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Multi Sources Water Supply System Optimal Control: A Case Study

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Abstract

The optimal operation of a multi quality network was analysed applying Linear Programming methods. The peculiar service condition of the industrial city of Gela (Italy) was investigated. The network is supplied both from waters derived from a desalination plant and other natural sources. The method aimed to minimise energy cost and find the optimal operation control, while satisfying demand and quality constraints, specifically with regard to water temperature. The method proved to be effective in the selection of the optimal management strategy after the definition of a specific water quality target.

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Keywords: Optimization; water quality; desalination; multi source supply.

1. Introduction

In management of water supply systems, many efforts have been made on planning and design of networks and facilities, real time operations, guidelines establishments. Designers, utilities, and regulating agencies are interested to develop simulation and optimization algorithms for modelling water quality, and several approaches have been proposed. Shamir and Howard [1] classified water quality models for water distribution system with respect to the flow conditions in the network and the substance concentration in the source. According to the systems analysed (agriculture, industry, municipal water distribution systems) water models can be divided in: 1) steady flow-steady concentration, 2) steady flow-unsteady concentration, 3) unsteady flow-steady concentration and 4) unsteady flow-unsteady concentration. As underlined by Ostfeld [2] the interest in modelling flow and quality has been oriented on both use of water from sources with different qualities in a single distribution system, concern in municipal water distribution system over quality changes such as decay of disinfectants and/or growth of organisms, and deliberate or accidental events in which contaminants enter into the system.

In literature, several optimization methodologies have been proposed to deal with multi quality water resource management problem. The optimal allocation of water derived from different commodities (e.g. surface water, ground water, desalinated sea water) is generally found by minimizing a cost function which includes pumping cost and source cost while satisfying water quality constraints. In fact, water agencies often find that it is necessary to impose blending requirements at certain control points in the system, in order to secure the desired water quality downstream of the control points. Yang et al. [3] proposed a nonlinear multicommodity flow model to optimize water delivery, while at the same time meeting blending requirements. Whereas, a linear programming approach was applied by Campbell et al. [4]. Tu et al. [5] developed a multicommodity flow model in a regional water supply system. The optimization problem was solved by coupling genetic algorithm and a generalized reduced gradient.

In addition to optimization of the water blending problem, Peng et al. [6] presented a rapid fuzzy optimization approach with regards to minimization of harmful reactions in water distribution networks. As shown by experimental studies [7] water quality can be affected by corrosion product release which changes with blends chemical and physical characteristics. Imran et al. [7] have developed a multiobjective technique to evaluate the blending rate to identify acceptable water quality for simultaneous control of corrosion.

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Recently, Avni et al. [8] focused on the optimization of desalinated sea water blending with other sources by considering source cost, pumping cost and re-mineralization cost. Mineral deficiencies are a very common problem in desalinated waters, and it can be overcome by adding minerals directly at the desalination plant or locally along water distribution networks. Alternatively, quality standards can be met by blending high quality and low quality water, which involves savings. Housh et al. [9] proposed a deterministic model designed to minimize operating costs, linked to desalination, extraction levy from natural resources and conveyance, over a planning horizon of several years with salinity constraint. In drought conditions sea water desalination appears as a viable solution, several planning activities are undertaken both by national and EU level [10].

In the present paper, the peculiar service condition of the industrial city of Gela (Italy) is analysed. The municipal water distribution system is supplied by multi quality commodities. In particular, the water utility receives free-water from the desalination plant of an oil refinery, as environmental repayment, and buys surface or ground water from a wholesale drinking water supplier. Such supply system leads on collecting much water as possible from the desalination plant, respect to surface/ground water source due to its reduced cost. Unfortunately, desalinated water is often not suitable for potable water use due to its temperature rather than salinity. Therefore, the aspect relating to operating temperature is investigated. The proposed method aimed to minimize energy cost, while delivering to all consumers required demand with acceptable water temperature.

In the following sections, after the description of the methodology, information about the case study are provided. Thereafter, results and discussion are presented and some conclusions are drawn.

2. Methodology

2.1. The optimization problem formulation

The optimization problem is formulated in order to minimize energy and source costs related to water supply systems fed by different quality water resources. Energy cost is linked to pumping station operational power, while source cost depends on water industry wholesale services. Water quality is investigated with regard to temperature: water from desalination process can be warmer than that from natural resource. Hence, water volumes can be mixed to reduce temperature up to the law threshold.

Linear Programming (LP) has been selected for determining optimal operation flow rate for each pumping station for each hour of the simulation period and the optimal water volume per unit time supplied by natural resources, while maintaining physical and hydraulic constraints [11]. Linear programming is one of the most widely used techniques in water resources system management [12, 13]. In addition to the well-known simplex algorithm, the Khachian's ellipsoid algorithm and the Karmakar's projective interior point algorithm are often used to solve linear programming problems [14]. Among many general algorithmic approaches, the most effective has proven to be the primal-dual infeasible-interior-point approach, including a number of variants and enhancements such as Mehrotra's predictor-corrector technique [15]. This last approach was implemented under MATLAB [16] environment by Zhang [15] to take advantage of MATLAB's sparse-matrix functions and external interface facilities.

The optimization of multi quality sources problem poses as follows:

$$\min \sum_{t=0}^{T} c_{p,t} \cdot Q_{p,t} + c_{s,t} \cdot Q_{s,t} \tag{1}$$

Subject to:

$$S_{\min} \le S_t \le S_{\max} \tag{2}$$

$$Q_{\min} \le Q_t \le Q_{\max} \tag{3}$$

$$\sum_{t=0}^{T} Q_t = \sum_{t=0}^{T} q_t \tag{4}$$

$$Q_t \cdot \Delta t + \left(S_t - S_{t-1}\right) \cdot A = q_t \cdot \Delta t \tag{5}$$

where $Q_{p,t}$ are the unknown pump station discharges, $Q_{s,t}$ the unknown flow rate from natural resources, $c_{p,t}$ and $c_{s,t}$ the objective function coefficients related to pump station and natural resources, respectively. S_{min}, S_{max} are the lower and upper bound of the tank water levels while Q_{min}, Q_{max} are those related to the pump station discharges and natural resources; q_t the known demand, A is the tank surface area, S_t, S_{t-1} are the tank water level at time t and $t – 1$ respectively; Δt is the optimization control interval (often fixed to 1 hour).

Prior to solving the system of linear equations, the objective function coefficients $c_{p,t}$ have to be evaluated. In addition to the electricity tariff, these coefficients take into account the network hydraulics, or more precisely, the effect of the water distribution system hydraulic conditions on pump hydraulic power. The pump energy consumption is dependent upon the pump total head which is connected to the pipe resistance curve upstream and downstream of the pump. If the head lift across the pump does not vary by more than few meters, the pump operates practically at the same point on its pump curve.

As mentioned above, the quality parameter selected for this analysis was water temperature. According to the heat transfer law, two fluids reach thermal equilibrium when temperature within the system is temporally and spatially uniform. For the temperature constraint definition, the following assumptions are needed:

- heat loss/gain along pipe system is neglected;
- heat transfer takes place only between waters entering in the tanks, in which complete and instantaneous mixing occurs;
- waters have the same chemical characteristics;
- only seasonal temperature variation is considered for the analysis.

Known temperature of waters entering in a tank, the optimal blending (or mixing) ratio *r*, with regard to resource with higher temperature, can be defined as:

$$r = \rho q_t \Delta t \frac{(T_e - T_1)}{(T_2 - T_1)} \tag{6}$$

Where ρ is water density which is considered constant, T_e is the temperature at the thermal equilibrium, T_1 and T_2 are the temperature of water provided by different sources, with $T_1 < T_2$.

2.2. Case study: Gela water supply system

The methodology above described was applied to the water supply system of Gela city (Italy). The water service conditions occurring in Gela are very peculiar. The water utility receives free-water from the desalination plant of an oil refinery compound according to environmental mitigation agreements. The desalinated water is pumped by three different pump stations to three tanks, respectively. Each pump station is characterized by four pumps of which characteristic curves are presented in Fig. 1.

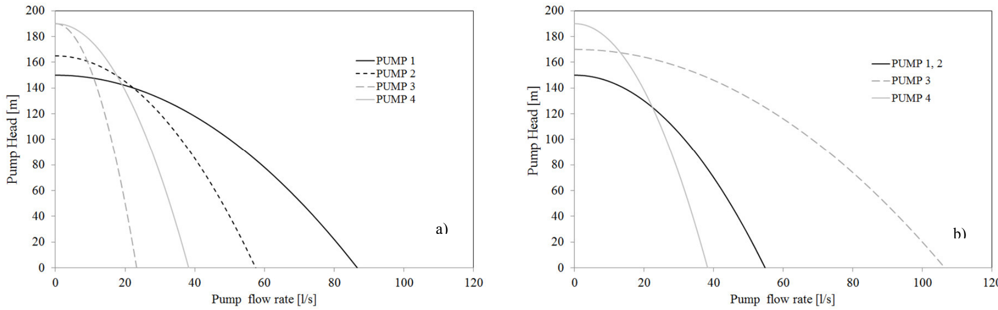

Fig. 1 Pump characteristic curves: a) pump station 1, b) pump stations 2 and 3

Although the use of the desalinated water represents, in principle, a cost-effective solution, often water is not suitable for potable use due to its temperature. As shown in Table 1 the water temperature can reach 30°C in the summer season (August-September). Several water sources, which water utility has to pay for, are also available. Most of them are located far away and connected to the water distribution system by means of several tanks, where water is mixed with that derived from the desalination plant. In Fig. 2 a schematic of the water supply system is shown. In Table 2 the average annual water volumes supplied to Gela by four different water resources are reported.

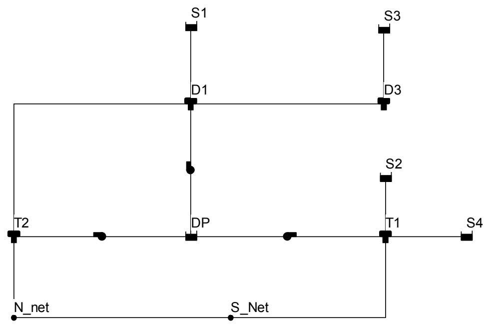

Fig. 2 Schematic of the water supply system

Table 1. Average monthly temperature of desalinated water

Average monthly water temperature (°C)					
January	February	March	April	May	June
22.0	22.0	22.0	22.0	23.1	26.1
July	August	September	October	November	December
28.4	30.5	31.0	26.5	22.0	22.0

Table 2. Average annual water volumes supplied to Gela and unit cost

Natural resource	Unit Cost [€/m^3]	Maximum available volume [Mm^3/year]
S1	0.67	4.5
S2	0.77	3.3
S3	0.57	0.63
S4	0.57	7.0

The water distribution network can be fed by two tanks at different levels, respectively T1 tank (86 m a.s.l) and T2 tank (59 m a.s.l), that can store up to 25,000 m^3 per day, and supply around 73,000 inhabitants.

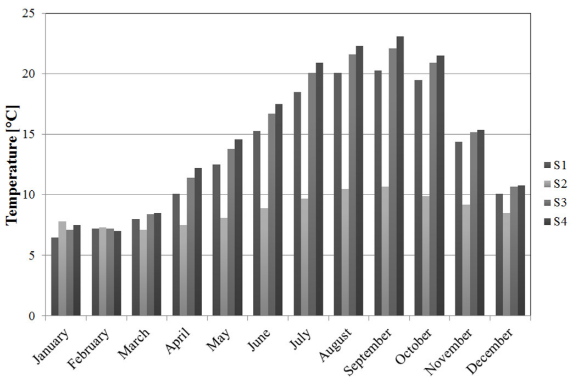

Fig. 3 Average temperature patterns for the different natural water resources

The electricity tariff is grouped in three hourly period: low charge (0.0934 €/KWh) from 10pm to 6am; moderate charge (0.1568 €/KWh) from 7am to 10am and 3pm to 9pm; and peak charge (0.1922 €/KWh) from 11am to 2pm. Natural water have to paid to the supplier according to a general regional agreement and the unit cost is presented in

Table 2 and the average weighted cost is 0.64 €/m^3. Temperature of natural waters is variable in time depending on climatic conditions: surface waters are characterized by larger variability and underground water resources have a more stable temperature during the year (Fig. 3)

3. Results and discussion

Some scenarios were considered in order to setup the optimal utilization of different water resources in order to comply with the limitations on supplied water temperature. Initially the Scenario 0 was considered in which water temperature is maintained under the law limits (25°C). In brief terms, this Scenario allows for the total utilization of desalinated water between November and May. During the remaining months, natural sources have to be mixed in the different urban tanks in order to maintain the prescribed temperature limits.

In the Scenario 1, network configuration is maintained like the present one with different districts supplied by different tanks. In such a Scenario, equilibrium temperature was reduced in order to increase the organoleptic qualities of supplied water. Three target temperature patterns were considered and presented in Fig. 4. The target temperature patterns were hypothesized maintaining the law limits for the summer period in which even natural surface water resources are characterized by high temperatures. During other seasons, water temperature was reduced in progressively in order to maintain organoleptic characteristics of drinking waters.

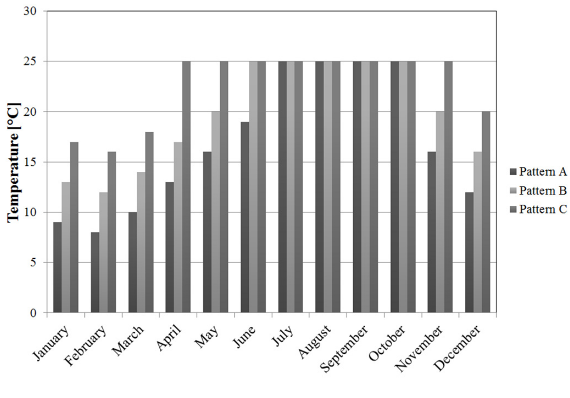

Fig. 4 Analysed temperature patterns

In the Scenario 2, all water resources are conveyed to the bigger tank of the network (T1), which elevation is compatible with the elevation of the whole network, they are mixed and then supplied to the users. This approach should provide a better mixing of water resources thus reducing overall costs. Also in Scenario 2, a constant temperature (like in Scenario 0) was considered as well as the three temperature patterns proposed in Fig. 4.

Fig. 5 shows the optimal results for Scenario 0 in which the only limit is given by law. The higher water supply costs are related to summer months in which higher amounts of natural water are needed to mitigate the desalinated water temperature. The costs during winter months are mainly due to pumping station energy and the minimum natural water supply that is needed for the connections between water resources and the local tanks.

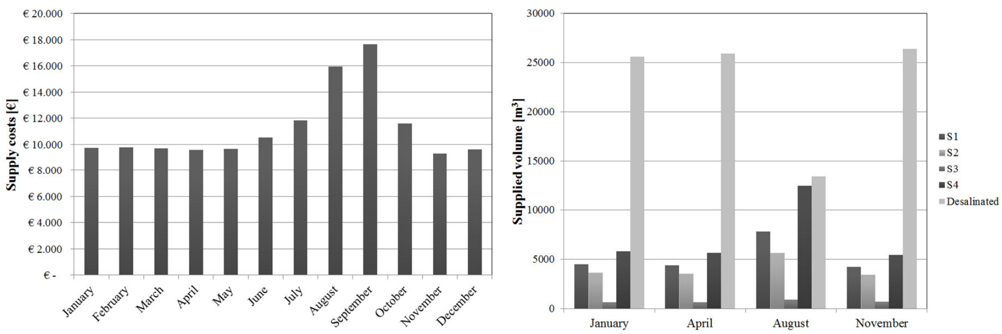

Fig. 5 Supply costs in Scenario 0 (on the right) and utilization of different water resources in selected months (on the right)

Fig. 6 shows the results analysis of the three temperature patterns. The patterns are all characterized by the adoption of the maximum allowed temperature in the period July – October; pattern A assumes lower temperatures during the rest of the year in order to improve the quality of supplied water thus requiring higher costs. Pattern A reports higher costs during winter due to the stringent limitations on maximum water temperature requiring higher amounts of natural resources. Patterns B and C shows lower costs and a large use of desalinated waters during winter. The costs are always higher than Scenario 0 even if the increment is limited to 15% for Pattern C and 32% for pattern B. The use of water resources is obviously imbalanced towards the use of natural resources with pattern C requiring the use of only 28% of desalinated resources (compared to 62% of Scenario 0).

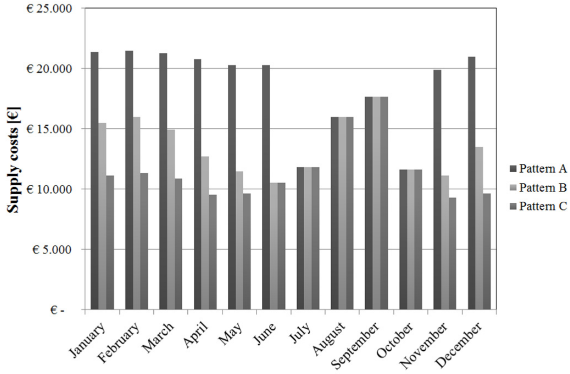

Fig. 6 Supply costs in Scenario 1

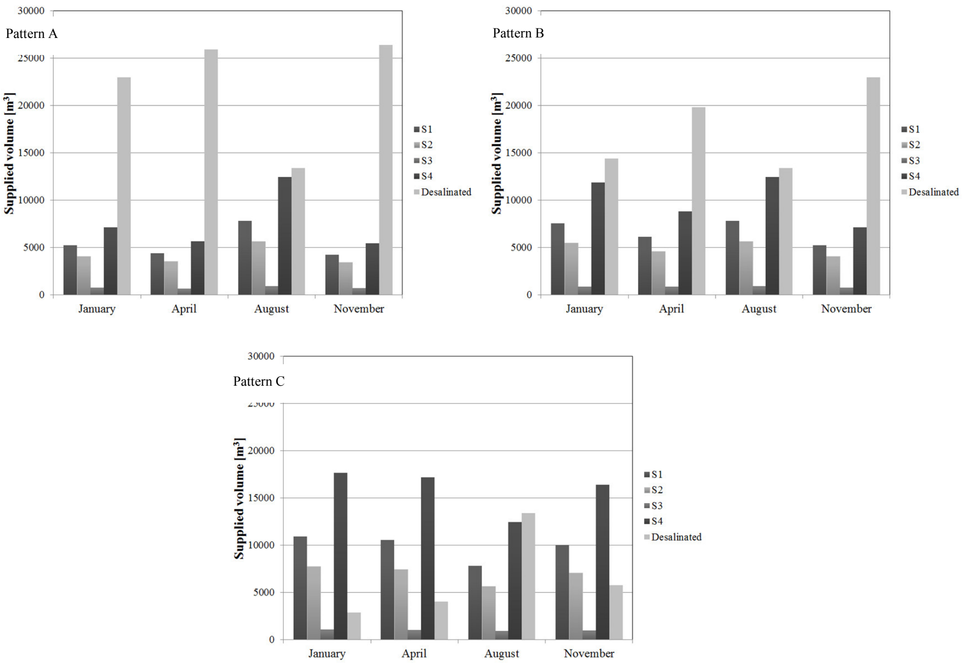

Fig. 7 Utilization of different water resources in selected months in Scenario 1 for the patterns A, B and C respectively

Fig. 8 and 9 show the results analysis for Scenario 2. The patterns are all characterized by the adoption of the maximum allowed temperature in the period July – October; pattern A assumes lower temperatures during the rest of the year in order to improve the quality of supplied water thus requiring higher costs. Pattern A reports higher costs during winter due to the stringent limitations on maximum water temperature requiring higher amounts of natural resources. Patterns B and C shows lower costs and a large use of desalinated waters during winter. The costs are always higher than Scenario 0 even if the increment is limited to 15% for Pattern C and 32% for pattern B. The use of water resources is obviously imbalanced towards the use of natural resources with pattern C requiring the use of only 28% of desalinated resources (compared to 62% of Scenario 0).

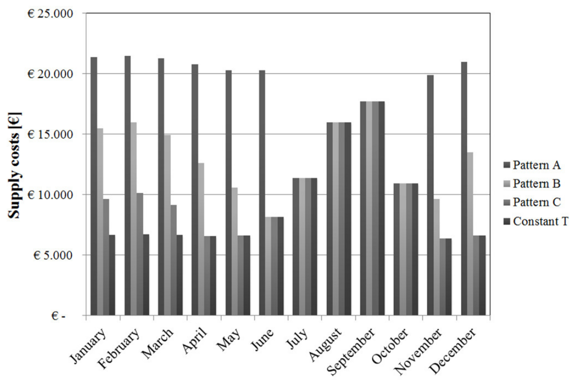

Fig. 8 Supply costs in Scenario 2 considering the three temperature patterns and the constant maximum temperature fixed by law

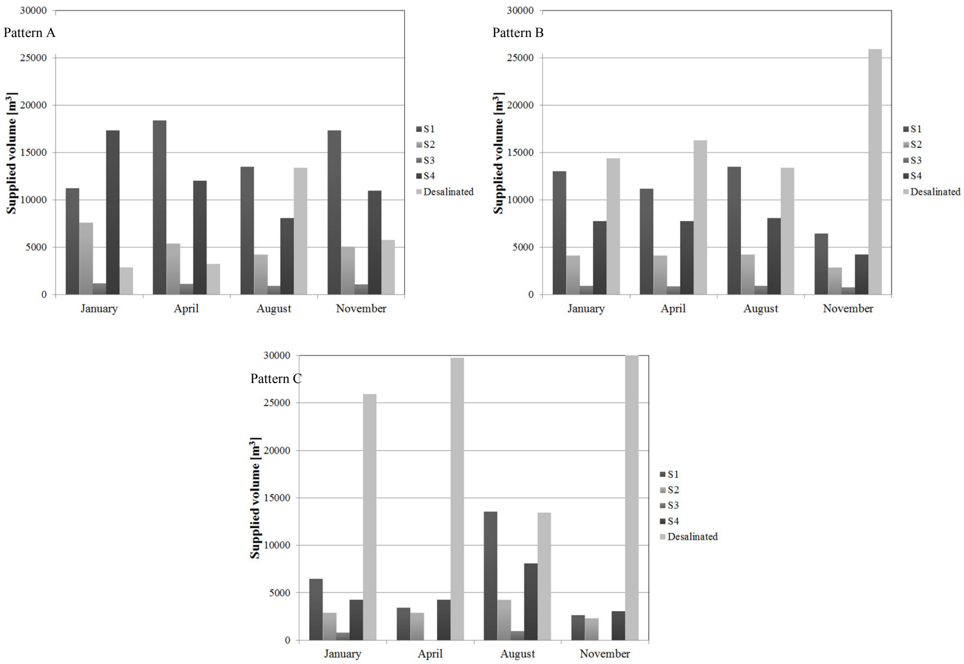

Fig. 9 Utilization of different water resources in selected months in Scenario 2 for the patterns A, B and C respectively

Interestingly, the use of a single mixing tank in Scenario 2 has an opposite impact on different target temporal patterns: analysing high temperature targets (Pattern C and fixed maximum temperature by law), Scenario 2 proved to be more efficient and the supply costs are lower especially in winter. Pattern A and B are indifferent or more expensive in every month. This can be explained with the better use of small amounts of natural resources to mitigate the temperature of desalinated waters. The mixture of waters has a negative effect in case large amounts of natural waters are mixed with small amounts of desalinated waters compromising the achievement of restrictive temperature targets (Pattern A and B).

4. Conclusions

The present paper showed the application of linear programming optimization aimed to the achievement of least cost management solution maintaining adequate supplied water quality targets.

The approach demonstrated to efficient to highlight the best compromise between the use of natural fresh resources and desalinated water considering that this last one is characterized by high temperature that are not compliant with drinking use.

The analysis demonstrated the efficiency of some management scenarios including the adoption of more restrictive temperature patterns to improve organoleptic characteristics of the supplied water and the use of a single mixing tank to collect all water resources before the distribution to different districts.

The analysis of results demonstrated that more restrictive temperature targets are feasible with small increase of the supply cost. Moreover the use of a single mixing tank is not always a good solution taking in some of the scenarios to the increase of supply cost with respect to the optimum.

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