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Multi-criteria optimization of supply schedules in intermittent water supply systems

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ABSTRACT

One of the problems for water supply systems with intermittent supply is the peak flow produced at some hours of the day, which is usually much larger than that in a system with continuous supply. The main consequence is the reduction of pressure and flow at the ends or highest points of the system network. This, in turn, generates inequity in water supply and complaints from users. To reduce the peak flow, some sectors of the system must be assigned a different supply schedule. As a result, the supply curve is modified, and the peak flow is reduced. This reorganization seeks some optimal allocation schedule and must be based on various quantitative and qualitative technical criteria. This paper hybridizes integer linear programming and multi-criteria analysis to contribute with a solution proposal to the technical management of intermittent water supply systems, which provides short-term results and requires little investment for implementation. This solution does not seek perpetuating intermittent water supply. On the contrary, this methodology can be a useful tool in gradual transition processes from intermittent to continuous supply.

1. Introduction

Intermittent water supply (IWS) is the way in which millions of people worldwide have access to water currently [1]. Some researchers suggest that the increasing water scarcity due to the climate change, and the increasing demand caused by the upsurge in population, may lead to a more frequent use of intermittent supply [2]. However, intermittent water supply should be the very last step to take in terms of water scarcity. This situation should be avoided by proactive planning and appropriate responses to critical conditions [3].

A water supply system is considered to provide IWS, when the supply of the service is performed for a limited period of time. Water is generally supplied daily. However, in extreme cases, this period may be longer than one day. In many small towns with IWS, the service is performed for some hours for the entire network regardless any sector differentiation. However, supply in larger cities is performed by sectors (also called district metered areas) with different delivery schedules. We address here this last situation.

When water companies opt for IWS, they generally aim to reduce the *per capita* water demand with the idea of saving in capital and operating costs. However, IWS brings negative consequences that prevail over the positive factors instead of being a smart strategy [4,5]. Thus, intermittent supply is adopted by necessity rather than by design [6].

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Due to the limited hours of supply, and the establishment of delivery schedules with little technical criteria, the peak factor (ratio of peak flow with respect to average flow) increases to values up to 4–6 [7]. As a result, much larger flowrates are delivered during peak hours in comparison with flowrates delivered in continuous systems [8]. This greatly impairs management since, among other drawbacks, it implies greater storage volume and larger diameters in the network to meet hydraulic and demand requirement. Several studies also show that intermittent systems produce insufficient pressure in unfavourable areas or sectors [9,10], generating dissatisfaction and complaints among users.

There is abundant literature on planning, design, operation and maintenance of systems with continuous supply. However, the operation of IWS systems is mainly based on personnel experience, and simple water supply and demand trade-off analyses.

This paper proposes a tool to aid technical management of IWS systems, built on a methodology to manage supply schedules for every sector of the network to improve the conditions of service based on multi-criteria optimization. The objective is to reduce the peak flow produced by the simultaneous supply of sectors by optimally assigning delivery schedules based on technical criteria that can be quantitative and qualitative. These criteria include pressure, amount of available water, effects of pressure increase or decrease, number of users, delivery times, and ease of sector operation, among others. In addition to various engineering variables, the technical expertise of the personnel of the water supply company is included into the optimization process through their opinion, using the Analytic Hierarchy Process (AHP) [11,12] as a multi-criteria decision technique.

In general, IWS is developed in scenarios of physical scarcity, economic scarcity and mismanagement [7]. Generally, the water companies that manage IWS have fewer economic resources. Therefore, proposals to improve the system performance must consist of alternatives that involve minimum human and economic resources. This is a crucial idea that has very important implications in the setting of the problem.

The case study we present corresponds to one of the subsystems of the water supply system of Oruro city (Bolivia), consisting of 15 sectors fed by a single tank.

2. Methodology

In this section, we detail our approach to optimal allocation of supply schedules to the network sectors with the final aim of efficiently maximizing the quality of service. The building elements are the *supply blocks*, which are first defined, then the criteria for block allocation are stated and, finally, the optimization problem is proposed.

2.1. Definition of supply block

In IWS, the pattern of supply tends to be constant by the presence of household deposits. Large flows occur in the first minutes and then flows are reduced at the end of the delivery period. The flow variation is not large, ranging from 20% to 30%. Therefore, the problem can be simplified by calculating the average volume per delivery period (Vs) [13], which we call *supply block*. For a given sector, j, of the network it is defined by

$$Vs_j = \frac{\text{daily volume supplied to sector } j}{\text{number of supply hours}}. \quad (1)$$

Supply blocks must be allocated to sectors and suitably organized in a new optimal schedule, which meets some technical requirements previously defined. These requirements are derived from a number of criteria, which we consider next.

2.2. Criteria for block allocation

Not only quantitative but also qualitative criteria may be used to decide the block allocation into a supply schedule. Quantitative criteria are typically normalized on the basis of values measured for each of the network sectors. Qualitative criteria are dealt with through surveys to experts who are responsible for IWS operation. To deal with qualitative criteria the AHP methodology is used in this paper. Four criteria in total, C1–C4, are considered here.

The quantitative criteria are the three following.

C1: Pressure. Pressure is an important variable to select the sectors whose water schedule must be modified. We consider that those sectors that have lower operating pressure are the ones that first should change their schedule. We assume that users with lower pressure accept the measures taken to improve their service conditions. The variable used on the basis of this criterion is pressure, with values, pv_j, measured at the inlet of each sector $j = 1, \ldots, n$. However, more adequate values may be introduced by considering the lack of satisfaction of a maximum pressure, $pv_{\max}$, since this better expresses lack of service quality, here in terms of pressure. So, first, pressure values are transformed into new (positive) variables, noted here p'_j,

$$p'_j = pv_{\max} - pv_j. \quad (2)$$