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Abstract

We describe a water distribution problem in the region of Kabylia, Algeria. We aim at distributing water in a reliable and cost-efficient way. The problem involves the optimization of the pump operational schedules, as well as strategic planning. The complex rules establishing energy fares depend on the daytime and the contractual issues of the pump facility. Inclusion of new pipes, tank sizing and placing and new pumps are also considered as design variables. The latter requires additional considerations regarding the water system operation over the demand period. The hydraulic simulation model of our network comprises about 100 pipes, 150 nodes, 38 storage tanks, and 22 pumps in six pumping stations. We discuss the relevance and implementation of different alternatives in this context which will, eventually, improve current management procedures.

Résumé

Cette étude décrit une problématique concernant la distribution d'eau dans la région de Kabylie, en Algérie. Le but principal est de distribuer l'eau d'une manière fiable et rentable. Le sujet en question concerne l'optimisation des horaires de fonctionnement de la pompe, ainsi que la planification stratégique. La complexité des règles qui établissent les tarifs d'énergie dépendent du rang horaire de la journée et du type de contrat d''installation de la pompe. L'addition de nouveaux tuyaux, d'un réservoir de dimensionnement et de placement sont également considérées comme des variables du modèle de conception. Celui-ci exige des considérations supplémentaires sur le fonctionnement du réseau d'eau pendant la période de demande. Le modèle de simulation hydraulique de notre réseau comprend environ 100 tuyaux, 150 nœuds, 38 réservoirs de stockage, et 22 pompes distribués en 6 stations de pompage. Nous discutons de la pertinence et la mise en œuvre de différentes solutions dans ce contexte, qui, à terme, amélioreront les procédures actuelles de gestion.

Keywords: Linear-integer optimization, pump scheduling**,** strategic planning.

1. INTRODUCTION

This study stems from a real case in water distribution in a rural area of Kabylia, Algeria. In a first approach, the scenario may be described as a relatively standard water distribution problem. In this way, water comes from several wells, with various intermediate water deposits and pumping stations, and consumption takes place in different villages, with a very disperse population. Traditionally, the Kabylians have preferred to live up in the mountains, and this creates important engineering problems, with a high distribution costs due to electricity consumption in pumping.

Water scarcity is a common issue in the Kabylia, mainly due to significant water losses in the network. This paper investigates the application of mixed linear-integer optimization models to identify the trade-off characteristics between the total cost and the quality of the water supply of Kabylia's water distribution system. Tank sizing, pump capacities, and pump operational scheduling are also considered as design variables. The latter requires taking into account the water system operation over the demand period. We provide results for the trade-off characteristics, for a 48-hour horizon, different infrastructure settings and demand scenarios.

2. THE KABYLIA NETWORK

The region of Tizi Ouzou (*La Grande Kabylie*), is in the North-east part of Algeria, bounded in the north by the Mediterranean Sea, in the east by the region of Bedjaia, in the West by the region of Boumerdes, and in the South by the region of Bouira. The total area of the region of Tizi Ouzou is 2957 km^2, 80% of which lies on slopes greater than 12%. It is composed of 67 municipalities (1380 villages), with a total population of more than 1.1 million people. However, in this first approach we have developed a model for a portion of the total distribution network, the so-called “Chaine de Tassadort”, with 110,000 people living in 90 villages. Most of the population is located in mountainous areas with altitudes over 900 m in some cases. Annual rainfall is around 900 mm. The *L’Algerienne des Eaux* Company (ADE) supplies water in the region. In 2009 the reported volume of water supplied amounted to 6,500,559 m^3, but only 1,696,294 m^3 (a 26%) was billed, a huge loss which results in a significant shortfall. These losses are mainly due to leakages, thefts and outdated conductions and components in the networks. The network is fed by groundwater (72%) through several wells that extract water from the Oued Sebaou river, specifically:

- 9 wells in the field of Bouaid with a total pumping capacity of 1,040 m^3 h^{-1}.
- 5 wells in the field of Takhoukhte with a total pumping capacity of 140 m^3 h^{-1}.
- Surface water drawn from the Taksebt reservoir, an alternative source, which has produced 295,347 m^3 in the first quarter of 2010.

The network also includes 38 reservoirs (with a total storage capacity of 28,000 m^3), 6 pumping stations (with 22 fixed-rate pumps and a total pumping capacity of 5,400 m^3 h^{-1}), and a network of pipes with a total length of 25,000 m. The daily average consumption is, approximately, 19.000 m^3. The peak demand within a one hour period is estimated to be around a 6% of the daily demand.

3. FORMULATING THE OPTIMIZATION PROBLEM

In our problem, we aim at optimizing the operational performance of the network, as well as minimizing the energy costs. To do so, we need some means of predicting the consequences of different pump settings on the behavior of the network. Some approaches have used hydraulic simulators (Salomons, 2007), but in this work we propose an optimization model, in which the behavior of the hydraulic transport is incorporated in the formulation of the problem as additional constraints. In this setting, some approaches use linear or dynamic programming (Kessler et al., 1989, Fujiwara et al., 1990) but in our case we have developed a mixed linear-integer optimization model, to deal with the integer character of the pumping decision variables.

3.1. Decision Variables

The operative pumps at each period time are represented by integer 0–1 variables, denoting the current state of the pump, OFF or ON. For the optimal operational scheduling problem, the linear variables are: the flow in each pipe, and the integer variables are relative to the pump state.

Regarding the strategic optimization problem, the model includes additional integer variables which represent the inclusion of new facilities, like bombs, tanks or pipes. Every node in the network is a possible location for new tanks, and every pump station has the possibility of adding new pumps.

3.2. Objective function

There is a great consensus in the literature around the fact that water systems are mostly multi-objective (DeNeufville et al., 1971, Walski, 2000). Therefore, the operational objective function tries to determine the most cost-effective pumping and storage scheduling. It also aims at providing an effective design to enhance the current system, satisfying the demands in a more reliable way, and without violating any of the operational constraints. Usually, the operating cost equals that of the energy cost needed for pumping.

The reliability in the supply may be regarded as an objective itself, or as an operational constraint, depending on the level of the demand. In water distribution systems, the term reliability usually refers to the capacity of the network to provide the consumers with an adequate and quality supply, under either normal or abnormal conditions. The reliability of water systems can be studied considering two types of failures. Mechanical failures usually refer to failures on the system components, such as pipe breakage or pumps being out of service. On the other hand, hydraulic failures have to do with random issues, such as forecasting the demand or estimating the cost.

3.3. Constraints

The operational constraints comprise the standards in customer's service, such as e.g. the minimum statutory delivery pressure, as well as physical constraints, such as the maximum and minimum water levels in storage tanks to prevent overtopping and emptying, respectively. Additional operational constraints that must be also taken into account are: maximum limit on power consumption at each pumping station, maximum capacity of each pipe and satisfaction of the demand.

3.4. Setting the initial and final simulation times

As we have previously said in Section 3, our aim is to minimize the operating cost. In this regard, a well-known fact is that the cost of supplying water from storages is always cheaper than pumping it. But we must be careful with that, because we could be tempted to extract too much water from the storages, making it impossible to refill them for the next daily cycle. Then, we must ensure that the possibility of jeopardizing the supplies for the future, in exchange for a short-term gain, will not occur. To do so, we must impose an operational constraint on each storage tank, requiring them to have a minimum prescribed water level at the start of each simulation period. Besides, the initial simulation time is set at midnight, local time, when a nightly energy fare applies and there is a lower demand.

3.5. Operating horizon and time-step

The choice of the time-step used in the simulation is crucial for the computational burden of the problem. A fairly conservative time-step of 1 h was adopted in our experiment, as a trade-off between what would be desirable in real-time scheduling and the need of completing the computation before the next update. While it is possible to envisage a rolling operating horizon longer than 24 hours in those places where the storage available is exceptionally large, most of the water-distribution networks operate on a 24 hours-cycle basis, refilling the tanks at night, and pumping water from them during the daytime. However we have set a 48 hours simulation period to consider two consecutive days with significant variations in demand.

3.6. Energy tariff structure

There are additional considerations regarding the energy fare policies existing in Tizi Ouzou that we must take into account in our problem. Table 1 shows the energy costs per hour, depending on the time period (night, flat, peak) and on the specific plant from which the water is pumped.

Table 1: Pumping cost for different day periods and facilities (DA: Algerian Dinar)

Facility fare	Day period	Cost (DA/kWh)
E41	Night	85.33
E41	Flat	161.47
E41	Peak	726.28
E42	Night	150.53
E42	Flat	150.53
E42	Peak	126.68

4. OUTLINE OF METHODOLOGY USED

We have set a basic 48 hours scenario in springtime (with an average demand of 150 liters per day per person), assuming losses in the network. Water demand variations also occur on a daily basis, and can be shown on a demand curve, which plots the percentage of daily demand versus time (Figure 1). In this approach, we assume the same daily water demand on every village. Different scenarios were generated varying the water demand and the infrastructure available on the network.

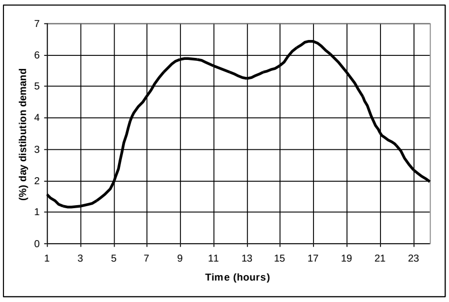

Fig 1: Average daily demand

Regarding the variations on the demand, one of the main problems to solve are network losses. We analyzed the current situation (without losses) and two hypotheses of distribution network losses.

Regarding to changes on the available network infrastructure, we have analyzed four alternatives. Two of them correspond to problems with any of the following network elements: the Takhoukhte pump station, and the pipe connecting Ait Anane to Djouad. The third one considers the optimal network infrastructure. To define this scenario, we have implemented an optimization model to perform an optimal infrastructure analysis. Thus, this strategic model selects which infrastructure should be changed in order to reduce the operational cost and maximize the reliability of the supply.

5. RESULTS

Table 2: Relative quality and cost for the different demand and infrastructures situations.

Scenario / Infrastructures	Base		50% Losses		80% Losses	
	Cost	Quality	Cost	Quality	Cost	Quality
Current	1,00	100%	1,27	99,8%	1,66	97,95
Optimal Infr.	0,88	100%	1,18	99,8%	1,62	98,1%
Takhoukhte failures	1,08	100%	1,68	98,7%	1,79	95,2%
Ait Anane-Djouad failures	1,11	96,6%	1,14	93,1%	1,25	89,3%

Table 2 shows a comparative summary in terms of the cost and quality of the supply in all the models explained above, combining the demand scenarios and different infrastructure settings. The cost is a relative value, compared to the basic scenario, for which it has a value of 1. The quality value is 100 % when the network demand is satisfied, and is reduced proportionally to the number of customers who are not supplied.

This causes that for the current network and the scenario with 80% of losses, increases by 274% the total pumping cost with respect to the base demand. With the "optimal" network infrastructure, significant reductions in the operation cost are achieved (12% in the basic case). The optimal network infrastructure essentially increases the Mezdata (500 to 1500 m^3) and Ait Annane Haut (200 to 800 m^3) storage capacity, and double the Takhoukhte (140 to 280 m^3 h^{-1}) pumping capacity. The saving in the cost is achieved through this increase because it is possible to pump more water at night when the electricity cost is lower. For situations with water losses, the saving is less significant because the infrastructure optimization is conducted in the base demand situation. Although originally dispatched from Takhoukhte came up with the idea of raising the guarantee of supply, is also seen that important cost reduction occurs. If we look at the Ait Anane-Djouad pipe failure, it may seem that leads to increased costs, but the most significant problem is the important deterioration in the quality of supply.

Table 3 shows pumped quantities comparison for each pumping station in the tree scenarios. It shows the m^3 average pumping cost in each station relative with the m^3 average pumping cost for all the pumping stations in the Base situation. Note that, the more expensive pumping costs are in Tassadort pumping station. This is logical, because it should be pump the water from Tassadort to Mezdata two villages with great altitude difference.

Table 3: Pumping stations data

Scenario / Infrastructures	Base		50% Losses		80% Losses	
	Q(m^3)	Cost	Q	Cost	Q	Cost
Agouni Arous	5600	0,50	5600	0,55	6580	0,87
Ait Anane	6480	0,47	12420	0,73	11880	0,76
Oued Sebadou	27290	0,62	43170	0,81	47320	1,02
Takhoukhte	5600	0,56	5600	0,61	6580	0,92
Taoudouft	2475	1,16	3525	1,72	3300	1,77
Tassadort	22050	1,85	35550	2,18	39150	2,95

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