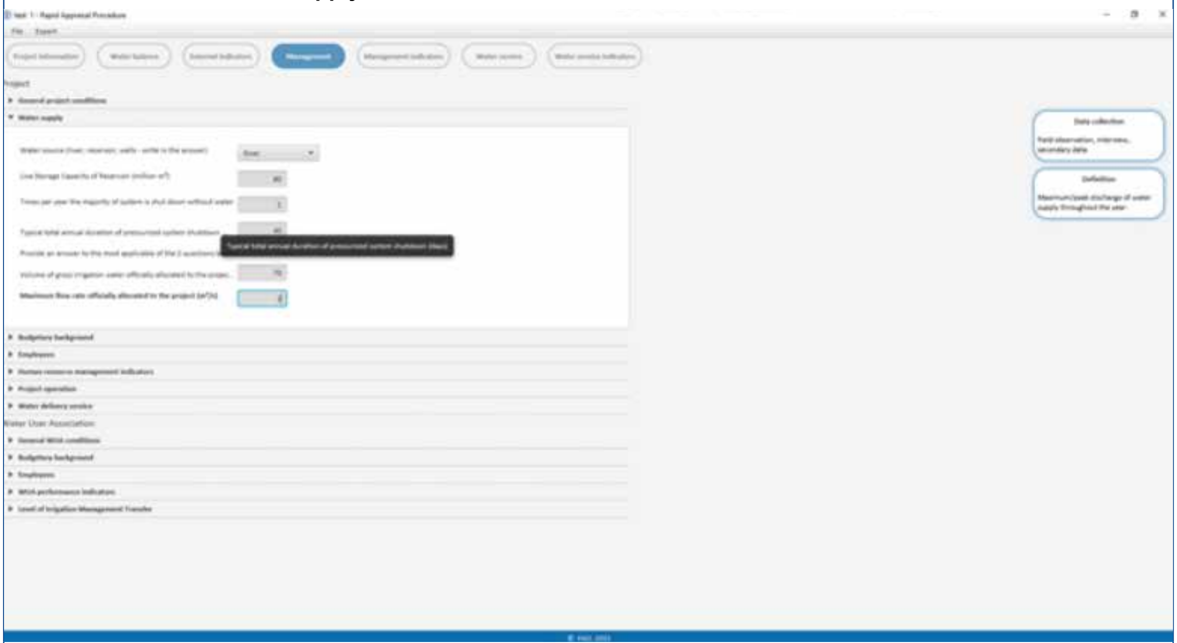
*Pumped water supplies for drinking water (percentage):* ratio of drinking water over total pumped water. This type of drinking water supply is more common in multiple water use systems.

*Ownership of the land (percentage):* share of farmers' land ownership.

*Field irrigation description (percentage):* share of on-farm irrigation systems.

## Water supply:

FIGURE A.3.24
**Main view of the water supply section**



*Source: Screenshot of RAP v1 software*

*Water source:* water source, from where irrigation water is supplied.

*Live storage capacity of reservoir (million m³):* if water is sourced from reservoir, live storage (dynamic) capacity of the reservoir.

*Times/year the majority of system is shut down without water:*

- off-irrigation period including the unintentional system closure (e.g. failure);
- this can indicate the performance flaws; a higher number of occasions might refer to serious performance issues.

*Typical total annual duration of pressurized system shutdown (days):*

- the typical duration of off period in days;
- this must be assessed in the context of the crop water requirement. If the annual duration exceeds the tolerance of crops' water stress, the indicator might be important to be flagged.

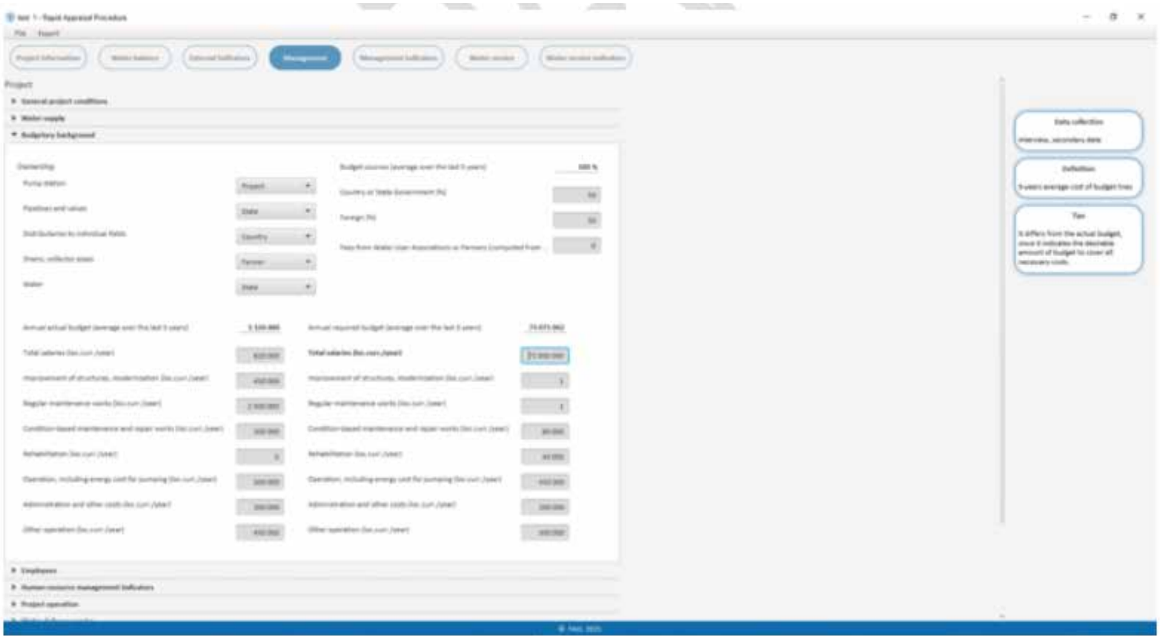
*Volume of gross irrigation water officially allocated to the project per year (million m³):*

- total water supply allocated by the project authority annually;
- this indicator refers back to the calculation of water supply.

*Maximum flow rate officially allocated to the project (m³/s):* maximum/peak discharge of water supply throughout the year.

## Budgetary background:

FIGURE A.3.25
**Main view of the budgetary background section**



*Source: Screenshot of RAP v1 software*

*Ownership:* the ownership of typical system component shared amongst country, state, project or farmers.

*Annual actual budget:*

- 5-years average cost of budget lines;
- if budget accounting has different cost categorization, it is recommended to seek for the most corresponding budget line.

*Budget source:*

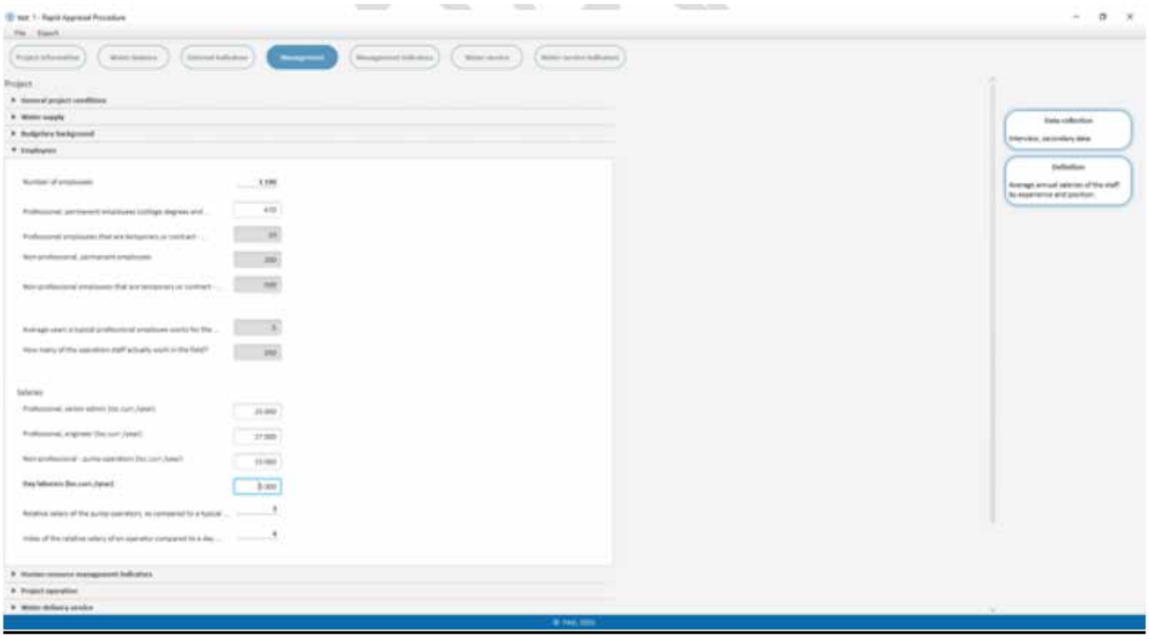
- 5-years average cost of budget lines.
- budget source refers to the total budget of the irrigation scheme that can consist of different sources.

*Annual required budget:*

- 5-years average cost of budget lines;
- the required budget differs from the actual budget. This indicate the desirable amount of budget to cover all necessary costs.

## Employees:

FIGURE A.3.26
Main view of the employees section



Source: Screenshot of RAP v1 software

*Number of employees:* total number of employees distinguished by experience and contract type.

*Average years a typical professional employee works for the project:* the turnover in the staff indicating the average duration of employees working in the project.

*Operation staff actually working in the field:*

- this refers to the staff physically working on the field regardless she/he is professional or non-professional;
- this includes all types of employees.

*Salaries:* average annual salaries of the staff by experience and position.

*Relative salary of the pump operators, as compared to a typical day laborer:* the result is calculated the ratio of the average salary of pump operators and day laborer.

*Index of relative salary of an operator compared to a day laborer:* the indicator assesses the adequacy of salary ratio of pump operators and day laborer. The index calculation applies the following scoring plan:

- 0 (<1) – very poor
- 1 (1-1.5) – poor
- 2 (1.5-2) – medium
- 3 (2-2.5) – good
- 4 (>2.5) – very good

## Human resource management indicators:

FIGURE A.3.27
**Main view of the human resource management indicators section**

*Source: Screenshot of RAP v1 software*

*Frequency and adequacy of training of operators and middle managers:*

- this should include employees at all levels of the distribution system, not only those who work in the office;
- scoring is based on guidance listed under the indicator;
- scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Availability of written performance rules*

- scoring is based on guidance listed under the indicator;
- scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Power of employees to make decisions*

- scoring is based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Ability of the project to dismiss employees with cause*

- scoring is based on guidance listed under the indicator;
- scoring should be based on interviews and field observation;

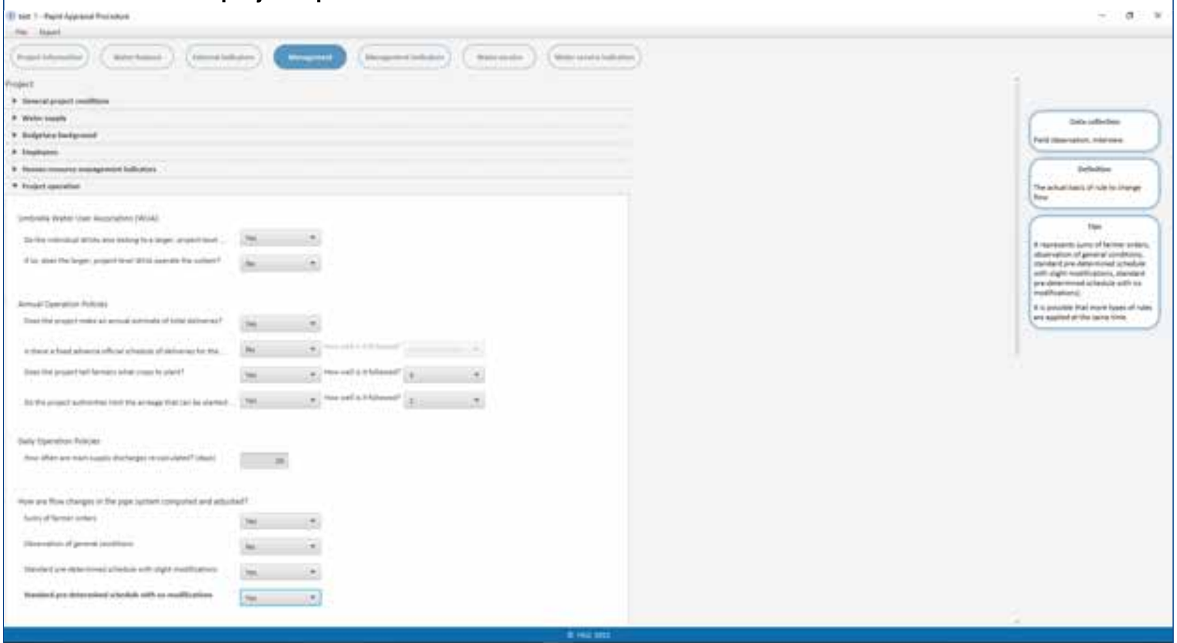
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Rewards for exemplary service*

- scoring is based on guidance listed under the indicator;
- scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Project operation:

FIGURE A.3.28
**Main view of the project operation section**



*Source: Screenshot of RAP v1 software*

*Umbrella water user association – a. individual WUA belonging to larger WUA:* the question refers to the fact if WUA belong to any higher-level WUA that coordinates, oversees, etc. its operation.

*Umbrella water user association – b. individual WUA belonging to larger WUA:* the question should be answered only if the answer to the previous question (a) is "yes".

*Annual operation policies – annual estimate of total deliveries:*

- the question requires information if there is any estimation about the required water amount to be delivered in given year;
- estimate of total deliveries might assume that the water supply is based on water requirement.

*Annual operation policies – fixed advance official schedule:*

- if there is any official schedule established, the question should be answered with "yes". In later question, user should estimate the actual compliance with this rule, whereas 4 is the excellent execution of planned schedule and 0 is the non-compliance with the schedule;

- if there is no official schedule, it is important to understand the principles of water distribution.

*Annual operation policies – crops to plant*: if there is any rule on cropping pattern, the question should be answered with “yes”. In later question, user should estimate the actual compliance with this rule, whereas 4 is the excellent execution of crop selection and 0 is the non-compliance with the crop selection.

*Annual operation policies – limited acreage that can be planted to various crops:* if there is any rule on production limit, the question should be answered with “yes”. In later question, user should estimate the actual compliance with this rule, whereas 4 is the excellent execution of limit and 0 is the non-compliance with the limit.

*Daily operation policies – recalculation of main supply discharge (days):*

- the frequency of recalculation of provided discharge;
- a frequent recalculation might assume a flexible and adjustable water distribution.

*Flow changes in the pipe system computed and adjusted:*

- the actual basis of rule to change flow (sums of farmer orders, observation of general conditions, standard pre-determined schedule with slight modifications, standard pre-determined schedule with no modifications);
- it is possible that more types of rules are applied at the same time.

*Daily or weekly instructions for field persons:*

- the question refers to four dimensions including pump operation, butterfly valves and other distribution devices, flow metering and flow rates at all offtakes;
- if given dimension applies to the irrigation system, the question should be answered with “yes. If the answer is “yes”, successive questions should be further answered;
- the first successive question is the application of the computers to carry-out the task. The question should be answered with “yes” or “no”;
- the second successive question is based on the estimation of the user. User should estimate the actual compliance with this rule, whereas 4 is the excellent execution of the task and 0 is the non-compliance with the established rules.

*Computers used for operation:*

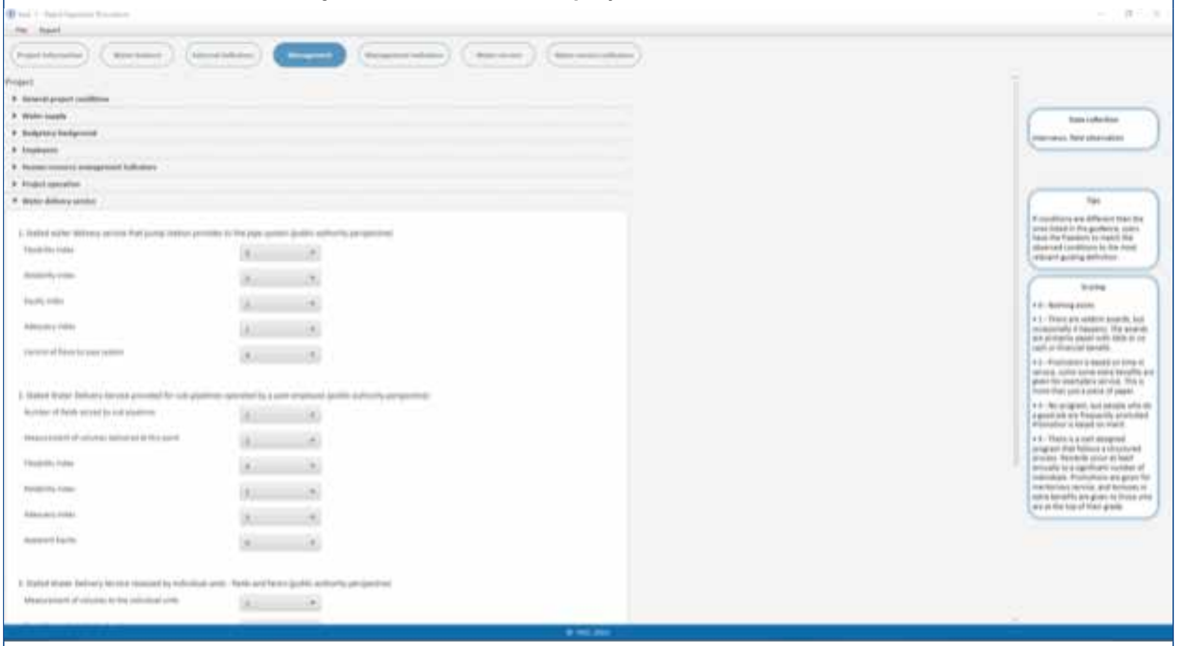
- scoring based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Computers used for billing and record management*

- scoring based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Water delivery service

FIGURE A.3.29
**Main view of water delivery service section in the project block**



*Source: Screenshot of RAP v1 software*

*Stated water delivery service that pump station provides to the pipe system:*

- the composite indicator consists of five sub-indicators: flexibility, reliability, equity, adequacy and control of flow;
- scoring is based on guidance listed under the sub-indicator;
- the sub-indicators should be evaluated considering only the system from pump station to main pipe system, not including the branch-pipes;
- the scoring should be based on the answers of the management/public authorities. "Stated" water delivery service refers to the perception of the management. In order words, how the authorities evaluate the performance of the water delivery along the defined sub-indicators.

*Stated water delivery service provided for sub-pipelines operated by a paid employee:*

- the composite indicator consists of six sub-indicators: number of fields by sub-pipelines (branches), measurement of volumes delivered at this point, flexibility, reliability, equity, and adequacy;
- scoring is based on guidance listed under the sub-indicator;
- the sub-indicators should be evaluated considering only the system at sub-pipelines if it is operated by paid employees;
- the scoring should be based on the answers of the management/public authorities. "Stated" water delivery service refers to the perception of the management. In order words, how the authorities evaluate the performance of the water delivery along the defined sub-indicators.

*Stated water delivery service received by individual units - fields and farms:*

- the composite indicator consists of five sub-indicators: measurement of volumes delivered at this point, flexibility, reliability, equity, and adequacy;
- scoring is based on guidance listed under the sub-indicator;
- the sub-indicators should be evaluated considering only the received service by individuals/farms or farmers;
- the scoring should be based on the answers of the management/public authorities. "Stated" water delivery service refers to the perception of the management. In order words, how the authorities evaluate the performance of the water delivery along the defined sub-indicators.

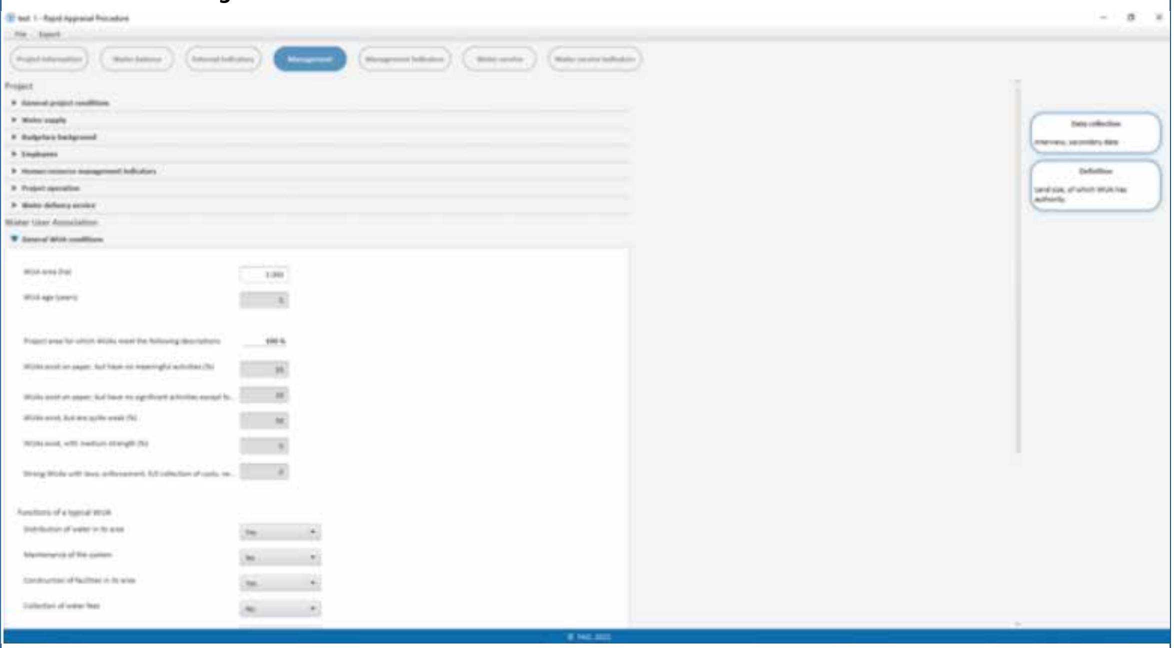
BOX A.3.4
**Water delivery service indicators**

The water delivery service (WDS) indicators are the backbone of the RAP. They are constructed to steer the management towards more service-oriented mindset. The WDS indicators match the evaluation by management with the evaluation of farmers. However, the WDS indicators represent the perception of the stakeholders. For example, farmers perceiving the water distribution equal does not necessarily mean that they receive equal discharge from engineering point of view, or vice-versa. The aim of the WDS is to understand the discord between the management and farmers. Therefore, it is always recommended surveying the management and farmers independently from each other. Otherwise, the two groups might influence each other.

Source:

## General water user association conditions:

FIGURE A.3.30
**Main view of the general WUA conditions section**



*Source: Screenshot of RAP v1 software*

BOX A.3.5

**Assessment of multiple water user association**

If users decide to define the boundaries of the assessed area as per the hydrological boundaries, it might incorporate more WUA at the same time. If more WUA operate in the irrigation scheme, the user can decide to analyse the WUA separately or apply average values.

If WUA are analysed separately, the Internal Indicators must be interpreted per WUA. In this case, the user can decide to create multiple assessment files. The Water Balance and Water Service chapters are filled identically, and the Management chapter is filled as per individual WUA. Even if the user analyses a multi-stakeholder irrigation scheme, the Water Balance and Water Service part should be interpreted as a whole.

Evidence shows that relatively close and/or neighboring WUA have different management mechanisms and performance. Therefore, if average values and analysis are applied to the total area, the Internal Indicators must be interpreted with the assumptions that performance of WUA can significantly differ from one place to another.

*Source: Authors' own elaboration.*

*WUA description per project area:*

- the ratio of descriptive characteristics over total land size should be estimated;
- in particular in large irrigation schemes, the power of WUA might differ, or more WUA can operate. It should be evaluated based on field observation, how effectively WUA/s can operate;
- the entire area must be taken into consideration, thus the total value must reach 100 percent.

*WUA area (ha):* land size, of which WUA has authority.

*WUA age (years):* the current age of the WUA from its establishment.

Functions of the typical WUA:

- each function should be evaluated and answered by "yes" or "no";
- after the identification of the functions, the effectiveness and efficiency of the WUA in the specific role must be assessed to understand the bottlenecks.

*Written rules in the WUA regarding proper behavior of farmers/employees:*

- the question should be answered by "yes" or "no";
- if there is no written rule, it must be assessed whether the lack of rule leads to discord/anomalies or the system is operated smoothly.

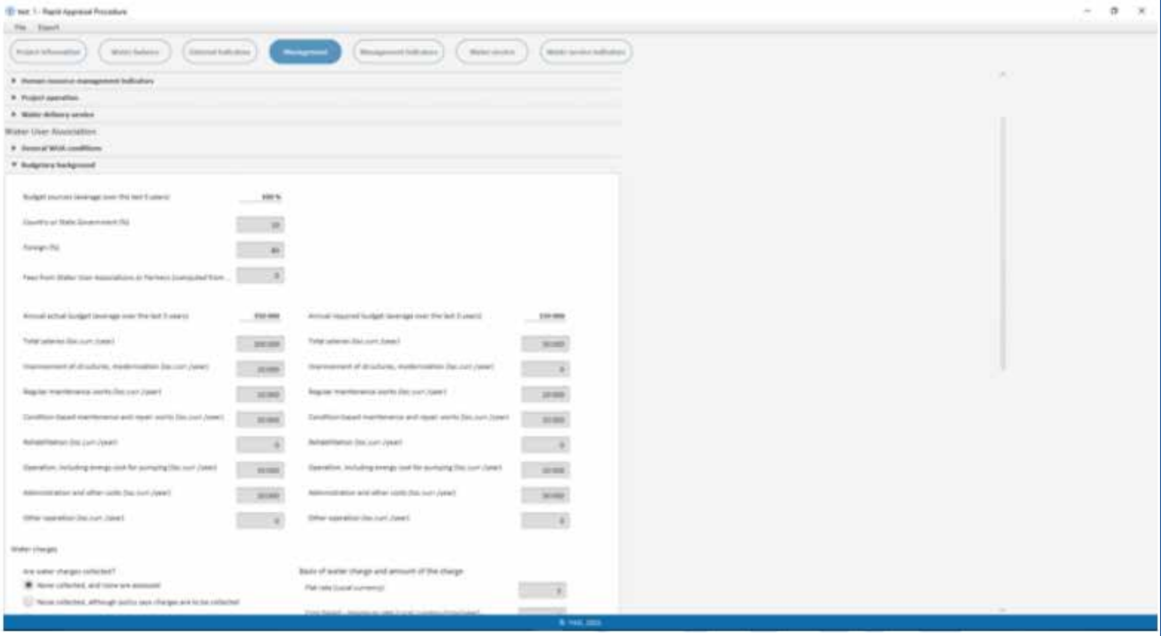
*Number of fines levied by a typical active WUA in the past year:*

- the actual number of fines issued by the WUA, following non-compliance of any of the rules;
- if there is no fine issued, it must be assessed whether it is the result of the full compliance with rules or the lack of capability to enforce compliance.

*Governing Board of WUA:* the question refers to the modality how governing board is set-up, either based on election, appointment or by government.

## Budget:

FIGURE A.3.31
**Main view of the budget section in the WUA block**



*Source: Screenshot of RAP v1 software*

*Annual actual budget:*

- 5-years average cost of budget lines;
- if budget accounting has different cost categorization, it is recommended to seek for most corresponding budget line.

*Budget source*

- 5-years average cost of budget lines;
- budget source refers to the total budget of the irrigation scheme that can consist of different sources.

*Annual required budget*

- 5-years average cost of budget lines
- the required budget differs from the actual budget. This indicate the desirable amount of budget to cover all necessary costs

*Water charges:* the question refers to the modality how water charges are collected.

*Group collection the water charges:* the authorized entity who physically collects the fee from the members.

*Basis of the water charge and the amount of the charge:* the question refers to the defined modality of calculating water fee. Depending on the applied basis, the average water fee should be indicated. If more bases are applied at the same time, each one should be indicated.

*Fee collection efficiency:*

- the actual ratio (percentage) of collected water fee over the expected amount of water fee, if every member paid the defined amount of fee. The ratio is an important indicator of the farmers' satisfaction with the water service and/or ability to pay. If the collection efficiency is low, the reason must be identified and explained;
- estimated total annual water charges refers to the total amount of actually collected water fee in local currency;
- based on the fee collection efficiency and the actually collected fee, the planned budget is calculated automatically. This indicated how the amount of budget that was expected if all members paid the defined fee.

*Special charge for private well usage:* if there is any private well, owned and operated by individuals, the question should be answered related to the water charge, basis of charge (unit) and the collection efficiency.

*Percentage of the total project (including WUA) Operation and Maintenance (O&M) collected as in-kind services, and/or water fees from water users:*

- the ratio of cost spent exclusively on O&M activities (regular maintenance works, condition-based maintenance and repair works, rehabilitation, operation including energy cost for pumping.) from the total collected in-kind service and water fee from farmers;
- in order to obtain results, relevant parts of WUA-related tables must be filled.

*Calculated Indicator of O&M sources:* The index calculation applies the following scoring plan:

- 0 (<40%) – very poor
- 1 (40-60%) – poor
- 2 (60-75%) – medium
- 3 (75-90%) – good
- 4 (>90%)– very good

*Annual value of in-kind services or contributions by water users:*

- in-kind services refer to any non-financial, but commonly agreed contribution to operate and maintain the system. For example, farmers can provide their labor work in constructions instead of paying contribution to contract personals;
- the question should be answered based on documentations and field observations, and estimation should be given on the monetary value of such in-kind service;
- the accuracy of estimation should be accurate as it will be calculated to the overall financial contribution of farmers to manage the irrigation system;
- frequency of the in-kind services should be also estimated;
- the rate of farmers who provide in-kind services should be estimated.

*Rate of the total budget spent on modernization of the irrigation system over O&M costs (project and WUA):*

- this refers to the rate of budget spend on system improvement compared to the O&M costs spend by both project authority and WUA;
- in order to obtain results, relevant parts of WUA-related tables must be filled.

*Calculated indicator of the modernization budget:* The index calculation applies the following scoring plan:

- 0 (<5%) – very poor
- 1 (5-10%) – poor
- 2 (10-15%) – medium
- 3 (15-20%) – good
- 4 (>20%) – very good

*Visitor's estimate of the adequacy of the actual dollars and in-kind services that is available (from all sources) to sustain O&M with the present mode of operation (percentage):*

- estimation of the adequacy of actual fund based on field observation and interview;
- this should be estimated based on the judgment of expert while taking into account the conditions, management, system performance.

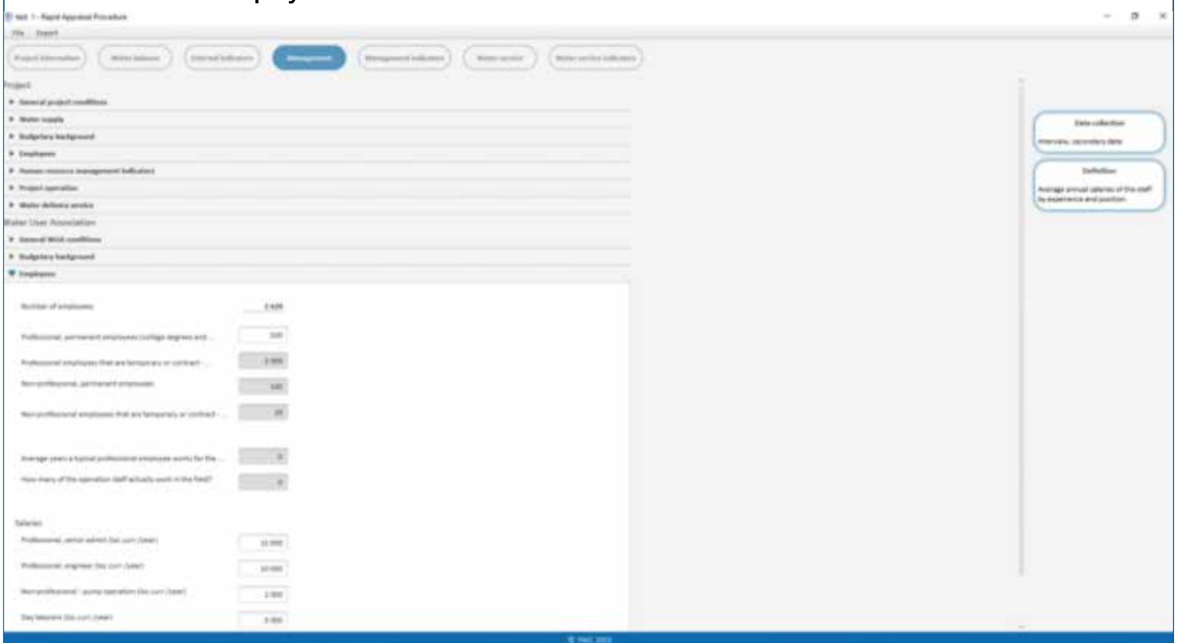
*Calculated Indicator of O&M adequacy:* The index calculation applies the following scoring plan:

- 0 (<40%) – very poor
- 1 (40-60%) – poor
- 2 (60-75%) – medium
- 3 (75-90%) – good
- 4 (>90%)– very good

*Type of volumetric water charge:* the question should be filled only if the basis of water charge is volumetric.

## Employees:

FIGURE A.3.32
**Main view of the employees section in WUA block**



*Source: Screenshot of RAP v1 software*

*Number of employees:* total number of employees distinguished by experience and contract type.

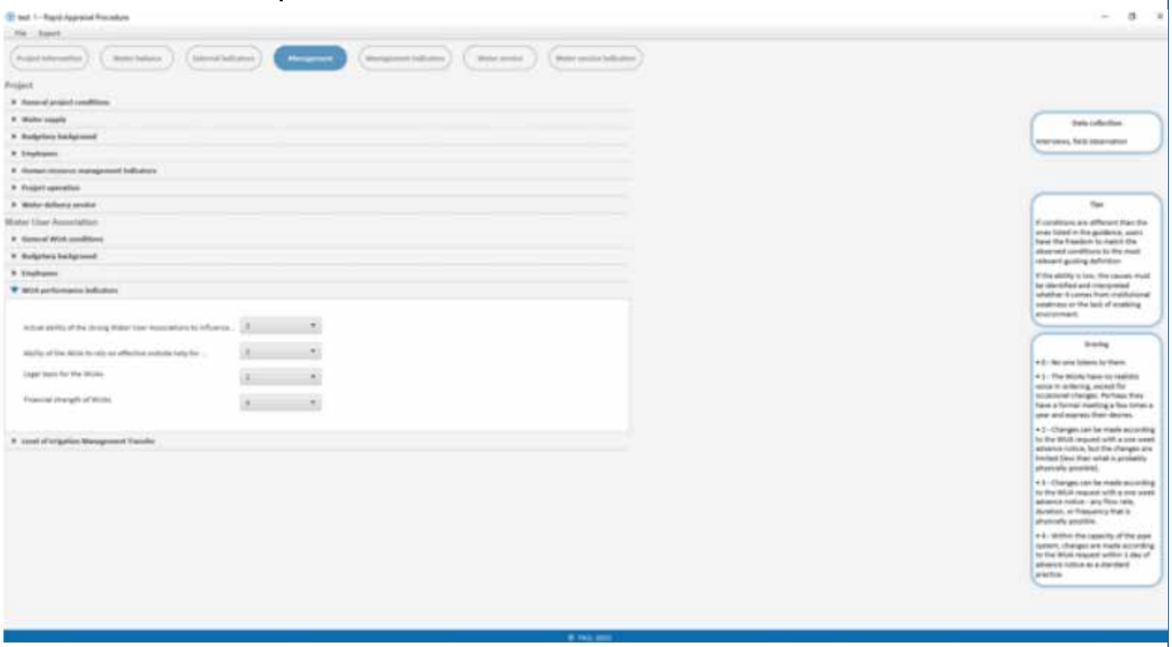
*Average years a typical professional employee works for the project:* the turnover in the staff indicating the average duration of employees working in the project.

*Operation staff actually working in the field:* this refers to the staff physically working on the field regardless she/he is professional or non-professional.

*Salaries:* average annual salaries of the staff by experience and position.

## WUA performance indicators:

FIGURE A.3.33
**Main view of the WUA performance indicators**



*Source: Screenshot of RAP v1 software*

*Ability of the strong WUA to influence real-time water deliveries*

- scoring is based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition;
- if the ability is low, the causes must be identified and interpreted whether it comes from institutional weakness or the lack of enabling environment.

*Ability of the WUA to rely on effective outside help for enforcement of its rules*

- scoring is based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition;
- if the ability is low, the causes must be identified and interpreted whether it is the result of the lack of mechanism or the low capacity of the organization.

*Legal basis for the WUA*

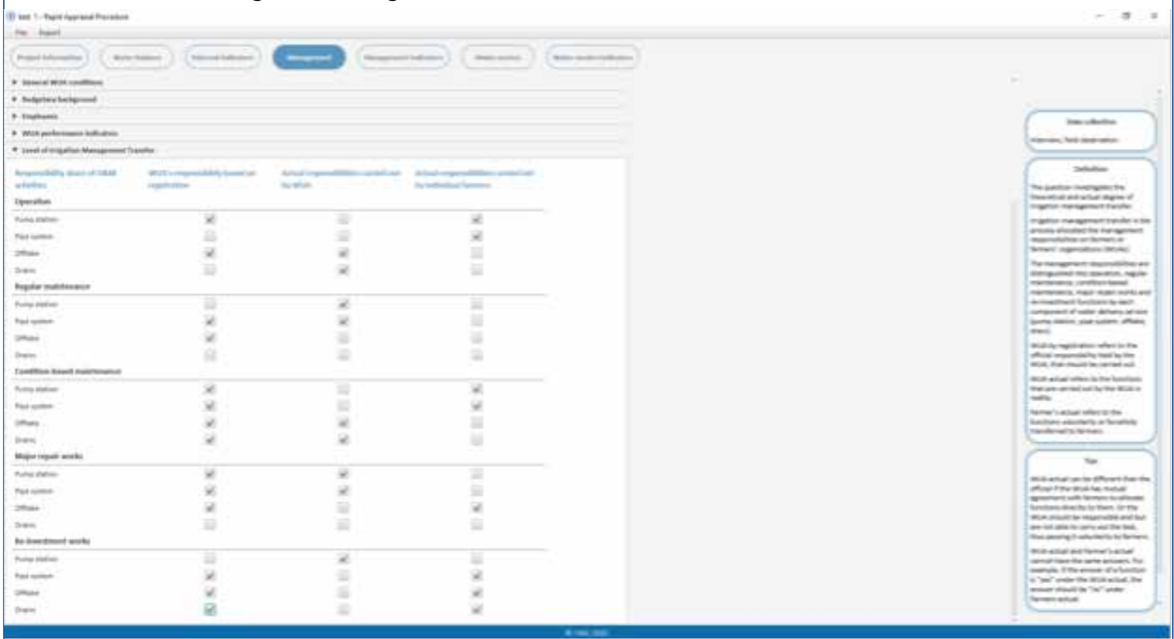
- scoring is based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition;
- legal basis must be interpreted always in the context of the national regulation.

*Financial strength of WUA*

- scoring is based on guidance listed under the indicator;
- the scoring should be based on interviews and field observation;
- if conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition;
- if the financial strength is low, it must be assessed whether it is the result of low management performance or the ability of WUA to elevate resources.

## Level of irrigation management transfer:

FIGURE A.3.34
**Main view of the irrigation management transfer section**



*Source: Screenshot of RAP v1 software*

This section investigates the theoretical and actual degree of irrigation management transfer. Irrigation management transfer is the process allocating the management responsibilities to farmers or WUA. The management responsibilities are distinguished into operation, regular maintenance, condition-based maintenance, major repair works and re-investment functions at each management level of the water delivery service (pump station, pipe system, offtake, drain):

- WUA by registration refers to the official responsibility held by the WUA that should be carried out;
- WUA actual refers to the functions that are carried out by the WUA in reality.

This can be different than the official if the WUA has mutual agreement with farmers to allocate functions directly to them. Or, the WUA should be responsible and but are not able to carry out the task, thus passing it voluntarily to farmers;

- farmers actual refers to the functions voluntarily or forcefully transferred to farmers;
- the WUA actual and Farmers actual cannot have the same answers. For example, if the answer of a function is "yes" under the WUA actual, the answer should be "no" under Farmers actual.

BOX A.3.6

**Irrigation management transfer**

The definition of participatory irrigation management (PIM) and irrigation management transfer (IMT) are often used interchangeably. Although, they represent different stages of management transfer. PIM is the type of management when farmers take over management responsibilities, but certain supervision or contribution from the state is maintained. IMT is the full turnover, when state hands over all management responsibility to farmers. Like in most of the cases, the IMT in the software can be used interchangeably with PIM.

WUA responsibilities are usually defined by national law. Therefore, the official responsibility must be understood from the constitution document of the WUA, together with national legislation. The difference between official and actual responsibilities can be easily understood from farmers, who are the direct "service receivers". In optimal cases, the official and actual responsibilities should not differ. However, most of the WUA are not able to properly carry out their tasks due to different issues, and they informally shift management tasks to farmers.

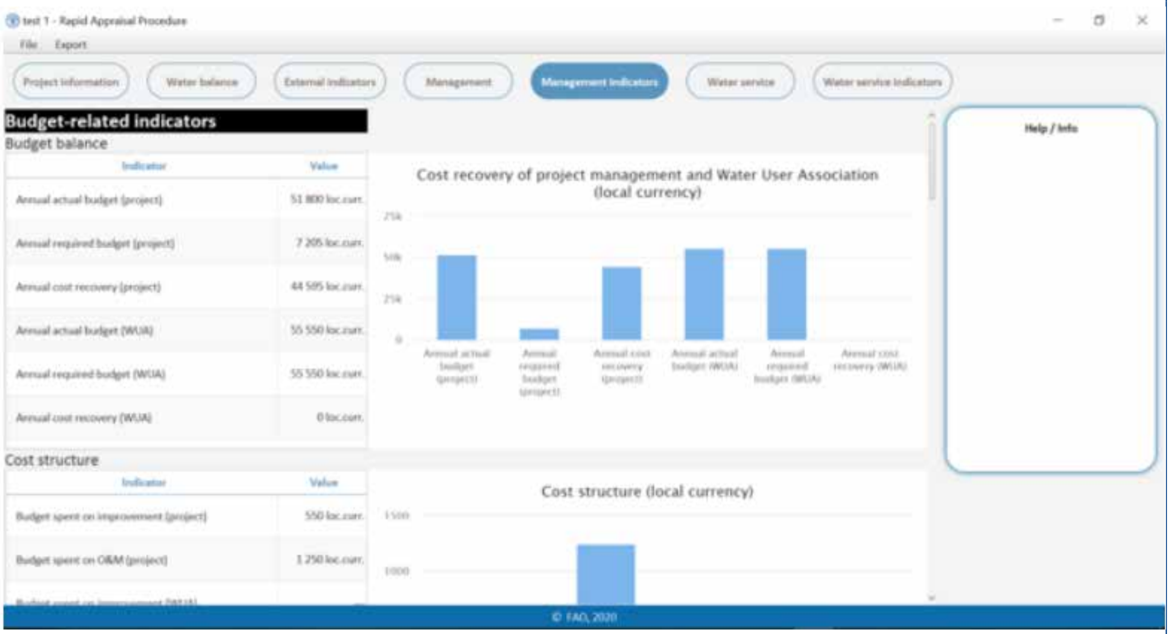
*Source: Authors' own elaboration.*

### A.3.5.5. Management indicators

The management indicators are calculated to provide an appraisal of institutional and organizational performance. Not all input data/information are directly analysed as performance indicator. While preparing the analysis and narrative of the chapter, it is important to understand that both the input data/information and the Indicators are necessary to compile a comprehensive report. While the input data/information helps users to properly frame the assessment, they provide underlying information about the results.

The management indicator page has five clusters that systematically analyse the performance. These clusters are budget related indicators, employees, operation, WUA indicators, level of irrigation management transfer.

FIGURE A.3.35
**Main view of the management indicators**




*Source: Screenshot of RAP v1 software*

TABLE A.3.4
**Calculated parameters of the management indicators**

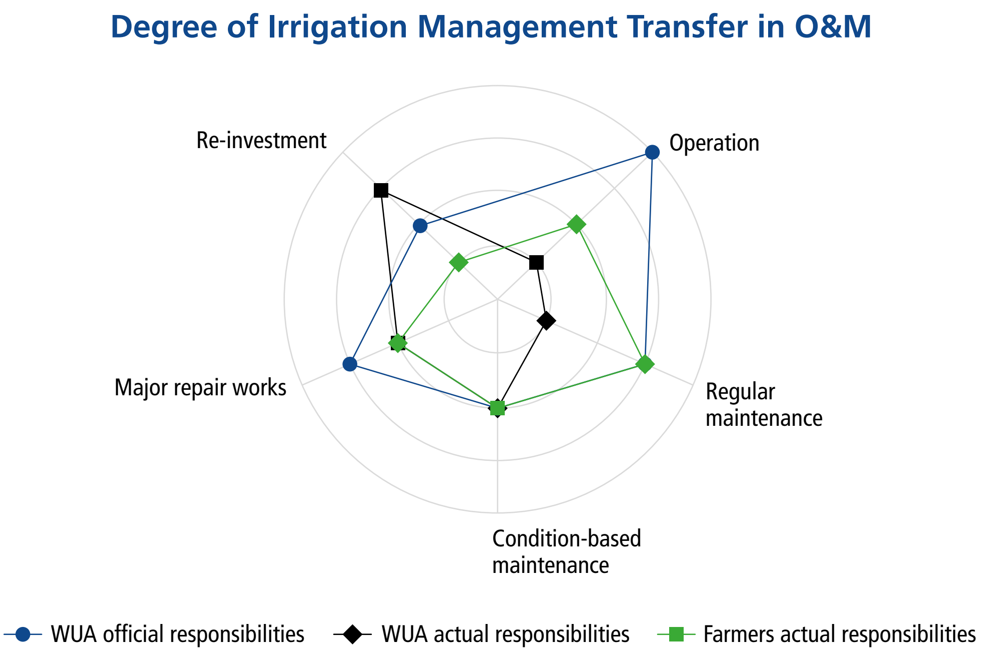
| Indicator | Unit | Definition |
|---|---|---|
| | | **Budget related indicators** |
| budget balance | Local currency | • The budget balance compares the actual budget with the required budget separately at project and WUA level.<br>• The annual cost recovery is the difference between actual and required budget. If the required budget is higher than the actual, it indicates budget deficit in negative value. This should be interpreted as the missing amount that should be allocated to cover all necessary costs. If there is surplus, it means that the available budget is higher than the required, thus assuming budget reserve and high liquidity.<br>• The analysis is conducted separately to project and WUA. |
| cost structure | Local currency | • The cost structure compares the expenditures on improvement/ modernization with the expenditures on O&M at project and WUA level.<br>• "Improvement" includes the cost line related to improvement and modernization. This considers only those activities that adds to the current function/value of the irrigation scheme.<br>• O&M includes the cost lines related to all operation and maintenance activities that are directly related to the day-to-day scheme management.<br>• Ratio of improvement and O&M is transferred value from the "rate of the total budget spent on modernization of the irrigation system over O&M costs (project and WUA)". This refers to the rate of budget spend on system improvement compared to the O&M costs spend by both project authority and WUA.<br>• The budget deficit/surplus for improvement compares the actual costs of improvement to the required costs of improvement at project and WUA level. If the actual expenses of improvement are less than the required, it indicates deficit in negative value. If the actual cost of improvement is higher than the required cost, it indicates over-spending. |

| Indicator | Unit | Definition |
|---|---|---|
| budget indicators | - | • Ratio (percentage) of users' contribution to overall budget is the rate of water charge actually collected from users by WUA over the sum of actual annual budget of project and WUA. Too low ratio would indicate that water fee is negligible compared to the overall budget of the irrigation scheme. Ratio close to 100 percent would indicate that the scheme is financed mostly from the water fees.<br>• Annual fee collection efficiency is transferred value. The actual ratio (percentage) of collected water fee over the expected amount of water fee, if every member paid the defined amount of fee.<br>• Ratio (percentage) of in-kind services and collected water fee from users indicates the value of in-kind services over the total collected water fee.<br>• Total O&M cost (local currency) per project area is the sum of all direct and indirect costs related to O&M and paid by the project (total salaries, regular maintenance works, condition-based maintenance and repair works, rehabilitation, operation, including energy cost for pumping, administration and other costs and other operation) per project area<br>• Total O&M cost (local currency) per project area is the sum of all direct and indirect costs related to O&M and paid by the WUA (total salaries, regular maintenance works, condition-based maintenance and repair works, rehabilitation, operation, including energy cost for pumping, administration and other costs and other operation) per project area<br>• Improvement cost (local currency) per project area is the cost related to improvement and modernization, paid by the project per project area<br>• Improvement cost (local currency) per project area is the cost related to improvement and modernization, paid by the WUA per project area |
| | | **Employees** |
| staff | - | • Number of employees financed by the project is transferred values from the aggregated number of paid employees by the project regardless their positions.<br>• Number of employees financed by the WUA is transferred values from the aggregated number of paid employees by the WUA regardless their positions.<br>• Number of project employees per project area is the number of employees per hectare paid by the project.<br>• Number of project employees per project area is the number of employees per hectare paid by the WUA.<br>• Number of professional project staff is the aggregated number of professional employees paid by the project, not including the permanent non-professionals and temporary non-professionals.<br>• Number of professional project staff is the aggregated number of professional employees paid by the WUA, not including the permanent non-professionals and temporary non-professionals. |
| indicators of human resource management | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the performance of human resource management per dimensions |
| salaries | - | • Share of salaries in total costs of project indicates the rate of salaries over the total project budget.<br>• Share of salaries in total costs of project indicates the rate of salaries over the total WUA budget.<br>• Ratio of non-professional to professional salaries of the project indicates the difference between salary levels between non-professional and professional paid by the project.<br>• Ratio of non-professional to professional salaries of the project indicates the difference between salary levels between non-professional and professional paid by the WUA. |
| | | **Operation** |
| operation policies | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the compliance of operation policies per dimensions. |

| Indicator | Unit | Definition |
|---|---|---|
| | | **WUA indicators** |
| Water user associations performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/ chart to compare the WUA performance per dimensions. |
| | | **Level of Irrigation Management Transfer** |
| WUA official responsibility | - | • The scores are transferred values indicating how many of the management activities per system components are official assigned to the WUA.<br>• Four management activities are assigned to each system components. The value shows the fraction of the officially assigned tasks from the four. E.g. 2/4 indicates that two activities are assigned from the four. |
| WUA actual responsibility | - | • The scores are transferred values indicating how many of the management activities per system components are actually taken by the WUA.<br>• Four management activities are assigned to each system components. The value shows the fraction of the actually taken tasks from the four. E.g. 2/4 indicates that two activities are taken from the four. |
| actual responsibilities of individual farmers | - | • The scores are transferred values indicating how many of the management activities per system components are actually taken by the farmers.<br>• Four management activities are assigned to each system components. The value shows the fraction of the actually taken tasks from the four. E.g. 2/4 indicates that two activities are taken from the four. |

Appropriate visualization helps understand the relationships amongst different indicators, where some of the indicators can outperform and underperform. The visual objects can be exported in pdf file.

FIGURE A.3.36
**Exported chart from the management indicators**




*Source: Elaboration through RAP v1 software*

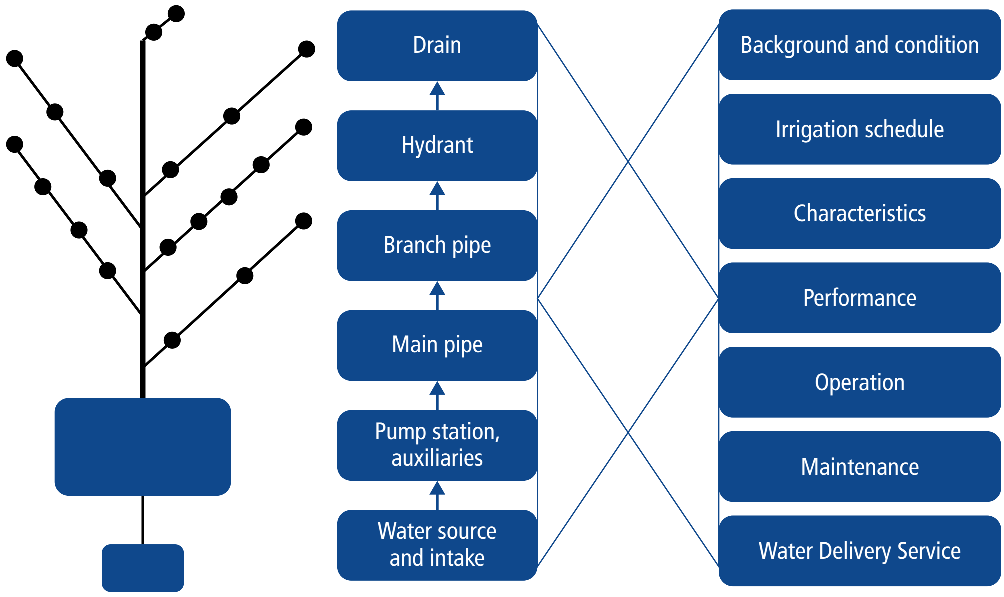
### A.3.5.6 Water Service

The water service chapter aims at appraising the physical infrastructure from water intake to the drains. The questionnaire provides sequential analysis of the levels of the infrastructure at system level – not including the on-farm irrigation technique: intake, pump station, main pipe, branch pipes, deliveries (hydrants) and drains. The appraisal is phased into two sub-chapters, complementing each other:

1. Pump station: the sub-chapter refers to those parts of the irrigation system, which are usually managed by higher-level institutions, and not directly by farmers. Usually, WUA or governmental authority is responsible to operate the overall water withdrawal at pump station level and drains, while farmers are usually responsible to operate the water distribution at farm level. Although this setting is not practiced equally everywhere in this way, the format of the chapter does not hamper the appraisal at different management setting.
2. Pipes and deliveries: the sub-chapter refers to those parts of the irrigation system, which are usually managed by farmers, such as pipe network and deliveries (hydrant).

The chapter structure is similar to the management chapter, it provides a "catchall" list of the infrastructure characteristics, irrigation schedule, performance, operation, maintenance and water delivery service at each infrastructure level. The list of input data functions as systematic stocktaking of relevant information describing and characterizing the performance of the physical infrastructure. Furthermore, composite indicators are crafted to provide systematic evaluation of performance.

FIGURE A.3.37
**Flowchart of the water service appraisal**




*Source: FAO. 2022a. RAP v1 User's Manual [online]. https://data.apps.fao.org/static/downloads/RAP/RAP%20v1%20Manual.pdf.*

TABLE A.3.5
**Data input support of Water service chapter**

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| | | **General project condition** | | |
| type of water source | - | - | - | Field observation, interview |
| type of water | - | - | - | field observation, interview |
| number of systems relies on the same water source | - | - | cadastral maps | cadastral maps |
| position of the system compared to other systems using the same source | - | - | cadastral maps | field observation |
| average number of days when the water/ piezometric level does not reach the minimum required | - | annual | - | field observation, interview |
| type of system | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation |
| pipeline type | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation |
| range of altitude of the area | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation |
| soil textural class of the system | - | - | - | field observation, interview, sampling |
| gypsum concentration of soil | percentage | - | - | field observation, interview, sampling |
| sulphate concentration of soil | percentage | - | - | field observation, interview, sampling |
| average groundwater depth during the year from the pipe level | m | annual | - | field observation, interview |
| number of days when shallow groundwater reaching the pipe occurs during the year | day/year | annual | - | field observation, interview |
| possible waterlogging and/or salination | - | - | - | field observation, interview |
| required continuous flowrate based on peak water requirement of command area | l/s | - | - | field observation, interview |
| average working hours of the system per day | hour | seasonal | - | field observation, interview |
| required flowrate according to elasticity based on peak water requirement of command area (l/s) | l/s | seasonal | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| number of water users within the irrigated area | - | seasonal | design, plans, master plans, technical drawings, field surveying | field observation, interview |
| total length of pipeline | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| total length of main line | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| total lengths of other feeder/sub-branches | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| number of sub-systems in the pipe system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| average size of sub-systems | ha | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| position of sub-systems | - | - | design, plans, master plans, technical drawings | field observation, interview |
| average number of farmers per sub-system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| branching type of the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of gate valves | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of drains | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of distributaries | - | - | design, plans, master plans, technical drawings | field observation, interview |
| average land size served by distributaries | ha | - | design, plans, master plans, technical drawings | field observation, interview |
| technique of on-farm irrigation | - | - | - | field observation, interview |
| layout of the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| | | **Irrigation schedule** | | |
| what percentage of the time is the flow officially scheduled at intake level | percentage | seasonal | WUA, project Office | interview, field observation |
| what percentage of the time is the flow actually scheduled at intake level | percentage | seasonal | WUA, farmers | interview, field observation |
| what percentage of the time is the flow officially scheduled at distributaries (hydrant) level | percentage | seasonal | WUA, project office | interview, field observation |
| what percentage of the time is the flow actually scheduled at distributaries (hydrant) level | percentage | seasonal | WUA, farmers | interview, field observation |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| | | Intake and pump station characteristics | | |
| altitude of the station | m | - | design, plans, master plans, technical drawings | field observation, interview |
| distance of station from water source - vertical | m | - | design, plans, master plans, technical drawings | field observation, interview |
| distance of station from water source - horizontal | m | - | design, plans, master plans, technical drawings | field observation, interview |
| intake classification | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| number of pumps in the pump stations | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of pumps operating simultaneously (max no of pumps) | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of pumps operating sequential | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of stand-by pumps | - | - | design, plans, master plans, technical drawings | field observation, interview |
| type of simultaneously operating pumps | - | - | design, plans, master plans, technical drawings | field observation, interview |
| type of pumps operating sequential | - | - | design, plans, master plans, technical drawings | field observation, interview |
| type of stand-by pumps | - | - | design, plans, master plans, technical drawings | field observation, interview |
| energy supply | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total head | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| maximum design capacity of the pump | l/s | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| type of pressure control device | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| type of pressure measurement device | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average pressure during operating hours | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| pressure in peak period | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| magnitude of the variation in pressure | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| average delivered discharge on daily base | $m^3/h$ | seasonal | design, plans, master plans, technical drawings, manufacturer recommendations | historical data, field observation |
| magnitude of the variation in discharge | $m^3$ | rotation | design, plans, master plans, technical drawings, manufacturer recommendations | historical data, field observation |
| average energy consumption per hour | kWh | seasonal | design, plans, master plans, technical drawings, manufacturer recommendations | historical data, field observation |
| peak energy consumption per hour | kWh | rotation | design, plans, master plans, technical drawings, manufacturer recommendations | historical data, field observation |
| the overall design efficiency of the pumps | percentage | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| estimated actual efficiency of the pumps | percentage | - | design, plans, master plans, technical drawings | field observation, interview |
| ability to variate the head pressure according to the water demand | - | - | design, plans, master plans, technical drawings | field observation, interview |
| type of drain | - | - | design, plans, master plans, technical drawings | field observation, interview |
| removal of excess water fromfield drains | - | - | design, plans, master plans, technical drawings | field observation, interview |
| area served by field drains | ha | - | design, plans, master plans, technical drawings | field observation, interview |
| area served by main collector drains | ha | - | design, plans, master plans, technical drawings | field observation, interview |
| **Pump station performance** | | | | |
| intake performance | - | - | - | field observation, interview |
| pump performance | - | - | - | field observation, interview |
| drain performance | - | - | - | field observation, interview |
| **Pump station operation** | | | | |
| operation policy | - | - | - | field observation, interview |
| operation personnel | - | - | - | field observation, interview |
| **Pump station maintenance** | | | | |
| condition of pump station | - | - | - | field observation, interview |
| maintenance infrastructure | - | - | - | field observation, interview |
| **Water delivery service** | | | | |
| actual water delivery service that pump station provides to the pipe system (water user perspective) | - | - | - | field observation, interview |
| actual water delivery service provided to sub-pipelines operated by a paid employee (water user perspective) | - | - | - | field observa iew |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| actual water delivery service received by individual units - fields and farms (water user perspective) | - | - | - | field observation, interview |
| | | **Pipes and deliveries characteristics** | | |
| diameter of main pipe/s | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| nominal pressure of main pipe/s | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| working pressure of main pipe/s | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average discharge in main pipe/s | l/s | seasonal | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| material of main pipe/s | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| diameter of of sub-pipelines/branches | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| nominal pressure of sub-pipelines/branches | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| working pressure of sub-pipelines/branches | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average discharge in sub-pipelines/branches | l/s | seasonal | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| material of sub-pipelines/branches | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average depth of main pipeline - if buried | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average depth of branch pipeline - if buried | m | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| corrosion protection | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| flexibility of the pipe | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| bedding of the pipe | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| internal lining | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| number of nodes in the pipelines/non-hydrant type | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| type of joints | - | - | design, plans, master plans, technical drawings | field observation, interview |
| number of nodes in the pipelines/hydrant type | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| type of joints | - | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| number of control equipment throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of shut-off valves throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of shut-off valves between main and branch pipes | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of check valves throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of pressure regulating device in the main pipe | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of metering devices throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of auxiliary devices throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of filters throughout the system | - | - | design, plans, master plans, technical drawings | field observation, interview |
| total number of hydrants in the system | - | - | design, plans, master plans, technical drawings | field observation, intervie |
| typical area size served by one hydran | ha | - | design, plans, master plans, technical drawings | field observation, interview |
| typical number of farms served by one hydrant | - | - | design, plans, master plans, technical drawings | field observation, interview |
| typical number of hydrants serving one farm | - | - | design, plans, master plans, technical drawings | field observation, interview |
| typical number of hydrants operating simultaneously | - | - | design, plans, master plans, technical drawings | field observation, interview |

| Required data | Unit | Time-step | Supporting documents | Methodology |
|---|---|---|---|---|
| nominal diameter of hydrants | mm | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| nominal design pressure in the hydrant | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| range of working pressure in the hydrant | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| range of pressure regulator in the hydrant | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| maximum discharge | l/s | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| average working discharge | l/s | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| range of flow regulator in the hydrant | bar | - | design, plans, master plans, technical drawings, manufacturer recommendations | field observation, interview |
| required hydrant elasticity as per design | - | - | design, plans, master plans, technical drawings | field observation, interview |
| hydrant type | - | - | design, plans, master plans, technical drawings | field observation, interview |
| | | **Pipes and deliveries performance** | | |
| pipe performance | - | - | - | field observation, interview |
| hydrant performance | - | - | - | field observation, interview |
| | | **Pipes and deliveries operation** | | |
| operation policy | - | - | - | field observation, interview |
| operation personnel | - | - | - | field observation, interview |
| | | **Pipes and deliveries maintenance** | | |
| condition of pipes and hydrants | - | - | - | field observation, interview |
| maintenance infrastructure | - | - | - | field observation, interview |

### *A.3.5.6.2. Involved stakeholders*

The chapter can be completed based on a field visit. The majority of the questions rely on expert observation, existing technical documentations and drawings, and manufacturer specifications. The following stakeholders are recommended to be involved:

- site engineer;
- constructer/manufacturer;
- WUA, irrigation associations, farmers' organization etc.

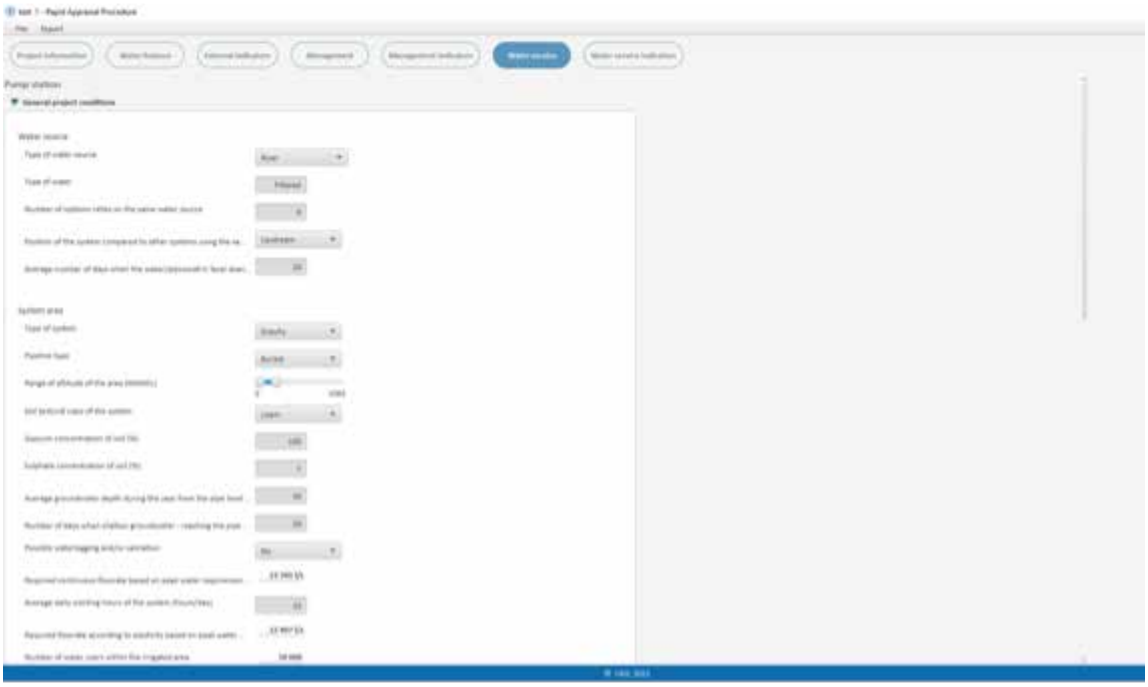
#### *A.3.5.6.3. Requested time*

The task should be implemented within not more than 2 week, balancing between field and desktop work.

#### *A.3.5.6.4. Data input and calculation scheme*

### General project conditions:

FIGURE A.3.38
**Main view of general project conditions section in the pump station block**



*Source: Screenshot of RAP v1 software*

*Type of water source:* the origin or the place of water, from where the water is pumped.

*Type of water:* source of water whether it is freshwater, recirculated or both freshwater and recirculated water.

*Number of systems relying on the same water sources:*

- the number of independent irrigation schemes sourcing water from the same origin;
- for example, if multiple irrigation schemes are supplied by the same branch canal/ reservoir.

*Position of the system compared to other systems using the same sources:*

- the upstream, middle or downstream position of the system compared to other systems sourcing water from the same origin;
- the position might be absolute or relative term;
- if the position is assessed in absolute term, it should be expressed based on the geometric mean;
- if the position is assessed in relative term, the vulnerability of the system to other systems' management should be expressed.

*Average number of days when the water/piezometric level does not reach the minimum required:*

- the average number of days during the periods, when the water/piezometric level is lower than the required, hampering the pump operation;
- the periods can last shorter or longer than a day, therefore, the average number of days should be estimated;
- only those periods must be taken into account when the low water/piezometric level effectively disables the pumping.

*Type of system:* type of the system, whether the pressurized conveyance is gravity-fed or pumped.

*Pipeline type:* type of the pipeline, whether it is buried, surface or suspended.

*Range of altitude of the area:*

- range of the altitude in the irrigation scheme;
- the range should be calculated per the difference between lowest and highest points.

*Soil textural class of the system:* soil class, whether it is sand, loam, silt or clay.

*Gypsum concentration of soil:*

- concentration of gypsum in the soil surrounding the buried pipes;
- the concentration must be assessed in the light of its effect on the buried pipes and the potential ability to cause corrosion.

*Sulphate concentration of soil:*

- concentration of sulphate in the soil surrounding the buried pipes;
- the concentration must be assessed in the light of its effect on the buried pipes and the probability of the sulphate attack inducing corrosion.

*Average groundwater depth during the year, measured from the pipe level:*

- the average distanced between the buried pipe and the groundwater table;
- the groundwater depth must be assessed in the light of its potential effect on the buried pipe (corrosion, flushing out, etc.)

*Number of days when shallow groundwater reaching the pipe occurs during the year:* the total number of days in a year, when the groundwater level reaches the buried pipe.

*Possible waterlogging and/or salinization:* the probability of waterlogging or salinization due to the malfunctioning irrigation system or management.

*Required continuous flowrate based on peak water requirement of command area:*

- continuous flowrate refers to the situation, when water supply is based on continuous flow (24/7), therefore, farmers have access to this flowrate over the year;
- the calculation is based on the assumption that the system capacity is designed as per the peak requirement;
- the required continuous flowrate is calculated from the maximum monthly crop water requirement of the irrigation scheme, assuming that the irrigation is always on;
- the calculation is based on peak water demand, coming from the most water consuming month;
- the calculated value provides baseline information for the on-demand system design.

*Average working hours of the system per day:*

- the average number of hours per irrigation day when the irrigation is on;
- this refers to the number of hours in irrigation days, and not in off-season.

*Required flowrate according to elasticity based on peak water requirement of the command area:*

- the calculation is the ratio of required continuous flowrate in peak period and the average working hours of the system;
- the value expresses the required system capacity considering the prevailing the irrigation practices (average working hours in irrigation days);
- the value can be compared to the actual design capacity to assess the adequacy, any negative deviation from the required flowrate assumes insufficient water supply in peak periods.

*Number of water users within the irrigated area: number of farmers in the area.*

*Total length of the pipeline:*

- the total length of all pipelines (main, branches) in the distribution system;
- this does not include the laterals of the on-farm irrigation systems;
- total length of the pipelines allows the assessment of the design, whether it is sufficiently optimized.

*Total length of the main line:*

- the total length of the main distribution line;
- total length of the main pipe allows the assessment of the design, whether it is sufficiently optimized.

*Total length of other feeder/sub-branches:*

- the total length of all feeder/sub-branches;
- this does not include the laterals of the on-farm irrigation systems;
- total length of the branches allows the assessment of the design, whether it is sufficiently optimized;
- the length of the branches allows the assessment of the network, whether it provides sufficient coverage for all farms.

*Number of sub-systems in the pipe system:*

- the total number of the sub-systems, which are separated by nodes;
- the number of sub-system allows the assessment of the management;
- the management and performance of the sub-systems might vary, therefore, a narrative on the individual performance can complement the assessment.

*Average size of sub-systems:*

- total area irrigated by an adjacent system separated from the other by nodes;
- the area size can vary amongst the sub-systems, therefore it is desirable to collect information on the largest and smallest systems and prepare a comparative analysis.

*Position of sub-systems:*

- number of sub-systems positioned in upstream, middle or downstream areas.
- the calculation can be based on geometric distribution or the exposure of sub-systems to the activity of upstream sub-systems;
- the question refers to the symmetry of the layout, and the potential inferiority of downstream systems.

*Average number of farms per sub-system:* number of farms supplied by one sub-system separated from other farms by nodes.

*Branching type of the system:* the design of the branch lines, whether they are branched (each outlet is supplied by one line) or looped (each outlet is supplied by multiple lines).

*Operating pressure range at hydrant level:*

- the minimum required pressure to operate the hydrant;
- pressure in hydrants can significantly vary throughout the system, therefore the operating pressure should be compared to the measured pressure to assess the pressure adequacy;
- in many larger systems, hydrants operate simultaneously, therefore, it is important to assess the pressure during simultaneous operation.

*Basis of carrying capacity of the system:*

- the basis of the system design, whether it is designed per crop water requirement (actual peak water demand at system level), allocation from national water budget (pre-defined water requirement of each crop as ceiling of water supply) or allocation by rotational schedule (supply-driven distribution based on periodically distributed supply);
- it is important to assess the adequacy of the design, and understand whether the design of the system allows adequate water service or it is a constraining factor.

*Number of gate valves:* number of valves responsible for water distribution and control in the system.

*Number of drains:*

- number of drains connected to the farms;
- the drain capacity and density must be assessed against the irrigation practices, on-farm irrigation technique, soil type, amount of supplied water and the land management practices;
- insufficient drain, particularly in heavy soil might drive to salinity, therefore, the drain assessment must be contextualized in potential scenarios of mismanagement.

*Number of distributaries:*

- number of final offtakes supplying water directly to the farms (most frequently hydrants);
- this does not include the on-farm irrigation systems.;
- the number of offtakes depends on many factors, for example the capacity of offtake in the context of the land size, the land structure and tenure, the original distribution layout etc.; therefore, the number of offtakes must be assessed in the context of the supplied land and required water supply.

*Average land size served by distributaries:*

- the average size supplied by one offtake;
- the size of the land must be assessed in the context of the capacity of the offtake, and the irrigation schedule to understand if the design of distributaries is adequate.

*Technique of on-farm irrigation:*

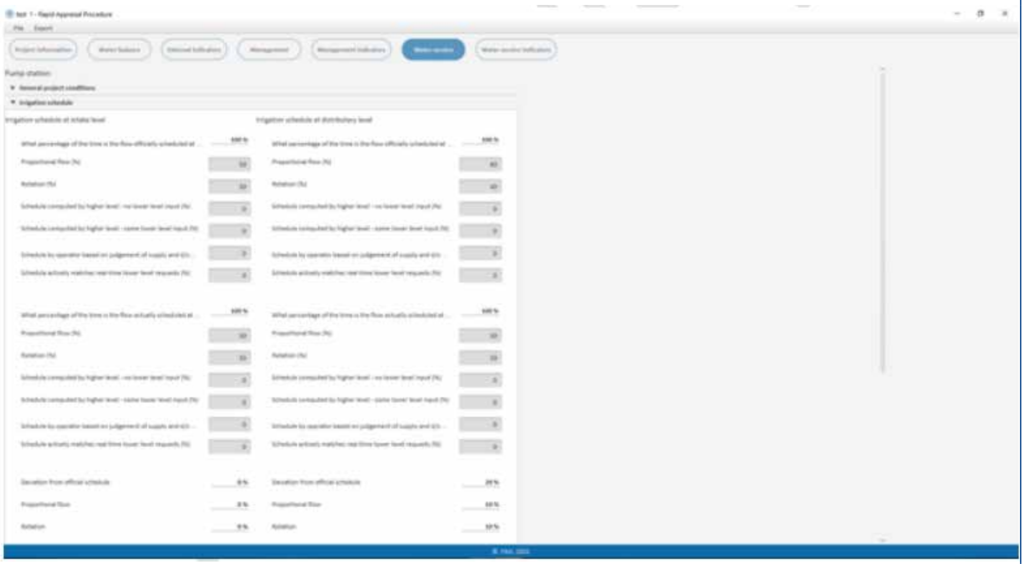
- type of on-farm irrigation system, whether it is a surface, drip or sprinkler irrigation system;
- the on-farm irrigation system might give information on the design principles of the distribution system;
- the on-farm irrigation system is not discussed and evaluated further in the RAP.

*Layout of the system:*

- location of the final distributaries as per compared to the water sources;
- calculated number of final distributaries close or far from the water sources.

## Irrigation schedule:

FIGURE A.3.39
**Main view of irrigation schedule section in pump station block**



*Source: Screenshot of RAP v1 software*

*What percentage of the time is the flow officially scheduled at intake level (rotational operation):*

- the official schedule of the pump station to withdraw water from the water source to the system;
- the official schedule refers to the schedule agreed by the authorities and/or managers on the water allocation quota and the type of schedule;
- the official schedule can include one type of allocation policy or a mixed type.

*What percentage of the time is the flow actually scheduled at intake level:*

- the actual schedule of the pump station to withdraw water from the water source to the system;

- the actual schedule refers to the schedule followed in the reality;
- the actual schedule does not necessary reflect on the official schedule;
- the actual schedule can include one type of allocation policy or a mixed type.

*Deviation from official schedule:*

- the difference between the official and actual schedule at pump station level;
- this refers to the degree of compliance with the official schedule;
- the higher the deviation the lower the compliance with the official schedule.

*What percentage of the time is the flow officially scheduled at distributaries level:*

- the official schedule of the distributaries to supply water to the farms;
- the official schedule refers to the schedule agreed by the authorities and/or managers on the water allocation quota and the type of schedule;
- the official schedule can include one type of allocation policy or a mixed type.

*What percentage of the time is the flow actually scheduled at distributaries level:*

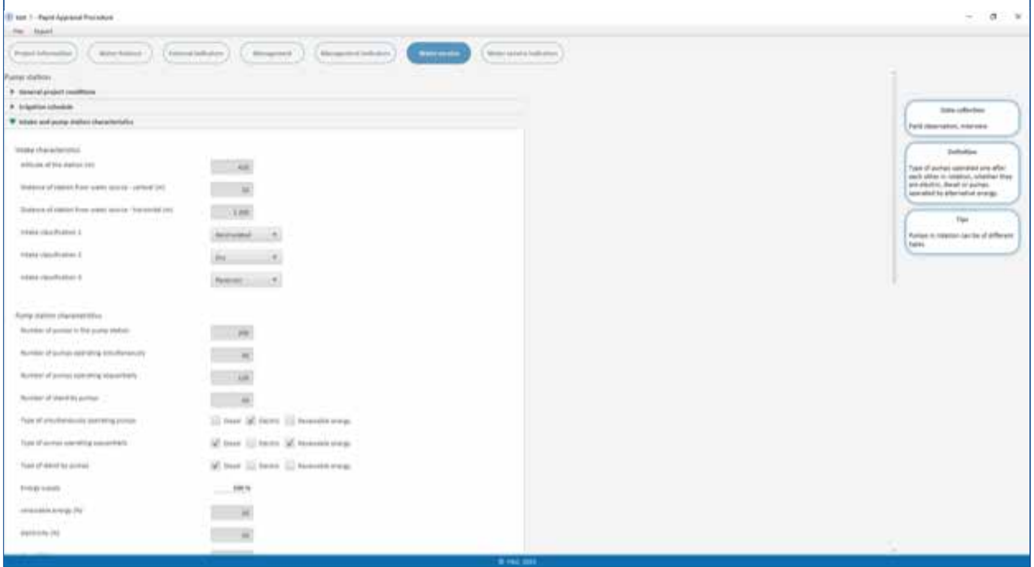
- the actual schedule of the distributaries to supply water to the farms;
- the actual schedule refers to the schedule followed in the reality;
- the actual schedule does not necessary reflect on the official schedule;
- the actual schedule can include one type of allocation policy or a mixed type.

*Deviation from official schedule:*

- the difference between the official and actual schedule at distributaries level;
- this refers to the degree of compliance with the official schedule;
- the higher the deviation the lower the compliance with the official schedule.

## Intake and pump station characteristics:

FIGURE A.3.40
**Main view of pump station characteristics section in pump station block**



*Source: Screenshot of RAP v1 software*

*Altitude of the station:* the altitude of the pump station.

*Distance of station from water sources - vertically:*

- the lifting height of water from source to the pump station;
- this gives a partial information on the total head, however, further information is required to calculate the total head.

*Distance of station from water sources – horizontally*: the horizontal move of water from source to the pump station.

*Intake classification 1.:* type of intake whether it is submerged or exposed.

*Intake classification 2.: type of intake whether it is wet or dry intake.*

*Intake classification 3.*: type of intake whether it is river, reservoir or canal intake.

*Number of pumps in the pump station (applies where applicable):*

- number of the pump in the station, including the back-up pumps;
- beyond the number, it is important to categorize the pumps as per the number of different types and capacities.

*Number of pumps operating simultaneously:* number of pumps operating at the same time in irrigation period.

*Number of pumps operating sequential:*

- number of pumps operated one after each other in rotation;
- this is most commonly applied in pump stations with continuous supply.

*Number of stand-by pumps:* number of pumps provided as back-up equipment in case of failure.

*Type of simultaneously operating pumps:*

- type of pumps operating at the same time whether they are electric, diesel or pumps operated by alternative energy;
- simultaneous pumps are of the same type.

*Type of pumps operating sequential:*

- type of pumps operated one after each other in rotation, whether they are electric, diesel or pumps operated by alternative energy;
- pumps in rotation can be different.

*Energy supply:*

- the share of energy sources;
- one system can be supplied by different energy sources;
- the ratio must be set up according to the annual consumption.

*Total head:*

- the required pressure to move fluids through a system;
- total head depends on the system configuration and layout;
- the total head must be justified by any kind of pump selection study.

*Maximum design capacity of the pump:*

- the maximum discharge supplied, when the system is fully operational and all pumps are on;
- the design capacity must be compared to the peak water requirement to understand the adequacy of supply.

*Type of pressure control device*:

- description of the type of pressure control device if it exists;
- it might be important to assess the suitability of the pressure control.

*Type of pressure measurement device:*

- description of the type of pressure measurement device if it exists;
- it might be important to assess the suitability of the pressure measurement device;
- existence of pressure measurement device refers to the availability of historical datasets;
- Average pressure during operating hours:
- the measured average pressure in a typical irrigation day;
- this does not refer to the peak demand, but rather to a normal operation mode;
- if more pumps are operated simultaneously, the average pressure must be taken into account.

*Pressure in peak period:*

- the maximum pressure registered during irrigation season;
- this baseline information gives an idea on the sufficiency of the design capacity of the system.

*Magnitude of the variation in pressure:*

- the average change in pressure during operation in a typical irrigation day;
- a large deviation from the design pressure might indicate some problem in the system (clogging, broken parts, etc.), therefore, the varying pressure must be assessed in the context of the design pressure and/or irrigation practices.

*Average delivered discharge on daily base:*

- the average water supply per day in a typical irrigation day (maximum irrigation duration);
- the average daily discharge must be assessed in the context of the water demand and the system capacity;
- if the average discharge is significantly different than the design discharge, the reasons behind must be investigated. Such reason can be the oversized design, declined performance, etc.

*Magnitude of the variation in discharge:*

- the average change in the discharge during operation. In a typical irrigation day;
- a large deviation from the design discharge might indicate some problem in the system (clogging, broken parts, etc.), therefore, the varying discharge must be assessed in the context of the design discharge and/or irrigation practices.

*Average energy consumption per hour:*

- average energy use for irrigation as per the typical irrigation practices;
- the average energy consumption might give information on the cost-efficiency of the system, while analyzing the ratio of energy consumption per delivered discharge;

*Peak energy consumption per hour:* the maximum energy consumption occurring during the season.

*The overall design efficiency of the pumps:*

- the overall design efficiency is the theoretical ratio of the water to the power;
- the average design efficiency of the pumps as per the manufacturer recommendation;
- the design efficiency is a baseline indicator to be compared to the actual efficiency.

*The estimated actual efficiency of the pumps:*

- the actual efficiency of the pumps;
- this can be significantly lower than the design efficiency, depending on the configuration, layout, condition, etc.;
- actual efficiency is an indicator of the performance of the system; a too high consumption might refer to structural (poor pump selection, design failure etc.) or operation (poor maintenance, inadequate irrigation practices, etc.) issues.

*Ability to variate the head pressure according to the water demand:* degree of the equipment of the pump station whether the head pressure can be modified or not.

*Type of drain:* type of drain whether it is surface drainage, tubewell drainage or subsurface drainage.

*Removal of excess water from field drains:* type of excess water removal whether it is gravity-fed or pumped.

*Area served by field drains:*

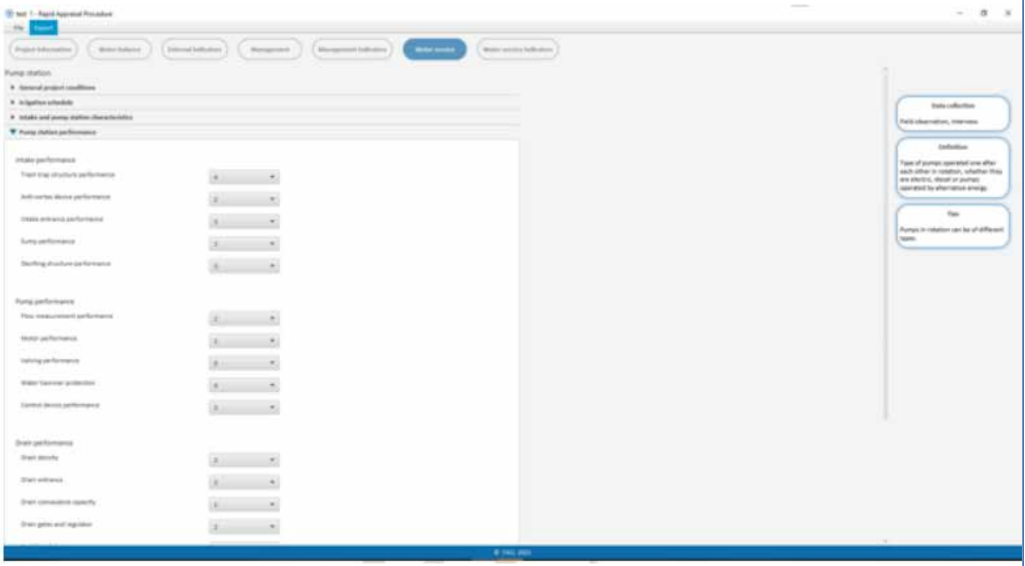
- the typical size of the area served by one field drain;
- it might be important to assess whether the drain is well-sized and suitable for serving the area.

*Area served by main collector drain:*

- the size of the area connected to the main drain collector;
- it might be important to assess the capacity and the suitability of the main collector.

## Pump station performance:

FIGURE A.3.41
**Main view of pump station performance section in pump station block**



*Source: Screenshot of RAP v1 software*

*Intake performance*

- the indicator consists of sub-indicators that describe the main items/functions of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators is not part of the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Pump performance*

- the indicator consists of sub-indicators that describe the main items/functions of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators is not part of the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition

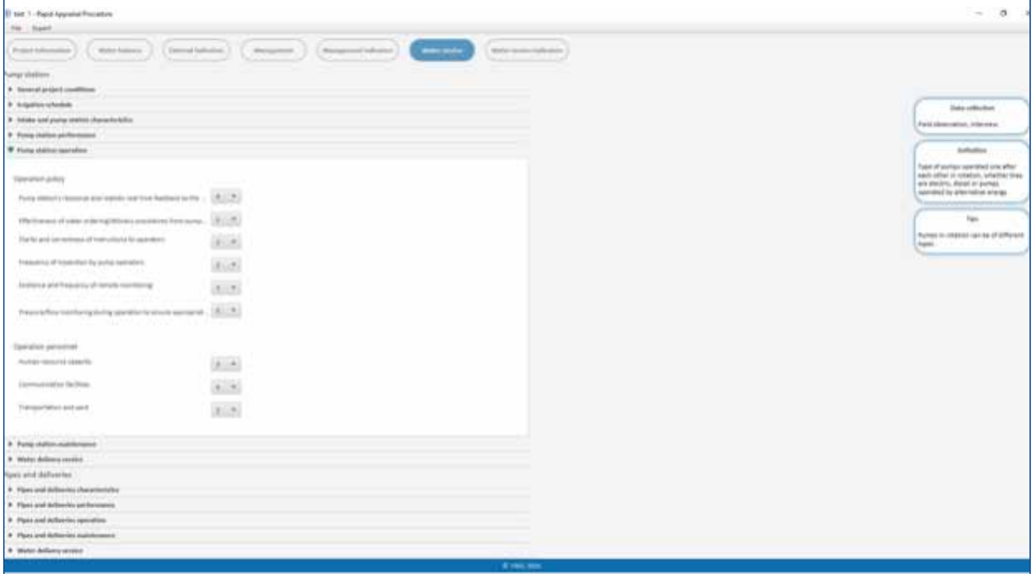
*Drain performance*

- the indicator consists of sub-indicators that describe the main items/functions of the system part;

- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators is not part of the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Pump station operation:

FIGURE A.3.42
**Main view of pump station operation section in pump station block**



*Source: Screenshot of RAP v1 software*

*Operation policy*

- the indicator consists of sub-indicators that describe the main management functions;
- the set of sub-indicators help underlining the most important management features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

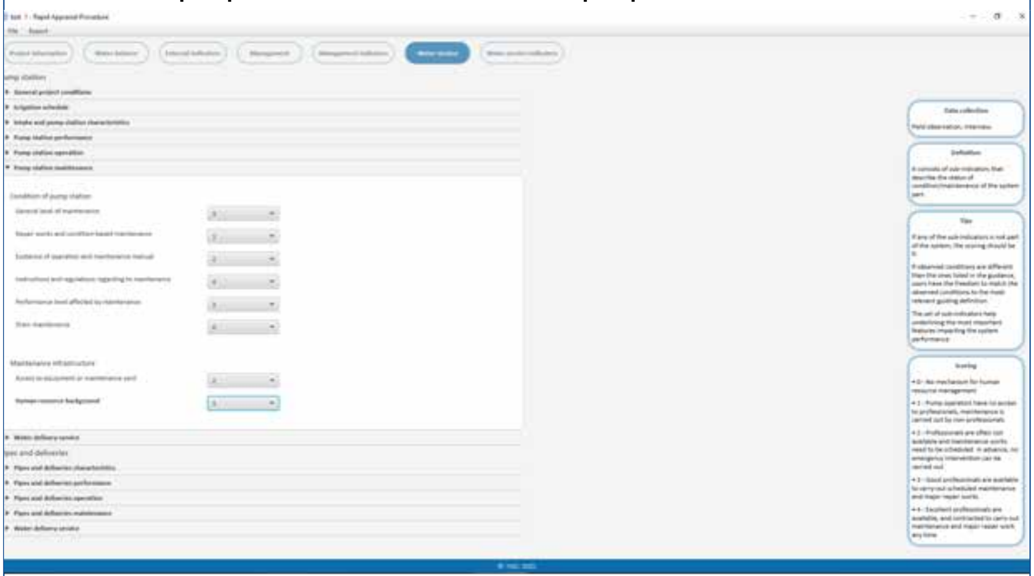
*Operation personnel*

- the indicator consists of sub-indicators that describe the main management functions;
- the set of sub-indicators help underlining the most important management features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;

- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Pump station maintenance:

FIGURE A.3.43
**Main view of pump station maintenance section in pump station block**



*Source: Screenshot of RAP v1 software*

*Condition of pump station*

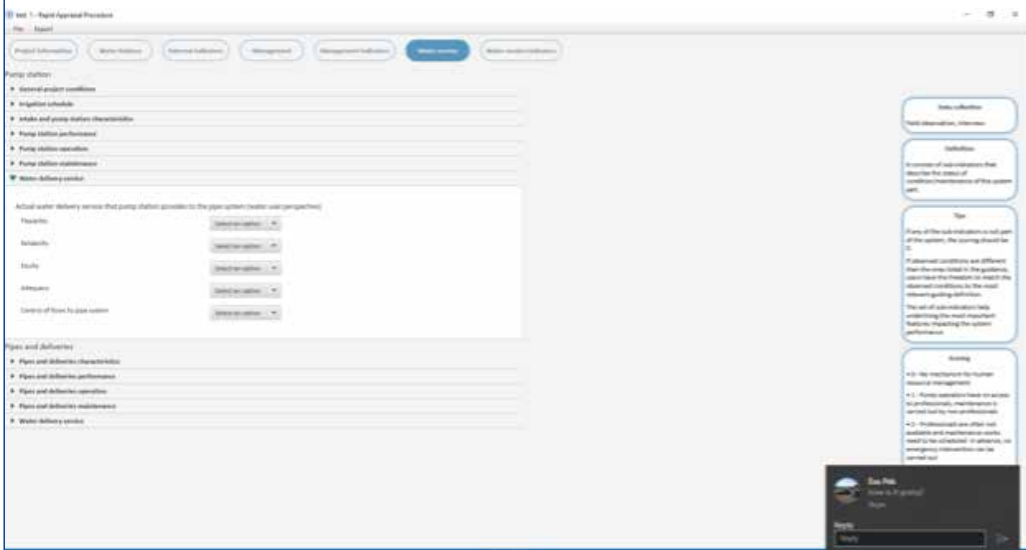
- the indicator consists of sub-indicators that describe the status of condition/ maintenance of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Maintenance infrastructure*

- the indicator consists of sub-indicators that describe the status of condition/ maintenance of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Water delivery service:

FIGURE A.3.44
**Main view of water delivery service section in pump station block**



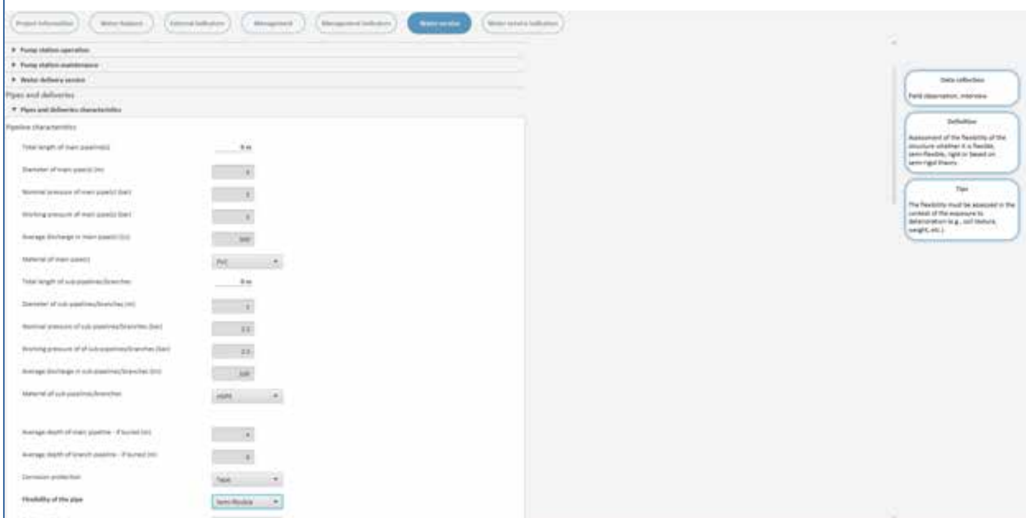
*Source: Screenshot of RAP v1 software*

*Actual water delivery service that pump station provides to the pipe system (water user perspective):*

- The composite indicator consists of five sub-indicators: flexibility, reliability, equity, adequacy and control of flow;
- Scoring is based on guidance listed under the sub-indicator;
- The sub-indicators should be evaluated considering only the system from pump station to main pipe system, not including the branch-pipes;
- The scoring should be based on the answers of the users. "Actual" water delivery service refers to the perception of the farmers directly. In order words, how the farmers evaluate the performance of the water delivery along the defined sub-indicators.

## Pipes and deliveries characteristics:

FIGURE A.3.45
**Main view of pipes and deliveries characteristics section in the pipes and deliveries block**



*Source: Screenshot of RAP v1 software*

*Total length of main pipeline/s:* the length of the main distribution pipe.

*Diameter of main pipe/s:* inner diameter of the main distribution pipe.

*Nominal pressure of main pipe/s:* the design pressure of the pipe, indicating the mechanical strength.

*Working pressure of main pipe/s:*

- internal maximum allowable pressure in a given point of the pipe;
- it might be important to assess the working pressure in the context of the pump station size and the required pressure of the distributaries;
- if the distributaries are connected to the pressurized on-farm techniques, the need for booster pump or high-pressure pump must be assessed.

*Average discharge in main pipe/s:*

- the average delivered discharge in the main pipe in a typical irrigation day;
- this must be assessed in the light of the water requirement;
- if the delivered discharge in the main pipe is sufficient, but water scarcity occurs in any part of the system, the water allocation policy must be revised and causes must be identified.

*Material of main pipe/s:*

- type of the pipe material (MSP, DIP, GRP, PVC, HDPE, RCC, RCCP, PSC, BWSC);
- the material of the main pipe depends on external (soil type, soil texture, depth of buried pipe, exposure to external pressure, etc.) and internal (required pressure/ discharge, maintenance facilities etc.) factors, therefore, the selected material must be assessed in the context of the system conditions.

*Total length of sub-pipelines/branches:*

- the total length of all feeder/sub-branches, but not including the on-farm irrigation systems;
- it is important to assess the layout of the system, the differences in branch sizing and the supplied area per branches.

*Nominal pressure in the sub-pipelines/branches:* the design pressure of the pipe, indicating the mechanical strength.

*Working pressure in the sub-pipe/branches:*

- internal maximum allowable pressure in a given point of the pipe;
- it might be important to assess the working pressure in the context of the pump station size, main pipe and the required pressure of the distributaries;
- if the distributaries are connected to the pressurized on-farm techniques, the need for booster pump or high-pressure pump must be assessed.

*Average discharge in sub-pipe/branches:*

- the average delivered discharge in an average size branch pipe in a typical irrigation day;
- this must be assessed in the light of the water requirement;
- if the delivered discharge in the main pipe is sufficient, but water scarcity occurs in any part of the system, the water allocation policy must be revised and causes must be identified.

*Material of sub-pipelines/branches:*

- type of the pipe material (MSP, DIP, GRP, PVC, HDPE, RCC, RCCP, PSC, BWSC);
- the material of the main pipe depends on external (soil type, soil texture, depth of buried pipe, exposure to external pressure, etc.) and internal (required pressure/ discharge, maintenance facilities etc.) factors, therefore, the selected material must be assessed in the context of the system conditions.

*Average depth of main pipeline:*

- average depth of buried pipe measured from the surface;
- the trench of the pipeline must be assessed in the context of the groundwater depth, soil depth, soil type and exposure to external pressures (e.g. heavy machines);
- the trench must be assessed whether it allows regular inspection of troubleshooting.

*Average depth of branch pipeline:*

- average depth of buried pipe measured from the surface;
- the trench of the pipeline must be assessed in the context of the groundwater depth, soil depth, soil type and exposure to external pressures (e.g. heavy machines);
- the trench must be assessed whether it allows regular inspection of troubleshooting.

*Corrosion protection:*

- type of corrosion protection whether it is cement coating, metal coating, painting, tape coating, other or no protection;
- it is important to take note of the corrosion protection and assess its efficiency.

*Flexibility of the pipe:*

- assessment of the flexibility of the structure whether it is flexible, semi-flexible, rigid or based on semi-rigid theory;
- the flexibility must be assessed in the context of the exposure to deterioration (e.g. soil texture, weight, etc.)

*Bedding of the pipe:*

- type of bedding whether it is concrete, sand or granular fill, fine granular fill or no specific bedding;
- the bedding must be assessed in the context of the depth of trench, the pipe type and exposure to deterioration (e.g. soil texture, weight, etc.)

*Internal lining:*

- type of lining whether it is corrosion resistant, cement lining, concrete lining, other or no lining;
- the lining must be assessed in the context of exposure to external factors.
- Number of nodes in the pipelines/non-hydrant type:
- nodes indicate the structures separating the sub-systems in the system;
- this refers only to the nodes for control and distribution, but not for final delivery.

*Type of joints:*

- type of joints whether they are socket and spigot, flanged, mechanical, flexible or expansion;

- the type must be investigated whether it is suitable for the conditions and pressure;
- the quality of the joints must be evaluated to understand the persistence of these critical system parts.

*Number of control equipment throughout the system:*

- control equipment include the following type of equipment: shut-off valve, check valve, metering devices and auxiliary devices;
- the number of control equipment is the total number of the abovementioned valves and devices.

*Total number of shut-off valves throughout the system:*

- number of the shut-off valves of different types throughout the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of shut-off valves between main and branch pipes:*

- number of the shut-off valves of different types between main and branch pipes;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of check valves throughout the system:*

- number of the check valves of different types throughout the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of pressure regulating device throughout the system:*

- number of pressure regulating equipment (valve, device, etc.) throughout the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of metering devices throughout the system:*

- number of metering devices (pressure or flow) throughout the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of auxiliary devices throughout the system:*

- number of auxiliary devices (air valves, safety valves) in the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of filters (gravel, hydro-cyclone, screen, disk, automatic self-cleaning) throughout the system:*

- number of filters of different types throughout the system;
- the efficiency and suitability of these equipment must be assessed in the context of the system as a whole.

*Total number of hydrants in the system:*

- the total number of hydrants as final offtake to farms;
- the hydrant density and layout must be estimated to understand the water allocation policy.

*Typical area size served by one hydrant:*

- the typical farm size per hydrant;
- the capacity of the hydrant must be estimated in the light of the area size;
- one hydrant might serve more than one farm, or more hydrant might serve one farm.

*Typical number of farms served by one hydrant:*

- the typical number of farms per hydrant, if one hydrant supplies one or more farms;
- this question refers to the land structure and is typically valid in smallholder systems.

*Typical number of hydrants serving one farm:*

- the typical number of hydrants per farm, if more hydrants supply one farm;
- this question refers to the land structure and is typically valid in systems with medium or larger size lands.

*Typical number of hydrants operating simultaneously:*

- the number of hydrants working simultaneously in irrigation periods;
- this refers to the hydrants operating exactly at the same time;
- if more hydrants operate at the same time, the irrigation schedule must be investigated.

*Nominal diameter of hydrants:* inner diameter of the hydrant.

*Nominal design pressure in the hydrant:* the working pressure of the hydrant.

*Range of working pressure in the hydrant:* difference between minimum required and maximum pressure in the hydrant to operate.

*Range of pressure regulator in the hydrant:*

- if the hydrant is equipped with pressure regulator, the range of pressure set in the hydrant;
- if the hydrant is not equipped with regulator, the reasons must be identified.

*Maximum discharge:*

- the maximum outlet discharge of the hydrant;
- this must be measured when the hydrant operates individually (not simultaneously with other hydrants);

*Average working discharge:*

- the average discharge of the hydrant in irrigation period;
- the average discharge must be measured in typical irrigation day;
- the average discharge must be assessed in the context of water requirement and the maximum discharge.

*Range of flow regulator in the hydrant:* the required pressure to operate the flow regulator, if the hydrant is equipped with regulator;

*Peak water demand at hydrant level:*

- maximum evapotranspiration-based water requirement per hectare, calculated from the most water demanding month;
- this does not include the other water requirements (leaching, special practices, system losses, etc.);
- this refers to crop water requirement calculated from the evapotranspiration.

*Required hydrant elasticity as per design:*

- elasticity indicates the "degree of freedom" to select irrigation practices;
- the elasticity means that the hydrant capacity is adjusted to the irrigation practices;
- elasticity is an important term, because calculating the capacity merely from the crop water requirement would require continuous flow; however, it is unlikely that farmers have the opportunity to irrigate continuously over the season;
- the degree of freedom must be estimated according to different criteria (e.g. duration and frequency of irrigation, number of farmers in the system, irrigation schedule, type of on-farm equipment, etc.);
- the capacity of the hydrant must be assessed not only according to the crop water requirement but in the context of the hydrant elasticity.

*Required hydrant capacity:*

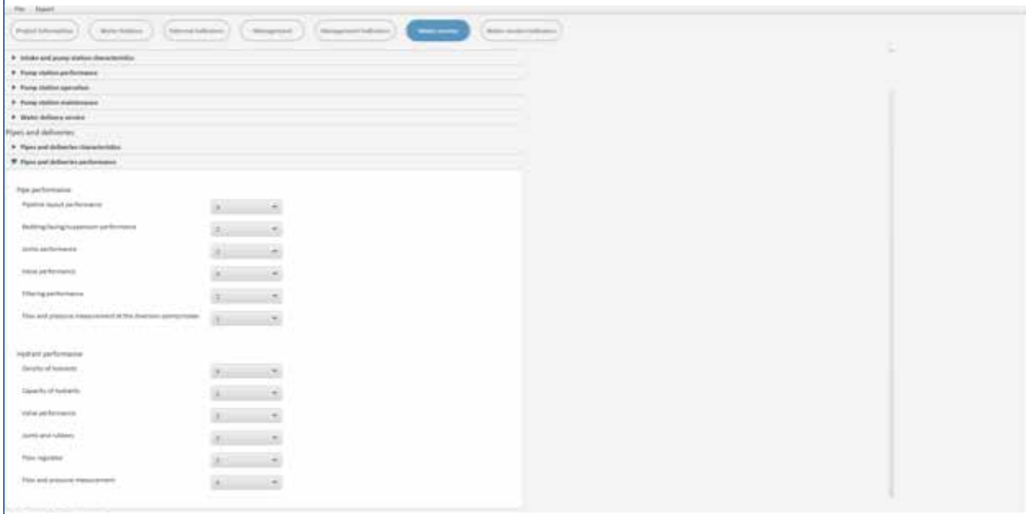
- the calculated hydrant capacity according to the evapotranspiration-based crop water requirement, hydrant elasticity and the typical land size served by the hydrant;
- this does not include the leaching requirement, special water requirements and other water needs (e.g. water losses);
- the calculated hydrant capacity must be compared to the design capacity of the hydrants.

*Hydrant type:* type of hydrant whether it is in-ground or surface.

*Hydrant design*: type of hydrant whether it is dry-barrel, wet-barrel, warm-climate, flush or flushing.

## Pipes and deliveries performance:

FIGURE A.3.46
**Main view of pipes and deliveries performance section in the pipes and deliveries block**



*Source: Screenshot of RAP v1 software*

*Pipe performance*

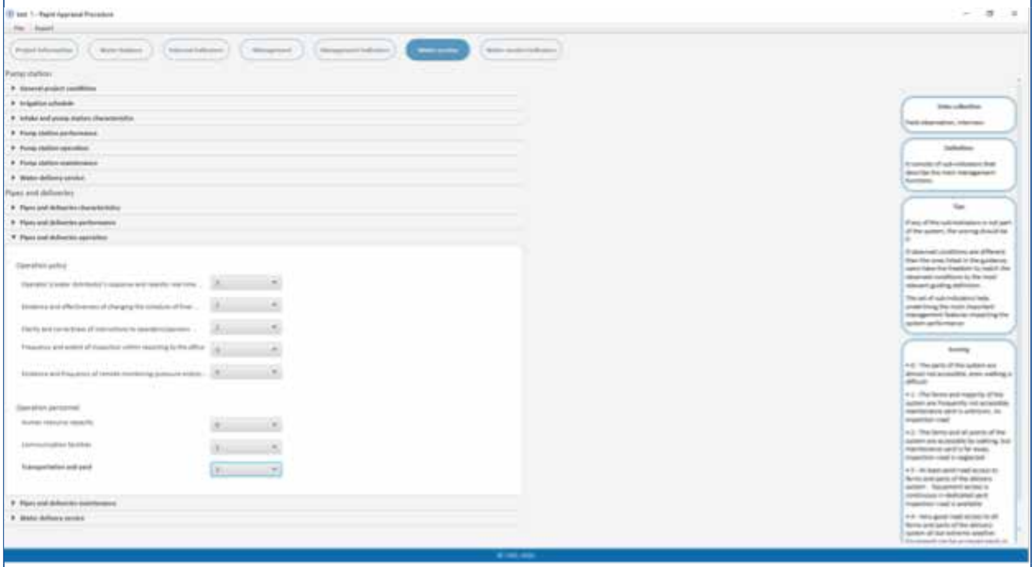
- the indicator consists of sub-indicators that describe the main items/functions of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators is not part of the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Hydrant performance*

- the indicator consists of sub-indicators that describe the main items/functions of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators is not part of the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Pipes and deliveries operation

FIGURE A.3.47
**Main view of pipes and deliveries operation section in the pipes and deliveries bloc**



*Source: Screenshot of RAP v1 software*

*Operation policy*

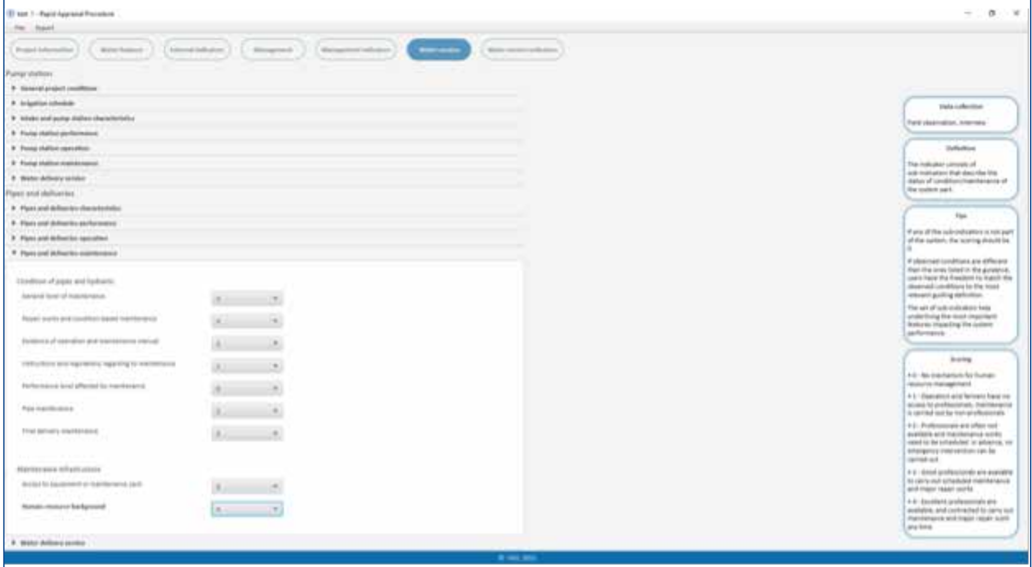
- the indicator consists of sub-indicators that describe the main management functions;
- the set of sub-indicators help underlining the most important management features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

*Operation personnel*

- the indicator consists of sub-indicators that describe the main management functions;
- the set of sub-indicators help underlining the most important management features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Pipes and deliveries maintenance

FIGURE A.3.48
**Main view of pipes and deliveries maintenance section in the pipes and deliveries block**



*Source: Screenshot of RAP v1 software*

*Condition of pipes and hydrants*

- the indicator consists of sub-indicators that describe the status of condition/ maintenance of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

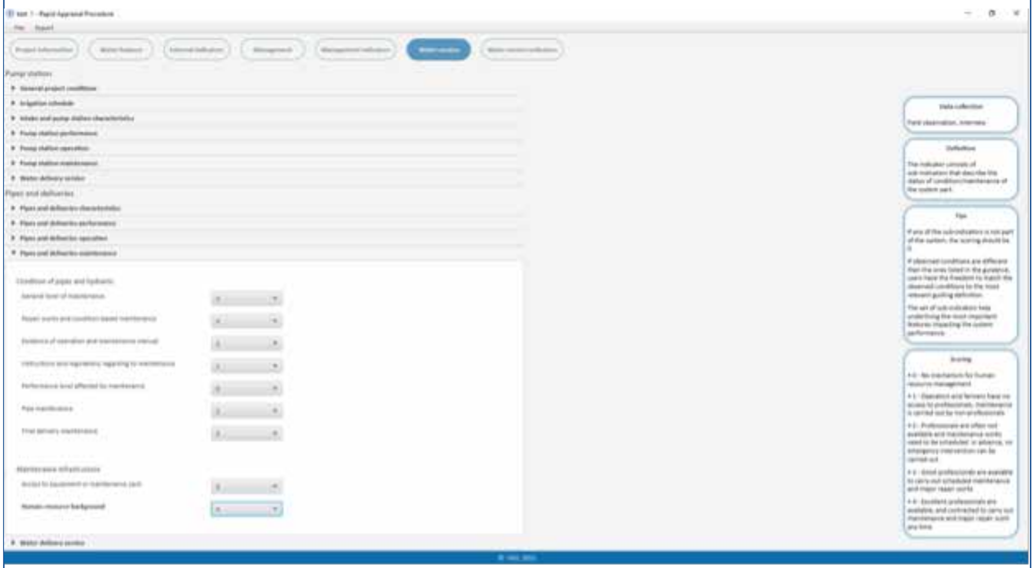
*Maintenance infrastructure*

- the indicator consists of sub-indicators that describe the status of condition/ maintenance of the system part;
- the set of sub-indicators help underlining the most important features impacting the system performance;
- scoring based on guidance listed under each sub-indicator;
- if any of the sub-indicators does not exist in the system, the scoring should be 0;
- the scoring (0-4) should be based on field observation and interview;
- if observed conditions are different than the ones listed in the guidance, users have the freedom to match the observed conditions to the most relevant guiding definition.

## Water delivery service

FIGURE A.3.49

**Main view of water delivery service section in the pipes and deliveries block**



*Source: Screenshot of RAP v1 software*

*Actual water delivery service provided to sub-pipelines operated by a paid employee (water user perspective):*

- the composite indicator consists of six sub-indicators: number of fields by sub-pipelines (branches), measurement of volumes delivered at this point, flexibility, reliability, equity, and adequacy;
- scoring is based on guidance listed under the sub-indicator;
- the sub-indicators should be evaluated considering only the system at sub-pipelines if it is operated by paid employees;
- the scoring should be based on the answers of the end-users. "Actual" water delivery service refers to the perception of the end-users (farmers). In order words, how the farmers evaluate the performance of the water delivery along the defined sub-indicators.

*Actual water delivery service received by individual units - fields and farms (water user perspective):*

- the composite indicator consists of five sub-indicators: measurement of volumes delivered at this point, flexibility, reliability, equity, and adequacy;
- scoring is based on guidance listed under the sub-indicator;
- the sub-indicators should be evaluated considering only the received service by individuals/farms or farmers;
- the scoring should be based on the answers of the end-users. "Actual" water delivery service refers to the perception of the end-users (farmers). In order words, how the farmers evaluate the performance of the water delivery along the defined sub-indicators.

### A.3.5.7. Water service indicators

The water service chapter results in internal indicators 2. that are constructed to interpret the physical water service performance. The definitions are explained according to the structure of internal indicators.

However, not all input data/information are directly analysed in the Internal Indicators. While preparing the analysis and narrative of the chapter, it is important to understand that both the input data/information and the Internal Indicators are necessary to compile a meaningful report. While the input data/information helps users to properly frame the assessment, they provide underlying information about the achieved indicators. While it is recommended to use the input data/information to set the scene and introduce the management, the Internal Indicators are the outputs, meaning the results of the performance assessment.

TABLE A.3.6
**Calculated parameters of Water service indicators**

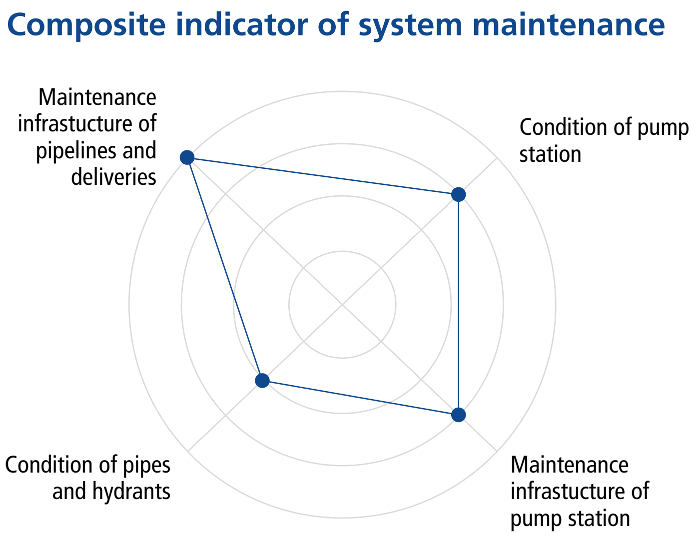
| Indicator | Units | Definition |
|---|---|---|
| | | **System capacity and delivery** |
| design capacity related to peak crop water requirement | unit | • The indicator expresses the ratio of pump capacity and the peak crop water requirement.<br>• If the ratio is less than 100 percent, the pump capacity does not supply sufficient water to meet the peak water requirement.<br>• If the ratio is more than 100 percent, the pump capacity exceeds the peak water requirement.<br>• The numerator refers to the total pump station capacity, and the nominator refers to the peak water requirement, calculated from the month with highest water demand. |
| criticality of pump capacity | - | • he qualitative assessment of the Design capacity related to peak crop water requirement:<br>o 0 (<80%) – very poor<br>o 1 (80-85%) – poor<br>o 2 (85-90%) – medium<br>o 3 (90-95%) – good<br>o 4 (>95%) – excellent |
| deviation from irrigation schedule at pump station (time based percentage) | percentage | • The difference between official and actual irrigation schedule at pump station level.<br>• The indicator shows the compliance with the official irrigation schedule, the higher the deviation the higher the non-compliance.<br>• The indicator calculates the deviation from the official schedule, therefore it takes account only of types indicated in the official schedule. |
| deviation from irrigation schedule at deliveries | percentage | • The difference between official and actual irrigation schedule at hydrant level.<br>• The indicator shows the compliance with the official irrigation schedule, the higher the deviation the higher the non-compliance.<br>• The indicator calculates the deviation from the official schedule, therefore it takes account only of types indicated in the official schedule. |
| criticality of irrigation schedule at pump station | - | • The indicator shows the compliance with the irrigation schedule. It is based on the calculated deviation of actual irrigation schedule from the official irrigation schedule at pump station level. The higher the deviation the lower the compliance.<br>• The qualitative assessment of the Irrigation schedule at pump station:<br>o 0 (>80%) – very critical<br>o 1 (60-80%) – critical<br>o 2 (40-60%) – medium<br>o 3 (20-40%) – good<br>o 4 (<20%) – excellent |

| Indicator | Units | Definition |
|---|---|---|
| criticality of irrigation schedule at deliveries | - | • The indicator shows the compliance with the irrigation schedule. It is based on the calculated deviation of actual irrigation schedule from the official irrigation schedule at final deliveries level. The higher the deviation the lower the compliance.<br>• The qualitative assessment of the Irrigation schedule at final deliveries:<br>o 0 (>80%) – very critical<br>o 1 (60-80%) – critical<br>o 2 (40-60%) – medium<br>o 3 (20-40%) – good<br>o 4 (<20%) – excellent |
| criticality of actual pump delivery capacity | - | • The qualitative assessment of the criticality of actual pump delivery capacity, calculated from the input data 'estimated actual efficiency of the pumps':<br>o 0 (<80%) – very critical<br>o 1 (80-85%) – critical<br>o 2 (85-90%) – medium<br>o 3 (90-95%) – good<br>o 4 (>95%) – excellent |
| criticality of hydrant capacity | - | • The indicator is calculated as the ratio of maximum hydrant discharge and required hydrant capacity.<br>• The required hydrant capacity is calculated from the peak water demand at hydrant level, the typical area size served by a hydrant and the indicated required hydrant elasticity:<br>o 0 (<80%) – very critical<br>o 1 (80-85%) – critical<br>o 2 (85-90%) – medium<br>o 3 (90-95%) – good<br>o 4 (>95%) – excellent |
| **Performance** | | |
| intake performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the intake performance per dimensions. |
| pump performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the pump performance per dimensions. |
| drain performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the drain performance per dimensions. |
| pipe performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the pipe performance per dimensions. |
| hydrant performance | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the hydrant performance per dimensions. |
| composite indicators of system performance | - | • The summary of composite indicator displays the overall performance of the system parts.<br>• It gives information on the comparative performance of the system parts. |
| **Operation** | | |
| pump station operation policy | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the effectiveness of pump station operation policy per dimensions. |

| Indicator | Units | Definition |
|---|---|---|
| pump station personnel | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the effectiveness of pump station personnel per dimensions. |
| pipes and deliveries operation policy | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the effectiveness of pipes and deliveries operation policy per dimensions. |
| pipe and deliveries personnel | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the effectiveness of pipe and deliveries personnel per dimensions. |
| composite indicators of system operation | - | • The summary of composite indicator displays the overall effectiveness of operation policies.<br>• It gives information on the comparative performance of the operation policies. |
| **Maintenance** | | |
| condition of pump station | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the condition of pump station per dimensions. |
| maintenance infrastructure of pump station | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the maintenance infrastructure of pump station per dimensions. |
| condition of pipes and hydrants | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the condition of pipes and hydrants per dimensions. |
| maintenance infrastructure of pipelines and deliveries | - | • The indicators are transferred values, whereas adequate score should be given, based on guidance.<br>• Together, the indicators can be visualized in one composite indicator/chart to compare the maintenance infrastructure of pipelines and deliveries per dimensions. |
| composite indicators of system maintenance | - | • The summary of composite indicator displays the overall effectiveness of operation policies<br>• It gives information on the comparative performance of the system maintenance. |
| **Water delivery service** | | |
| composite indicator of water delivery service that pump station provides to the pipe system | - | • The comparison between the indicators of the water delivery service from pump station to pipe system.<br>• The indicator compares the stated and actual water service, meaning the perspective of management and perspective of end-users.<br>• It shows the discord between the perceptions of farmers and the management. Therefore, whenever the difference between the indicators is high, the issue must be flagged and described. |
| Composite indicator of water delivery service provided for sub-pipelines operated by a paid employee | - | • The comparison between the indicators of water delivery service for sub-pipelines.<br>• The indicator compares the stated and actual water service, meaning the perspective of management and perspective of end-users.<br>• It shows the discord between the perceptions of farmers and the management. Therefore, whenever the difference between the indicators is high, the issue must be flagged and described. |
| Composite indicator of water delivery service received by individual units | - | • The comparison between the indicators of water delivery service received by individual units.<br>• The indicator compares the stated and actual water service, meaning the perspective of management and perspective of end-users.<br>• It shows the discord between the perceptions of farmers and the management. Therefore, whenever the difference between the indicators is high, the issue must be flagged and described. |

Similar to the management chapter, the indicators are visualized in charts. The visual objects can be exported in pdf file.

FIGURE A.3.50
**Exported chart from the water service chapter**




*Source: Elaboration through RAP v1 software*

## A.3.6. Update information about the RAP software

The manual is designed to the RAP software v1 launched in May 2021. Any change will be documented in the revision history file appended to the RAP software on the dedicated webpage.

## A.4. DESCRIPTION TEMPLATE FOR PRESSURIZED IRRIGATION SYSTEMS

| | | |
|---|---|---|
| Country: | | Location: |
| Analysis date: | | |
| Project name: | | |
| Project description: | | |
| Construction year:<br>• New project Year:<br>• Rehabilitation Year:<br>• Modernization Year: | | |
| Delivery schedule: | • On-Demand | • Rotation |
| Total project area (Command Area): | | Hectare |
| Total irrigated area (Served Area): | | Hectare |
| On-farm irrigation methods: Percentage from Total Irrigated Area | • Drip<br>• Sprinkler<br>• Surface | percent<br>percent<br>percent |
| Water source:<br>Note: | • Surface | • Groundwater |
| Maximum upstream piezometric elevation: | | m |
| Maximum upstream discharge: | | Liter/second |
| The number of served hydrants: | | |
| Minimum head at hydrants:<br>Note: | • Constant | • Variable |
| Hydraulic analysis:<br>Note: | • For the entire system (Indexed characteristic curve)<br>• At the hydrant Level (AKLA) | |
| Considered Indicators | • Relative pressure deficit<br>• Reliability | |
| Percentage of failed hydrants (from total):<br>Note: | | percent |
| The magnitude of failure: | • Acceptable<br>• Fair<br>• Bad<br>• Severe | |

| | |
|---|---|
| Failure description: | • Concentrated in one location<br>• Spread out through the network<br>• Old system |

Possible proposed solutions:

- Increase pipe sizes only in the sections of the network that cause significant pressure losses upstream of the critical zones;
- Install additional in-line lifting units, e.g. booster pumps;
- Impose restrictions on the freedom of farmers. This may be possible by installing special devices capable of stopping irrigation during peak demand hours;
- Adjust management guidelines;
- Increase the upstream pressure head (in case of pumping station);
- Improve on-farm practices;
- Enhance the design of the on-farm system to reduce head loss;
- Recommend irrigation out of peak hours for users in critical zones;
- Recommend low-pressure on-farm irrigation methods.

## A.4.1. Bazin roughness parameter (Γ) for different types of pipes

| TYPE OF PIPE | EQUIVALENT HOMOGENOUS ROUGHNESS E ( mm ) | Γ ( $m^{0.5}$ ) |
|---|---|---|
| **1- Technically smooth tubes (glass, brass, drawn copper, resin)** | 0 - 0.02 | -- |
| **2- Steel pipes** | | |
| A ) Time degradable coverings | | |
| - New pipes, varnished by centrifugation | 0.05 | -- |
| - Bitumened by immersion | 0.1 - 0.015 | ≤ 0.06 |
| - In current duty with light rust | 0.2 - 0.4 | 0.10 |
| - With asphalt or tar applied by hands | 0.5 - 0.6 | 0.16 |
| - With diffused tubercolisation | 1 - 3 | 0.23 |
| B ) Non degradable coverings | | |
| - Cement applied by centrifugation | 0.05 - 0.15 | ≤ 0.06 |
| **3- Welded sheet-pipes** | | |
| - In good conditions | 0.2 - 0.3 | 0.10 |
| - In current duty with crusting | 0.4 - 1.0 | 0.16 |
| **4- Nailed sheet-pipes** | | |
| - 1 line of longitudinal nails | 0.3 - 0.4 | 0.10 |
| - 2 lines of longitudinal nails | 0.6 - 0.7 | 0.16 |
| - Idem with crusting | Up to 3.0 | 0.30 |

| **TYPE OF PIPE** | **EQUIVALENT HOMOGENOUS ROUGHNESS** E **( mm )** | Γ **( $m^{0.5}$ )** |
|---|---|---|
| - 4-6 lines of longitudinal nails | 2.0 | 0.23 |
| - 6 lines of longitudinal nails + 4 transversal | 3.0 | 0.30 |
| - Idem with crusting | Up to 5.0 | 0.36 |
| **5- Cast iron pipes** | | |
| - With centrifuged-cemented covering | 0.1 | ≤ 0.06 |
| - New, covered internally with bitumen | 0.15 | 0.06 |
| - New, not covered | 0.2 - 0.4 | 0.10 |
| - With light crusting | 0.4 - 1.0 | 0.16 |
| - In current duty, partially rusted | 1.0 - 2.0 | 0.23 |
| - strongly encrusted | 3.0 - 5.0 | 0.36 |
| **6- Cement-pipes** | | |
| - Asbestos cement | 0.1 | ≤ 0.06 |
| - New reinforced concrete, plaster perfectly smooth | 0.1 - 0.15 | 0.06 |
| - Reinforced concrete with smooth plaster, in work for many years | 2.0 | 0.23 |
| - Tunnels with cement plaster, depending on the degree of finish | 2.0 - 5.0 | 0.23 - 0.36 |

# Mapping System and Services for Pressurized irrigation systems – MASSPRES

In 2007, FAO produced Irrigation and Drainage Paper 63: Modernizing irrigation management – the MASSCOTE approach. This is a methodology specifically designed to assist technical experts, irrigation professionals, and managers, engaged in the difficult task of modernizing medium and large-scale canal irrigation systems.

Pressurized systems bring simplicity to irrigating farmers, but they are inherently complex both in terms of their design and operation in meeting the changing water demands associated with on-demand irrigation. To support both improving the performance of existing systems and the design of future systems, pressurized irrigation needs the equivalent of MASSCOTE methodology to provide a step-by-step process to diagnose deficiencies and establish plans for modernization.

This publication builds on the holistic approach of MASSCOTE to provide a framework for assessing and improving the overall performance of medium and large-scale pressurized irrigation schemes. Known as Mapping System and Services for Pressurized irrigation systems (MASSPRES), it introduces the MASSPRES approach and the step-by-step diagnosis of system performance. An important first step is the Rapid Appraisal Procedure (RAP), which is central to mapping the system performance. The complexities of managing demand under unsteady flow conditions are described together with innovative methods for assessing acceptable pressures and discharges at farm hydrants under a wide range of operating configurations rather than relying on the earlier methods of statistical analysis. Various indicators are developed to assess capacity, reliability, equity of distribution, sensitivity to change, and the risks of perturbation and incorporated into user-friendly software. Practical examples and case studies in Egypt, Italy, Spain, and Tunisia demonstrate the effectiveness of this approach and offer evidence-based solutions to improving performance.

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