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Harmony Search Algorithm for Optimal Management of Chlorine in Water Distribution Network

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***Abstract*: Due to chlorine decay, the concentration of chlorine at the end of distribution system will be less than the concentration at the water treatment plant. In this study, the amount of chlorine levels in water at the point of consumption is assessed and an optimization algorithm for determining optimal management of chlorine is determined. In addition, recommendations on the appropriate chlorine dosage rates that ensure free residual chlorine levels are determined and also an identification of the re-chlorination locations is also done. The harmony search algorithm was used for the optimization model. This model was applied to water supply system at the Ongata Rongai water distribution network and verified using different number of re-chlorination points. The results showed the bulk decay of the worst scenario to be -0. -3.27d^{-1} at a temperature of 25 degrees Celsius. The proposed model can be used as an efficient water quality analysis and decision-making tool in showing the optimal re-chlorination points and doses.**

***Keywords*: Meta-heuristic, harmony search algorithm, re-chlorination, optimization.**

1. Introduction

The development of Kenyan economy and with the fast urbanization process, the demand for water supply has been on the rise. The lack of enough water supply has immense effects on agricultural and industrial sectors and it may endanger the safety of cities in Kenya. The recurrent water shortages mean a lot of efforts must be put on the existing foundations to save water resources more importantly water supply in the densely populated cities. Studies have been done on the maintenance of residual chlorine concentrations within a particular range by minimizing the mass of the disinfectant at the previously planned chlorine injection facilities. Optimization design of water supply pipe network is important with the development of economy and the increasingly fast urbanization. Harmony search algorithm for the optimal design of water supply networks provides a better nonlinear optimization method.

Chlorine's main purpose in water is that it destroys disease causing organisms and is the one of the most commonly used disinfectant in all regions of the world. In addition, chlorine eliminates slime bacteria, molds and algae that commonly grow in water supply reservoirs, on the walls of water mains and in storage tanks, [1]. The three principal forms, which chlorine is applied to water is essential chlorine, sodium hypochlorite solution or dry calcium hypochlorite. Chlorinated isocynurates are also used for some applications especially in swimming pools. All produce free chlorine in water, [2]. The main secondary cause of deteriorating water quality may be sediments which build up on the inside of pipelines, [3]. Researches have indicated that iron sediments may occur inside water supply pipelines at iron consideration of 0.05 mg. Thus, majorly leads to an increase in iron concentration despite of good water chemical composition when pumping water into the network. This is mainly caused by picking off sediments due to changes in water flow direction or rate in water distribution network and iron penetration into water by its dissolution. It has been demonstrated that in the latter case an appropriate oxygenation can inhibit the diffusion of iron II chloride from the sediments into water, [4].

The quality of the treated water depends, to a large extent on factors related to technical condition and the age of the water supply network. Pipeage that decides on the failure rate is of special importance. A long period of use significantly accelerates the wear of the pipe materials. This increases the risk of water supply system. Hydraulic conditions in the water supply outages have an important effect on the quality of water delivered to consumers, [5].

One of the major factors causing the deterioration of water supplied to customers is corrosion processes in outdoor an indoor water pipe. Corrosion is enhanced by the presence of aggressive carbon in water that deteriorates the passive films. Corrosion rate is affected not only by water pipeline materials but also by physiochemical composition of water. The effect of corrosion is the deterioration of water supply network materials and enrichment of water delivered to customers with dissolved forms of materials. Therefore, the quality of water delivered to consumers de-pends primarily on processes that occur in the water distribution system. The water corrosivity index plays an important role in these processes, [6]. Metaheuristic Optimization Algorithms (MOA) have been widely used in engineering to solve complex and nonlinear problems an also employed for optimal designs of Water Distributions Systems. In the water design system, the size, capacity and location of water distribution components such as pipes, pumps and tanks are determined [7].

[8], studied the booster facility location and injection-scheduling problem. They formulated a multi-purpose optimization that minimized the total disinfection dose while simultaneously maximizing the volume of water supplied to solve that particular problem. They used a multi-objective GA for that purpose [9], made a proposal to use a water quality index as a method to maintain an adequate residual chlorine level. This water quality index is an overall index that considers the combined microbial, chemical and aesthetic quality [10], studied the formation reaction of trihalomethane which is one of the disinfection by-products. They adopted a two-phase approach using a multi-purpose optimization technique. The booster chlorination operational injection cost was used as the objective functions. The standard range of the trihalomethane, a GA, and EPANET multi-species extension were used as the constraint, optimization techniques, and hydraulic analysis tool, respectively.

2. Methodology

In this section we discuss harmony search algorithm. The objective function, constraints and the decision variables to be used and the proposed algorithm will be presented here.

A. *Model formulation and construction*

In order to be able to explain the HS in more detail, we will first idealize the improvisation process by a skilled musician. When a musician improvising, he or she has three possible choices: play any famous piece of music exactly from his or her memory, play something similar to a known piece or compose new or random notes. *Zong Woo Geem etal. formalized these three options into quantitative optimization process in 2001 and the three corresponding components become: usage of harmony memory, pitch adjusting and randomization. The usage of harmony memory is important in that it is similar to the choice of the best-fit individuals in Genetic Algorithm. This will ensure that the best harmonies will be carried over to the new harmony memory.

B. *Problem formulation*

The HS algorithm was devised for solving optimization problems. Thus, in order to apply HS, problems should be formulated in the optimization environment, having objective function and constraints.

C. *Objective function and constraints*

The purpose of equation (1) is to minimize the additional mass of disinfectant that will be injected into the water distribution network at specific predetermined nodes. The model decision variables are the booster injection concentration by the inflow rate at each node. The locations of the designed booster chlorination stations can also be determined.

$$\text{Minimize } f = \sum_{i=1}^{n} M_i \qquad (1)$$

Here f denotes the total disinfectants dose (kg/d), Mi is the disinfectants mass at node i and n is the number of nodes. There are two important constraints used in this optimization model. The first has to do with the concentration of residual chlorine at each node,which should range between the minimum and the maximum values asshown in equation (2).

$$CL_{min} \le CL_i \le CL_{max} \text{ (I = 1,2 …, n)} \qquad (2)$$

where CL_i denotes the residual chlorine concentration at consumer nodei; CL_{min} and CL_{max} are the minimum and maximum residual chlorinerequirements respectively and n denotes the number of nodes.

The second constraint has to do with the number of re-chlorination points to be installed. The number of re-chlorination points will be set as the preliminary constraint in this model. Therefore, the various number of points will be set up for each scenario, and the optimization model was simulated and analyzed.

D. *Optimization scheme and flowchart*

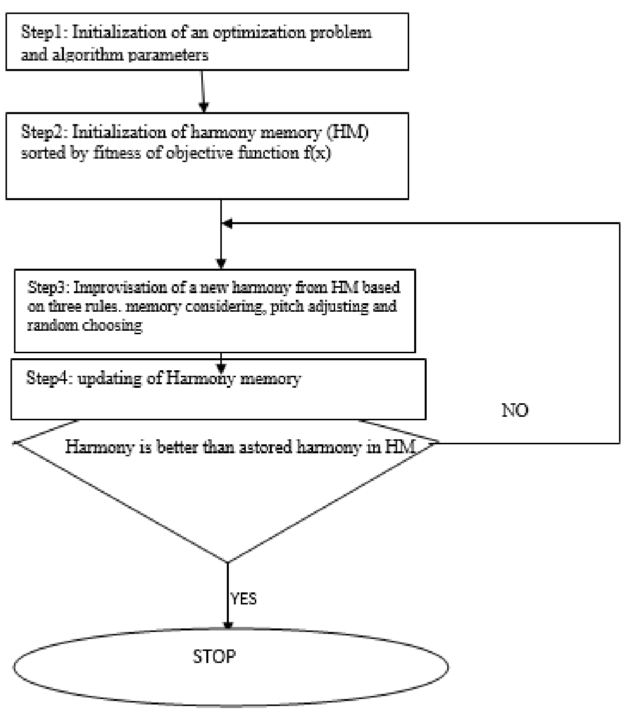

Fig. 1. Flowchart

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After the improvisation [8] of the new harmony is completed, it is evaluated by its objective function. If the value of its objective function is better than the value of the worst of the objective function of the worst harmony in the HM, then new harmony is included in the HM and the existing worst harmony is excluded from the HM. then the cycle repeats itself which represents a quasi-optimal solution to the given problem.

E. Study site

A map of the Ongata Rongai water distribution network and is presented as shown below in figure 2.

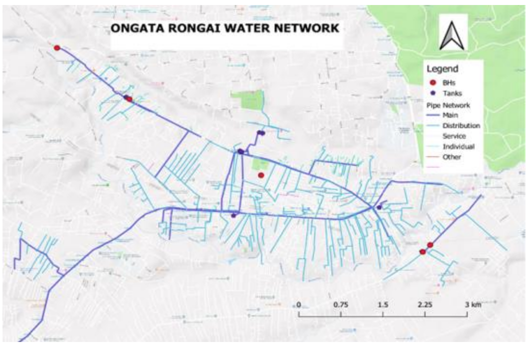

Fig. 2. Ongata Rongai water distribution network

3. Results and discussion

A. The chlorine decay model

To obtain the chlorine decay coefficient, a bottle test was carried out using the serum bottle and a Teflon coated cap. The experiment was done at varying temperatures of 5^0C, 15^0C and 25^0C. The residual chlorine concentration were measured for a period of less than 24 hours. A 24 hour period was selected because the simulation period for the distribution of water from the source to the end consumer would be 24 hours. The period was also selected because the chlorine residual declined as the reaction time increases.

The experimental data used the Arrhenius equation to determine the decay coefficient correlation equation of the pipes in the water distribution network. The bulk decay coefficients in the pipes were also varied at -0.0046, -0.0135 and -0.024h^{-1} and the temperatures were also varied from 5^0C, 15^0C and 25^0C.

The Arrhenius equation is denoted as follows,

$$k = Ae^{-E_a/(RT)}$$

Where K is the rate constant of chemical reaction, T is the absolute temperature (in degree Kelvin), A is the pre-exponential factor, E_a is the activation energy and R is the universal gas constant.

Figure 3 shows a graph of *lnk* against the absolute temperature was plotted from the experimental data. A linear trend line was obtained enabling the study estimate the bulk decay coefficient with the temperatures. The equation is as follows

$$lnk = lnA + E_a/RT$$

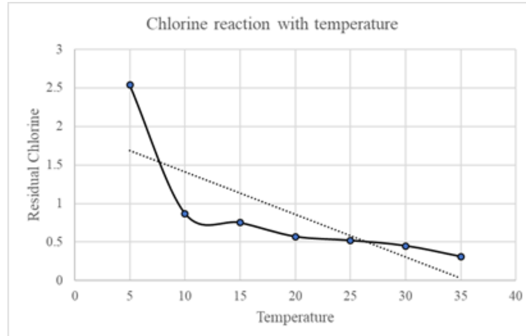

Fig. 3. Chlorine reaction with temperature

Where lnk and E_a/RT ae constants, E_a/R = 1000 and 273 converts the temperatures into degrees Kelvin. From the experimental data, the equation is given by

$$nk = -0.06\left(\frac{1000}{T} + 273\right) + 1.97$$

It from this equation that the study was able to find the relationship between temperature (T) and lnk. The final decay coefficients in the pipes were as follows -2.82, -2.91 and -3.27d^{-1} at temperatures 5^0C, 15^0C and 25^0C respectively. The research study used the worst-case scenario (-3.27d^{-1} at temperature 25^0C) as the parameter for the bulk decay coefficient of chlorine in the simulation process. Previous studies have recommended the use of the worst-case scenario for the selection of the chlorine bulk decay coefficient. The study considered using -3.27 as the bulk decay coefficient.

The map was loaded to the EPANET software for the simulation purpose where different parameters were entered for the simulation to take place. The first step was to identify the links to each of the nodes. The design principal for getting the number of links was to draw lines from the source to the end consumer of the main pipe on the map. The length of the pipes were estimated using the scale at the bottom of the map and entered directly to the EPANET software. The elevation of the sources, tanks and junction nodes were collected physical from the ground. The demand of water data by the consumers at each of the nodes was collected from Ongata Rongai water offices. Other parameters such as the decay coefficient were collected from the chlorine decay model results in subsection.

Once the simulation was done in EPANET and figure 4 below shows the simulated values on a 24 hour period. It is clear from the diagram that as the water flows from the sources to the consumption point the level of residual chlorine concentration also goes down. This then stress the fact that re-chlorination needs to take place at specific nodes.

The simulation model for the optimal re-chlorination injection points and dosage was simulated for the purpose of the study where sensitivity analysis was carried out. A sensitivity analysis was performed to investigate the effects of the

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harmony search algorithm parameters. The parameters include Harmony Memory Considering Rate and Pitch Adjustment Rate. Various parameter was set to investigate the optimal solution for the Ongata Rongai Water distribution Network.

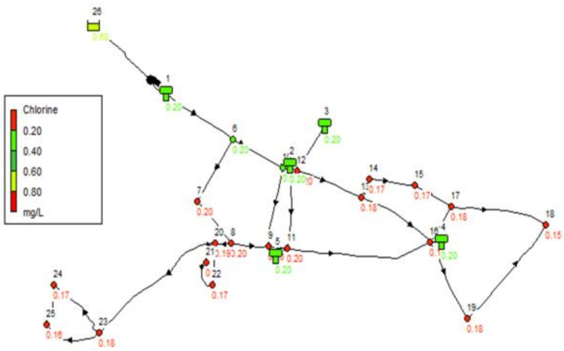

Fig. 4. Epanet simulation on a 24-hour period

Table 1
Optimal solution on considering two re-chlorination points

Case	HMCR	PAR	Node 7	Node 13	Total mg/l	Rank
1	0.7	0.1	0.52	0.28	0.8	4
2	0.7	0.2	0.59	0.24	0.83	5
3	0.7	0.3	0.29	0.34	0.63	3
4	0.8	0.1	0.21	0.34	0.55	1
5	0.8	0.2	0.31	0.27	0.58	2
6	0.8	0.3	0.43	0.57	1	7
7	0.9	0.1	0.56	0.47	1.03	8
8	0.9	0.2	0.52	0.45	0.97	6
9	0.9	0.3	0.52	0.52	1.04	9

The HMCR was varied from 0.7 to 0.99, PAR varied from 0.1 to 0.5. specifically, the following values were set HMCR (0.7,0.8 and0.9), PAR (0.1,0.2 and 0.3). The number of injection points were pre-selected in a such a way that there were 3 re-chlorination points. The criteria for choosing the nodes was such that the residual chlorine level was less than 0.2 mg/l for the 24-hour period. The HMS and bandwidth were selected as 30 and 0.01 respectively. The optimal solution was selected based on the rank of the best combination of the parameters and the results were summarized in the tables.

Table 4
Rank Aggregation

Case	HMCR	PAR	Total Rank	Rank
1	0.7	0.1	15	7
2	0.7	0.2	11	2
3	0.7	0.3	14	4
4	0.8	0.1	9	1
5	0.8	0.2	13	3
6	0.8	0.3	14	4
7	0.9	0.1	26	9
8	0.9	0.2	14	4
9	0.9	0.3	18	8

Table 4 above shows the rank aggregation of the parameters of the Harmony search algorithm. It is clear a Harmony Memory Considering Rate of 0.8 and Pitch Adjustment Rate of 0.1 gives the first rank of the whole process. Next Step now involved carrying out a water analysis after chlorination to find which scenario gave the minimum amount of chlorine dosage.
In scenario 1 (two injection points) above case 5, shows the minimum total amount of chlorine injected into the water distributed network as compared to scenario 2 (Three injection points) and scenario 3 (Four Injection points). The total amount of chlorine injected in scenario 1 is 0.55 while the total amount of injected chlorine for scenario two and three are 1.45 and 0.76 respectively. Another key thing to note is that the total amount of chlorine injected into the water distribution network is less than 0.6 mg/l that is within the recommended range of 0.2 and 0.6 mg/l.

Table 2
Optimal solution on considering three re-chlorination points

Case	HMCR	PAR	Node 7	Node 13	Node 16	Total mg/l	Rank
1	0.7	0.1	0.55	0.33	0.32	1.2	3
2	0.7	0.2	0.36	0.45	0.24	1.05	2
3	0.7	0.3	0.49	0.54	0.4	1.43	6
4	0.8	0.1	0.5	0.5	0.45	1.45	7
5	0.8	0.2	0.46	0.51	0.35	1.32	5
6	0.8	0.3	0.54	0.41	0.26	1.21	4
7	0.9	0.1	0.39	0.49	0.59	1.47	9
8	0.9	0.2	0.3	0.26	0.43	0.99	1
9	0.9	0.3	0.46	0.43	0.56	1.45	7

Table 3
Optimal solution on considering four re-chlorination points

Case	HMCR	PAR	Node 7	Node 13	Node 16	Node 20	Total mg/l	Rank
1	0.7	0.1	0.25	0.29	0.46	0.31	1.31	8
2	0.7	0.2	0.49	0.33	0.33	0.21	1.15	4
3	0.7	0.3	0.48	0.45	0.28	0.32	1.21	5
4	0.8	0.1	0.22	0.29	0.25	0.27	0.76	1
5	0.8	0.2	0.56	0.32	0.35	0.33	1.23	6
6	0.8	0.3	0.57	0.25	0.32	0.22	1.14	3
7	0.9	0.1	0.3	0.58	0.52	0.55	1.4	9
8	0.9	0.2	0.34	0.36	0.58	0.48	1.28	7
9	0.9	0.3	0.25	0.3	0.24	0.28	0.79	2

4. Conclusion

This study proposed an optimization model to determine the re-chlorination points and the doses for water supply network in Ongata Rongai which require maintenance in order to ensure appropriate residual chlorine concentration at the point of consumption. A meta-heuristic optimization technique, the Harmony Search Algorithm was used for the optimization model for the study and a simulation done through case studies using different numbers of re-chlorination points (two, three, and four points). The results satisfied the recommended residual chlorine concentration which has a range of 0.2 mg/l to 0.6 mg/l.

As water travels downstream in the distribution system, water interacts with chlorine reactive substances which leads to reduction of residual chlorine concentration. If re-chlorination points are installed upstream, then large amount of re-chlorination doses will be required to maintain stable concentration of residual chlorine. Therefore, it is important to ensure the chlorination points are distributed along the distribution system in order to minimize the required injection quantities. The model presented an efficient water quality analysis, which showed the optimal re-chlorination points. An increase in the re-chlorination points made it simple to maintain a low residual chlorine concentration. In this regard, the model presented in this paper can be used as an efficient water quality analysis and decision making.

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