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Optimization of Water Distribution System within Tented Camps

Abdullah ALHAMAD[*1] **ORCID** *0000-0003-1876-6285*
Ayşe Yeter GÜNAL[2] **ORCID** *0000-0002-4866-2914*

[1] *Gaziantep University, Faculty of Engineering, Civil Engineering Department, Gaziantep*

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Abstract

This paper proposes an optimized, gravity-looped water network for tented camps as a replacement of the water trucking method, which depends on conveying water from resource to water tanks set up within camps by trucks, allowing people to carry water through containers to their tent; this method is used to supply people live in tented camps with water when providing water cannot be met in other ways. The cost of installing the gravity-looped network is minimized using Linear Programming to select pipe diameters from commercially available pipes. The method proposed was developed by Alperovits and Shamir (1977) and modified by Goulter and Coal (1986); linear formulations were solved by MATLAB, builds upon results obtained from EPANET. Tulol camp, located in Syria, was chosen as a case study, being supplied with water by trucking. Diameter changes, after optimization, are observed where the total cost of pipes decreased by 9.75%.

Keywords: Linear programming, Gravity-looped networks, Tented camps, Water trucking, Water supplying

Çadır Kamplar İçerisinde Su Dağıtım Sisteminin Optimizasyonu

Öz

Bu makale, suyun kaynaktan kamplarda kurulan su tanklarına tankerlerle taşınmasına dayanan ve insanların çadırlarına su taşımasına izin veren su taşıma yönteminin yerine, çadır kampları için optimize edilmiş cazibeli bir su şebeke ağı önermektedir; bu yöntem, başka yollarla su temini mümkün olmadığında, çadır kamplarında yaşayan insanlara su temin etmek için kullanılmaktadır. Cazibeli su şebeke ağının kurulum maliyeti, Doğrusal Programlama kullanılarak piyasada bulunan boru çapları seçilerek en aza indirilmiştir. Önerilen yöntem, Alperovits ve Shamir (1977) tarafından geliştirilmiş ve Goulter ve Coal (1986) tarafından modifiye edilmiştir; MATLAB tarafından çözülen lineer denklemler,

[*]Corresponding author (Sorumlu yazar): Abdullah ALHAMAD, *alhamad.abdullah92@gmail.com*

EPANET'ten elde edilen sonuçlara dayanmaktadır. Suyun tankerlerle sağlandığı Suriye'deki Tulol kampı vaka çalışması olarak seçilmiş ve toplam boru maliyetinin %9,75 azaldığı gözlemlenmiştir.

Anahtar Kelimeler: Doğrusal programlama, Yerçekimi döngülü ağlar, Çadır kampları, Su taşıma, Su temini

1. INTRODUCTION

Natural and human-made crises enforce people, in many cases, to leave their homes and lands, seeking safer places until they become able to return safely. Those people, who flee to other areas, may not find any place to live or settle in; hence, they live in tents within camps temporarily or maybe for prolonged times such as, Syria crisis, that entered its 9th year. Tents might be provided by governments, donors, or any civil organizations and supplied, in many situations, with water by trucks as a water distribution network is usually not in place. In Syria, for example, at most tented camps, water is provided by water trucking; the allocated amount ranges between 20 and 50 liters per capita per day. In this paper, supplying water at tented camps is improved by installing a water distribution network and using Linear Programming (LP) optimization to minimize capital cost by ensuring that hydraulic conditions are satisfied. The objective function of LP does not consider pump or operation cost, where the high tank is installed and supplies network with water, based on pressure and level water head differences. LP, employed in this study is derived from a model developed by Goulter and Coals [1] which is originated earlier by Alperovits and Shamir [2] with neglecting reliability constraint, that considers the number of breaks, as there is no historical data available of breaks rate occurred in past years [3-4]. Instead, to ensure the reliability of the network and maintain the provision of water to the consumer in case of any pipe's failure, a looped network was selected to be installed [5], as looped configuration provides alternative paths, connecting nodes with the resource. Linear Programming formulations are solved by using MATLAB [6,7], where inputs are obtained from EPANET [8], which is employed to solve network, that uses basic hydraulic principal to analysis networks.

1.1. Water Supply in Camps

1.1.1. Water Needs in Emergencies

Sphere (Humanitarian Charter and Minimum Standards in Humanitarian Response) [9] mentions that all people in emergencies should have safe access to a sufficient amount of water for their basic needs for drinking, cooking, and hygiene, and according to its standards, minimum needs of water per person per day in emergency responses for people affected, should be 15 liters, as depicted in Table 1.

Table 1. Minimum needs of water per person per day [9].

Needs	Quantity (liters/per son/day)	Adapt to context based on
Survival: water intake (drinking and food)	2.5–3	Climate and individual physiology
Hygiene practices	2–6	Social and cultural norms
Basic cooking	3–6	Food type and social and cultural norms
Total basic water	7.5-15	

The minimum amount of safe water (short-term survival level) that is required for drinking and implementation of basic hygiene such as cooking for an individual is 20 liters per day [10] (Figure 1).

Figure 1 shows the hierarchy of water requirements following Maslow's hierarchy of needs. The most important water needed is at the top of the hierarchy; in the short-term survival, water required for drinking and cooking is more important than water, for example, for washing clothes. However, in the medium- and longer-term periods more water is needed for better meeting the health and other benefits.

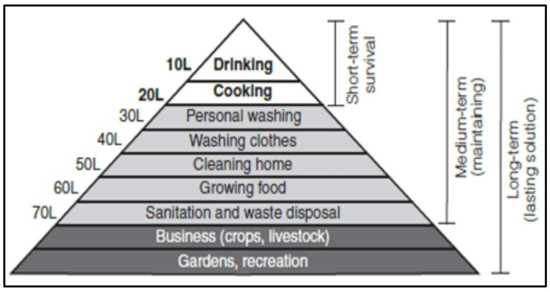


Figure 1. Hierarchy of water requirements (after Maslow's hierarchy of needs) [10]

1.1.2. Water Trucking in Tented Camps

In UNHCR's [11] paper; "water trucking can be a very quick method of providing a refugee population with access to life-saving quantities of safe drinking water. However, water trucking operations can be inefficient, expensive, time-consuming to administer, hard to monitor, and difficult to get out of once started. If a decision is made to start water trucking it must be carried out in a sanitary manner to ensure that water does not become contaminated and pose a risk to public health". The amount of water provided to support life and health during disasters varies with the availability of water, disaster or crisis period, location of camps, funding (money donated to supply water). A dedicated person observes and monitors water points (water tanks) during supplying water to ensure that each family takes their allocated amount of water. Adopting the water trucking modality, to provide tented camps, has some negative implications, such as, in some cases, children help their parent collect water and carry the containers from tanks to their tent even for some times for long distance which causes a burden on both parents and children. FRC (Free Residual Chlorine), which is one of the water quality standards, should range between 0.2 to 0.5 mg/l [8] to maintain public safety and destroy pathogenic organisms, and exceeding these values may cause various types of water-borne diseases. These values sometimes are not observed well and trucks, which provide camps with water, don't consider these values during conveying from resource to consumers. FRC should be monitored to ensure that amount in water is ranged in its allowable values.

This paper proposes installing a gravity-looped network, consisting of a high tank, which is used to store water and feed network, pipes, and smart water meters. This system was selected instead of the pumping system, due to the operation cost of pumps, as at most tented camps in Syria, for instance, supplying water is based on donations. This network supplies water to each tent through pipes, and there is no need to carry out water by container to the tent from water tanks. To monitor that each family takes their allocated amount of water, each tent will be provided with a smart water meter set up on a pipe laid out inside their tent. The smart water meter is to limit the amount of water taken by each family by providing each family with a card, and this card will be charged weekly by the administration of the camp, determining the weekly amount of each family based on the number of members.

1.2. Minimum Pressure in Network

In any network, the pressure, which is one of the hydraulic conditions that should be satisfied, is expected to be kept between the minimum and maximum standards for safe, reliable, and economic operation.

The recommend values of pressure within water distribution system are [12]: above 0 m during emergencies, such as main breaks and power outages; more than 14 m (20 psi) under maximum day demand and fire flow conditions; more than 25 m (35 psi) under normal conditions; less than 70 m (100 psi) under normal conditions; within ±7 m (±10 psi) of average pressure greater than 95% of the time) to optimize WDS in regarding of reducing unnecessary water losses, main breaks, and/or energy usage.

Some countries [13] have their minimum standards under different conditions, their standards range between 10 m (14 psi) and 14 m (20 psi) at most to satisfy fire flow, or at some to satisfy normal conditions.

In camps, achieving these standards has no feasibility, where there is no sewer system, fire hydrants, multi-story buildings and the usage of water is limited to water their basic needs such as drinking and cleaning of clothes, where each tent has one faucet installed. Not to mention that to achieve high-pressure value in the network, pumps are required, or water tanks should be installed at a high level and in both more costs added to capital and operational costs.

Minimum pressure value should be determined during the design of the network, ensuring that the water supply is maintained and delivered to all consumers in all tents within camps.

2. METHODOLOGY

2.1. Analysis Tool

EPANET [7] software is employed to analyze the network, which uses basic hydraulic principles to solve and analyze the water distribution network, where the results obtained by this solver are prepared as an input file for MATLAB to start optimization. For this study MATLAB [8], was used to solve LP. It has varied built-in functions to solve different types of optimization problems algorithms; such as, Linear programming, Non-linear programming, Genetic Programming...etc.

2.2. Optimization by Using Linear Programming and MATLAB

This approach [1, 6, 14], which seeks to determine the pipe diameters and associated lengths to minimize the cost of the network with maintaining and satisfying initial hydraulic criteria and reliability requirements, is originated from a model developed by Alperovits [2] and Shamir, which in turn developed by Goulter and Coals [1] with modification related to reliability consideration, as follows:

1. Objective Function:

Minimization of network Cost (Equation 1).

$$\text{Cost } (c)=\sum_{j=1}^{Nl}\sum_{k=1}^{n(j)} C_{jk}X_{jk} \tag{1}$$

Where;

C: total cost of the network ($)
C_{jk} : cost of pipe of diameter k in link j ($/m)
X_{jk}: associated length of pipe of diameter k in link j (m)
Nl: total number of links within the system
n(j): number of different pipe diameters in link j
j: link index
k: diameter type index

Subjected to the following constraints

2. Constraints:

1. Length: the sum of the lengths of link j in each link equals the total link’s length j, where a link represents a pipe connecting two nodes directly (Equation 2).

$$L=\sum_{k=1}^{nj} L_{oj} \tag{2}$$

Where; L_{oj}: equals the total length of link j

2. Head loss: minimum permissible head at each node must be satisfied (Equation 3).

$$H_0-\sum_{j=1}^{Nl}\sum_{k=1}^{n(j)} J_{jk}X_{jk} \geq H_{min} \tag{3}$$

For all nodes

Where; J_{jk}: Stands for the hydraulic gradient of link J

H_{min}: Minimum permissible head at any node.

3. Loop: for a looped system, the total head loss around a loop must equal zero (Equation 4).

$$\sum_{j=p'(b)}^{Nl}\sum_{k=1}^{n(j)} J_{jk}X_{jk} = B_p \tag{4}$$

Where; $p'(b)$= links in the path associated with net head loss Bp, in looped network Bp equals 0.

4. non-negativity: which assumes that all pipe length is positive (Equation 5.)

$$X_{jk} \geq 0 \tag{5}$$

5. Reliability: an estimate of reliability is embedded into this constraint which limits the expected (average) number of leakages or breaks in a given period in any link within the network (Equation 6).

$$X_{jk} r_{jk} \leq R_j \tag{6}$$

r_{jk}: number of the expected number of break /m/yr for diameter k in link j

R_j: maximum allowable number of failures per year in link j.

However, due to the unavailability of historical data [3-4] on the number of breaks rate, this constraint will be neglected during preparing this study. This type of data might not be available, particularly in countries that have conflict, displacement, missing, or losing documents at the municipality which keeps records.

To analyze and minimize the total cost of water distribution network, the following steps of the algorithm are considered:

Step 1 of the algorithm: Analysis of network by EPANET

Hydraulic properties and components of network are defined in EPANET, which include pipes' diameters, lengths, node demand, coefficients, elevations, and hydraulic analysis options.

Step 2 of the algorithm: Obtain results from EPANET.

The analysis is run and obtained results, which are flows' rates and directions, are prepared to be used in optimization formulations.

Step 3 of the algorithm: Prepare inputs of Linear programming

The required inputs for Linear Programming are links' (pipes) lengths and the outputs of the analysis, which are the flow rate for each pipe in between two nodes.

The Linear Programming uses the Hazen William equation to determine the unit head loss that is used in constraints of alternative diameters in each link.

Step 4 of the algorithm: Analysis Using Linear Programming (LP) by MATLAB.

LP optimization, by utilizing objective function and constraints, tries to find the best optimal diameter, satisfying hydraulic conditions.

MATLAB program solves any linear program by defining matrices for inequalities, equalities, low bound, upper bound, and objective function; where unknown variables are associated lengths of diameters at any link, not pipe diameters.

The predefined available diameters for any link of the network are 16, 20, 25, 32, 40, and 50; and associated cost and lengths for these diameter types are C1, C2, C3, C4, C5, C6 and X1, X2, X3, X4, X5, X6

The objective function for any sample link is:

$$F = C_1{*}X_1{+}C_2{*}X_2{+}C3{*}X_3{+}C4{*}X_4{+}C_5{*}X_5{+}C_6{*}X_6$$

These variables are subject to constraints in Equations (2, 3, 4, and 5)

After preparing all matrices of objective function and constraints in MATLAB, optimization started by writing in commend window, as follows:

[X, Z] = linprog (f, A, b, Aeq, beq, lb, ub)
As,
X: Variable Vector;
Z: Objective function Value;
f: Object function;
A, b: Inequality matrices;
Aeq, beq Inequality matrices;
lb, ub: Lower bounds and upper bounds of values of variables X
Optimization, then, is terminated, and results obtained.
Step 5 of the algorithm: Output of Linear Programming Optimization

After the results are obtained, the respective diameters of each link j are observed and the diameter with higher length is chosen for each link [6-14], as EPANET cannot split a link to more than one pipe. The chosen diameters to all links are prepared as input for EPANET and the solver is re-run again. The results obtained are used to compare if the following conditions are stratified or not.

1. Are the design conditions satisfied?
2. Is the flow direction constant?

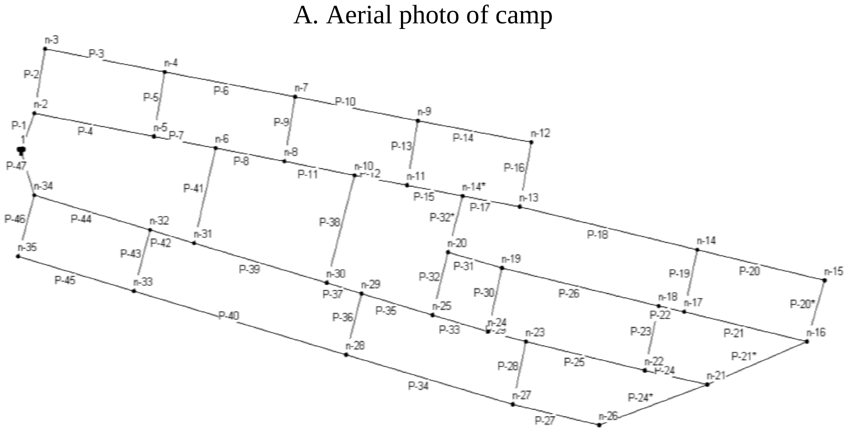
If the answer is yes; then results are maintained, and the algorithm is terminated.

If the answer is no, the procedures followed are maintained for all the links with updated results until all conditions are satisfied [6-14].

2.3. Description of Case Study Area

Tulol camp is located in Tulol in the Northwest of Syria in Idleb governorate. It extends on an area of 19500 m^2 and hosts approximately 1,020 Internally Displace Persons (IDPs), living in 170 tents. (Figure 2)

A. Aerial photo of camp



B. Drawing of pipes and nodes (EPANET).
Figure 2. Tulol camp layout

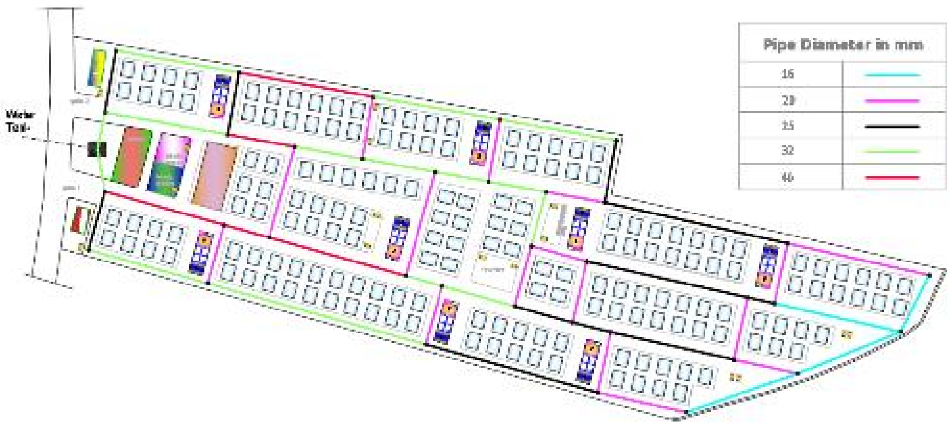
2.4. Water Supplying in Tulol Camp

Tulol camp is provided by water trucking; the water amount per person per day is 35 liters. Gravity-looped water distribution network will be installed with a high tank to store water and feed network, pipes and a smart water meter, to deliver water to each tent, considering water amount per person per day is 50 liters. Five different diameters were used in the analysis of design, which are 16, 20, 25, 32, and 40 mm, satisfying hydraulic conditions.

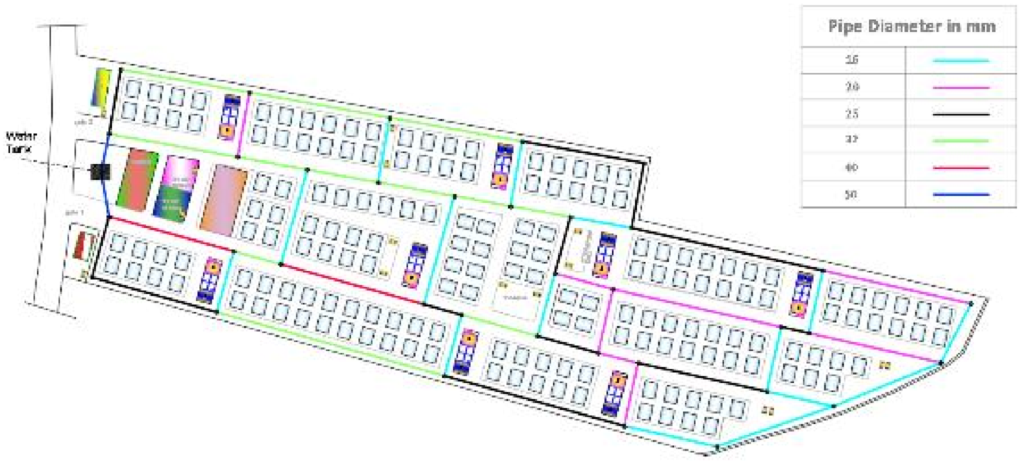
The 3-meter head pressure was selected in the network as minimum pressure at all points (i,e pressure at each point should be equal to or more than 3 meters).

3. RESULT AND DISCUSSION

The proposed network is analyzed by EPANET, and outputs (results) obtained were used in MATLAB, which in turn, solved LP formulations. The results obtained accordingly shows an additional 50mm diameter in the network added and it has 6 different diameters (layout of the camp is updated as shown in Figure 3, comparing layout before and after optimization)



A. Layout of network (Before Optimization)



B. Layout of network(After Optimization)

Figure 3. Comparison before and after optimization

Analysis of network with regards to;

1. Cost: A comparison of the cost of pipes before and after optimization indicates that solving the Linear Programming optimization equations by MATLAB, led to a decrease in capital cost of pipes in the water distribution network by 9,75% with satisfying hydraulic conditions.

2. Pressure: One can notice that the pressures after optimization increased comparing to pre-optimization analysis, as the two main pipe feeding system, which are p-1 and p-47 have larger diameter after optimization. This indicates that the pressure increases with in flow rate and increase in pipe diameters within the nodes. The maximum pressure in initial proposed system is at node 2 of value 8.32m while the same node has the maximum pressure of value 9.82m after optimization.

3. Consumption Controlling: Setting up a smart water meter will guarantee that each family draws its allocated amount of water from the network without exceeding or drawing an extra amount allocated to other families.

4. Quality of Water: Free Residual Chlorine (FRC) will be monitored effectively and closely to ensure 0.2 and 0.5 mg/l would be in this range without any violation, as camp administration will take a sample of water before running water into the network to monitor FRC range.

5. Reliability: Experience has shown that when a network is designed for a single loading unless a minimum diameter is specified for all pipes, the optimal network will have a branching configuration [2]. So, to maintain looped network configuration after optimization, a minimum diameter was predefined for each link.

4. CONCLUSION

As a conclusion of this study, installation of an optimized water distribution system at tented camps would play the main role in enhancing access to water service during crises and disasters, particularly in situations and circumstances where people would have to live for a prolonged duration at tented camps and water trucking is the only available method. Besides, installed system would maintain lives of affected persons against water-borne diseases through observing water's quality. The capital cost of a water distribution system is enormous relatively. As a result, engineers and acting organizations who intervene during emergencies are looking for new method of designing water distribution systems with a minimum cost that satisfies affected people's demands. In this research, the methodology of ensuring minimization of objective function is Linear Programming that uses linear objective function and constraints with considering lengths and associated diameter as variables.

5. RECOMMENDATIONS

This study gives a crucial and initial step to promote resilience of affected people and enhance water supplying in tented camps with improving accessibility to water services. Future works may focus more on including all system components in objectives; such as, high tank's location and sizing to reach low-cost objective. Moreover, other studies about installation of an optimized sewer and treatment of water system may be associated with the design of a water network to bring about a greater impact.

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