Energy Efficient Water Resource Management and Optimisation: A Multi-Agent Approach

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ABSTRACT

Water supply remains one of globally recognised challenging problems due to the scarcity in the sources, the environmental concerns and hardness in access to clean and fresh water. Besides, energy consumption is also under focus as much as access to fresh water is. Substantial research efforts have been spent to produce good solutions for each of these global problems. However, there is not much investigated on considering both issues together in the same problems structure. This paper focuses on how the efficiency of water supply in a middle size water reach city can be optimised with respect to a number of key performance indicators including energy efficiency, given a variety of water resources including constructed and natural reservoirs. A particular case scenario is considered and its mathematical model is developed in order to optimally plan and control fresh water supply to the metropolitan area of the city introduced in the scenario. It is assumed that the fresh water is supplied from a number of different types of resources/reservoirs; natural lakes, constructed reservoirs (dams) etc. The proposed framework also includes a multi agent approach to manage the system in water supply control phase.

1 INTRODUCTION

Fresh water supply and distribution are two key functions of water resource management, which remain as prominent and urgent issues for the modern urban life. It attracts lots of attention and investigations over the years. Clean and fresh water supply is reconginsed as one of the global issues under the focus of United Nations across the globe due to the fact that very large populations live in difficulties to access clean and fresh water for drink and sanitation purposes, while the wasted volume of natural water resources are substantially solid [1]. This obliges to optimise use of water resources and efficiency in supply subject to the needs and cleanness. A number of studies have been carried out to optimise water supply systems with various respects. [2, 3].

Water resource management is not a new subject, which has been studied for long time, however, it has taken so much attention due to the scarcity of fresh water resources, and environmental challenges. Works have been done considering more integral views and changing circumstance [4, 5, 6, 7, 8]. Researchers keep investigating new approaches and studying for better solutions and further performance enhancements taking many issues and requirements into account from all stakeholders, whom were not counted before [2, 3, 9]. That enforces use of new technologies, e.g. internet of things (IoT) and artificial intelligence (AI), and the ever-growing computing power for higher efficiency in delivery and management.

Energy efficiency and power consumption are another two very important issues, globally under focus, and attracts significant attention. The scarcity in power resources obliges energy saving and efficiently use similar to fresh water cases. It is known that a number of water resources can help generate hydro-electric power without harming water quality with respect to cleanness. Although a number of studies have undergone to investigate for better water supply and management systems, none of them have considered power generation and water supply in the same problem structure, to the best knowledge of the authors. This paper proposes an optimisation model for water supply planning and a multi agent system for control as part of water resource management.

The rest of the paper is organised as follows: Section 2 introduces water resource management in general following with a scenario and a mathematical model for the scenario. Section 3 presents a multi agent system as the proposed control approach for water resource management, while Section 4 provides final discussions and conclusions.

2 WATER RESOURCE MANAGEMENT

Water resource management involves all levels of enterprise/corporate management including strategic, tactic and operational levels. The scope of this paper is limited to operational level, where interaction with tactic level is reasonably frequent. The activities in operational level are handled in two stages; the planning and control stages. The research reported in this paper mainly focuses on planning and its relations to control stages. For planning level, we develop a mathematical model to optimise water supply and feed these results into the control stage, where a multi agent system is proposed to manage all control activities.

A number of recent researches have paid attention on comprehensive approaches to resolve the issues around water resource management, with all relevant aspects, within a larger enterprise scope. The authors of [4] and [5] widely discuss a comprehensively integrated system for water resource management and optimisation, while [6] proposes an integrated approach for solving the same problem for a particular metropolitan area of a Chinese city. Similarly, [7] introduces an approach for Peru. The main difference of these works with this study is the role of energy efficiency and power generation within the problem structure. We propose this approach with the vision of water resources optimisation together with power generation and use. The involvement of many geographical sites and compulsory collaboration, one of state-of-art technologies, internet of things [10] extended with multi agent modelling [11, 12], has been considered in this study. The main motivation behind this idea is to furnish the nodes of IoT system with intelligent components so that the developed bespoke IoT model can be as decisive and timely as possible for high efficiency in performance. Multi agent systems were used to model water resource management systems in various respects. [13]. The authors of [14] have proposed a game-theoretic multi agent system for optimisation of water resource allocation. [9] introduces a water allocation system modelled and optimised as a multi-objective optimisation problem. [15] provides a nice review on use of mathematical programming for water resource management under uncertainty.

The rest of this section introduces a realistic scenario in which water supply to metropolitan areas is considered together with power generation and energy efficiency. First, a scenario is introduced, then a mathematical model is developed to be used for planning stages of the whole process. Later, the model is implemented for the data and circumstances. The proposed approach for the control stage and an implementation of planning model come in the next section.

2.1 A Water Supply Scenario

In this scenario, a hypothetical company is assumed to be in charge of water supply in a medium-size metropolitan area, where a number of water resources are used to supply clean water in a certain quality to the urban area within corresponding metropolitan region. XYZ Co. is the company in charge of water supply and sewage management responsible to the metropolitan municipality of the region. The company manages distribution infrastructure and aims to increase efficiency of energy control throughout a project. The scenario has been sketched out in Figure 1, where a water tower is supplied with two reservoirs; a natural lake (Lake), and a constructed dam (DAM). It is known that Lake has been used as the main water resource for the metropolitan area to this day, but, it is also known that it cannot afford the growing volume of demand. This enforces the company to invest in constructing new reservoirs on the river passing through the metropolitan area being conscience about the quality of the water with respect to cleanness and sanitation requirements and standards. The new reservoir (DAM) commissioned by the company is expected to supply more water to be consumed within the urban area for any kind of domestic use. DAM is also planned to generate power through a hydro-power plant (HPP), which can be used for pumping water to the towers and to the final destinations. Meanwhile, it is known that water supply from Lake requires extracting from the bottom of the lake, which consumes a substantial amount of power.

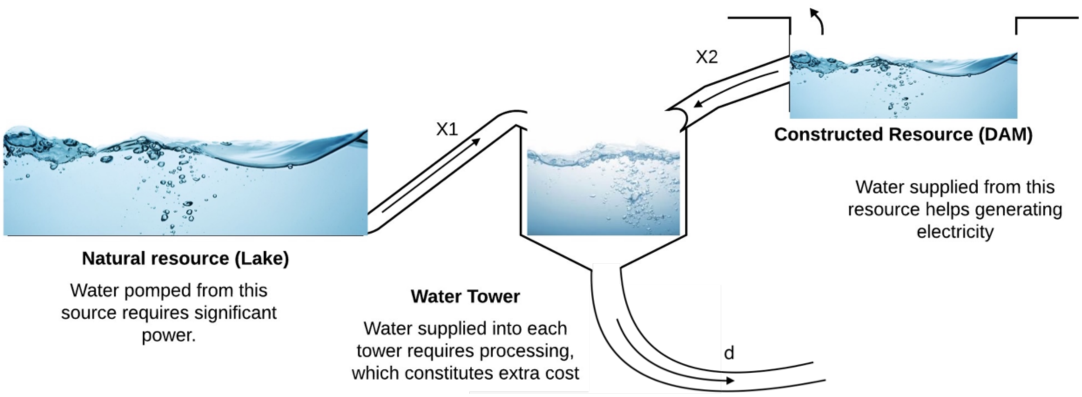

Figure 1: An integrated water system to supply urban areas.

The resource planning and optimization for described case in the scenario would be implemented in two stages; in the first stage, the water supply will be planned through the optimization model for planning purposes, while in the second stage the real delivery of water supply will be controlled, accordingly. The control model is developed based on an internet-of-things model extended with intelligent components, and hence, converted in a multi-agent system to function in real time.

2.2 Mathematical Model

This mathematical model aims to optimise water volume extracted from different types of reservoirs, mainly including natural lakes, or constructed reservoirs (dams) to supply in the metropolitan area of a city described in the previous subsection. It integrates water supply allocation problem with energy efficiency bringing the impact of energy upon the supply through cost coefficients. Here, it assumed that the power generation is separately handled and the results are fed into the model in costing form. In addition, the model is aimed to be used for planning purposes and, hence, considers discrete data flow over the periods of time, e.g. days, weeks or months. The quality of the water to be supplied requires to be over a particular level for health and safety concerns (regulations), while the cost of supply varies due to reservoirs circumstances. Therefore, the volume of water to be supplied is required to be a mixture from different resources, where the quality level and pumping costs need to be optimised. The notations used in the following mathematical model is presented in Table 1.

Table 1: Notations used in the mathematical model.

Notation	Description	Notation	Description
$x_{t,n}$	water volume from resource *n* at time *t*	D	Total demand over time period of *T*
$c_{t,n}$	cost of a unit of water obtained from resource *n* at time *t*	λ_n	Minimum level of water in tower *n*
$c^c_{t,n}$	cleaning/processing cost of a unit of water obtained from resource *n* at time *t*	$l_{t,n}$	Existing water level in tower *n* at time *t*
$c^p_{t,n}$	pumping cost of a unit of water obtained from resource *n* at time *t*	$\omega_{t,n}$	The quality of water extracted from resource *n* at time *t*
$c^q_{t,n}$	profit gained of a unit of water obtained from resource *n* at time *t*	Ω	The threshold for level of water quality
d_t	demand volume at time *t*	Φ	Naturally generated water volume

The following model helps plan water supply per period in chosen time window, e.g. days, weeks, or months. This model only aims optimum plans for water supply given that the demand per chosen time period is assumed to be estimated accurately.

The objective function:

$$Z_{min} = \sum_{t=1}^{T}\sum_{n=1}^{N} c_{t,n}\, x_{t,n} \tag{1}$$

Subject to:

$$\sum_{t=1}^{T}\sum_{n=1}^{N} x_{t,n} \geq \sum_{t=1}^{T} d_t \tag{2}$$

$$x_{t,n} = \begin{cases} 0, & l_{t,n} < \lambda_n \\ x_{t,n}, & \text{otherwise} \end{cases} \quad \forall n \in N \text{ and } \forall t \in T \tag{3}$$

$$l_{t,n} = l_{t-1,n} + \Phi \quad \forall n = 1,2\,;\ \forall t \in T \tag{4}$$

$$c_{t,n} = c^c_{t,n} + c^p_{t,n} - c^q_{t,n} \quad \forall n \in N \text{ and } \forall t \in T \tag{5}$$

$$\sum_{n=1}^{N} x_{t,n}\, \omega_{t,n} \;\geq\; \Omega \qquad \forall t \in T \tag{6}$$

$$\sum_{n=1}^{N} \omega_{t,n} \;=\; 1 \qquad \forall t \in T \tag{7}$$

$$x_{t,n},\ c_{t,n},\ \omega_{t,n},\ l_{t,n},\ \lambda_n, \Omega, \Phi \;\in\; \Re \tag{8}$$

In this model, Eq (1) refers to the objective function and the water to be supplied from each resource/reservoir to optimise each corresponding volume. Here, $x_{t,n}$ is the amount of water obtained from a typical water source in time period of t and from resources n while $c_{t,n}$ is the corresponding unit cost. Total unit cost is calculated based on three main components: (i) water pumping, (ii) cleaning and (iii) contribution to energy production. The breakdown of these cost variables is introduced in constraint (4). Constraint (2) indicates that the total amount of water supplied within the planning time period should not be less than the total demand in the same period. Constraint (3) ensures that water extraction from a particular reservoir is limited to a safety level, which should not be exceeded.

Constraint (4) breaks down the cost details, as referred above, where functions and procedures can also be used to make the costs more precise. The constraints (5) and (6) provide the mixing ratios of unprocessed water volumes to balance the quality. Here, as the cleanliness and mineral structure of the water sources would be different, the provision of optimum quality may require supplying water from multiple resources. Presumably, the characteristics of water obtained from rivers and DAM will differ from those of drawn from Lake. As a result, the time and processing operations for each volume of water extracted from resources will vary due to different cleanness level and the mineral contents in this respect, thus, the costing will be different.

In this model, the time frame is kept flexible and adaptive. T can be applied on a daily, weekly, monthly or seasonal basis. This feature makes it easier to plan according to time sensitivity. On the other hand, with N, the number of resources is kept flexible and new resources can be included in the planning at any time. In the model, the distribution centre is assumed to be made from a single location. If there is more than one distribution warehouse, there will be a variety in costing and a change of model will be needed

3 PROPOSED APPROACH FOR CONTROL: A MULTI AGENT SYSTEM

The control stage of water source management is about running the management system in real time for delivering the required services. Planning stage helps develop master plans for water supply and use of resources efficiently. That is the starting step for control stage. Given the circumstances in the scenario above, the aim of the company is to supply water optimally dispatching from multiple resources/reservoirs subject to circumstances. The company also aims to generate power while supplying from constructed dams using hydro-power-plants built with the dams. This mainly differentiates this work with other related ones, which is considered in the planning stage. In order to control the water supply whether the water quality of appropriate and if there is any way of better delivery, a multi agent system is proposed in this paper, where a number of autonomous agents collaborate towards running the systems as efficient as possible. The reason motivation behind proposing a multi agent system is that the success in use of multi agent systems in various other problem-solving purposes [16, 17], and running control systems successfully [18].

3.1 Multi agent system for control

The proposed approach for the purpose of controlling water resource management is sketched in Figure 2. First of all, the logic presented in the figure is implemented into a model of internet-of-things (IoT), where a network of sensors equipped and arranged for real-time data flow and exchange. Then, each node of IoT is converted into an autonomous agent with adding components to the nodes to produce intelligent behaviours. The reason to do this is to set up an intelligent cooperative system, which can deliver more than what an IoT system can do. A good example for use of IoT in water resource management can be seen in [19].

The autonomous agents are represented into pentagons and hexagons, where the operative agents, Planning, Lake, DAM, Demand Control, Energy Control, are in shape of pentagons, while only Moderator is in hexagon for differentiation purpose. There is not any central control imposed upon the whole system in which autonomous agents are capable of one-to-one connection. This means that each agent is allowed to communicate with every other single agent subject to the need of information and knowledge exchange. It can be noticed that the communication among operative agents is depicted with solid arrows, while with dashed arrows for communications with moderator agent. The agents are furnished with all required capabilities; sensing information from the environment, communicating with other peer agents, deliberating and concluding knowledge, decision-making and actuating upon decisions made. The operative agents need to be devised with different capabilities subject to the role taken up.

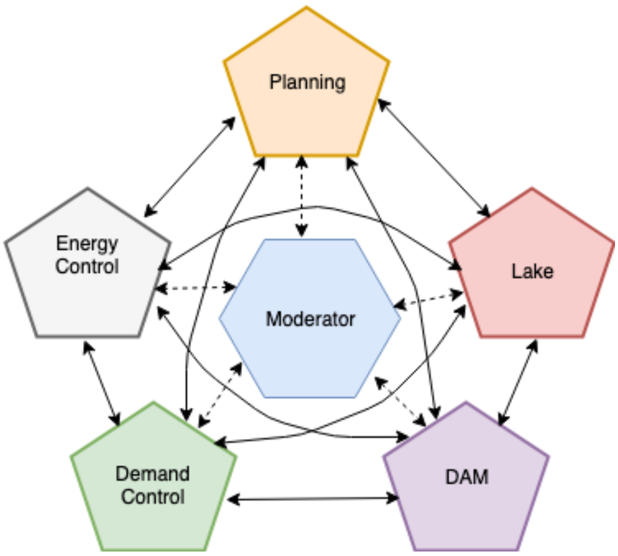

Figure 2: The proposed multi-agent system to handle control stage of water resource management

The logic presented in Figure 2 is a conceptual structure, and not necessarily to be the final since it has not been completely implemented yet, while it can be revised, as requirements impose, in the later stages upon needs. It is expected that each agent associated to water resource and distribution site will share instant status information every particular time window and ensure the rest of agent team with up-to-date information so that the joint decision making can be timely and efficient. In the following subsection, a simpler implementation for planning agent is described and discussed. The other agents have not been considered for implementation, yet, but will be as the research is ongoing.

3.2 Planning Agent: Implementing mathematical model

This subsection provides an implementation of the mathematical model presented in Section 2.2 with data provided for a more specific case. It is supposed that there are 2 water reservoirs; one natural lake and one constructed dam. As described above, the fresh water from the natural lake is much cleaner and in better mineral structures that what is extracted from constructed dam, while the water from constructed dam can be used for power generation. There is one water tower in which extracted water volumes are further processed towards desired quality level. It can pump water to water tower if its cleanness is above a particular quality level, otherwise the water will be used for power generation only. The following model, Eq: (9) – (16), is derived to be more specific to the circumstances described above for a time period of 1 week with time window of 1 day. Obviously, the new model requires to be further specific with more data, which come in the next paragraph.

$$Z_{min} = \sum_{t=1}^{7} c_{t,1}\, x_{t,1} + c_{t,2}\, x_{t,2} \tag{9}$$

Subject to:

$$\sum_{t=1}^{7} x_{t,1} + x_{t,2} \geq \sum_{t=1}^{7} d_t \tag{10}$$

$$x_{t,n} = \begin{cases} 0, & l_{t,n} < \lambda_n \\ x_{t,n}, & \text{otherwise} \end{cases} \quad \forall n = 1,2 \; ; \; \forall t \in T \tag{11}$$

$$l_{t,n} = l_{t-1,n} + \Phi \quad \forall n = 1,2 \; ; \; \forall t \in T \tag{12}$$

$$c_{t,n} = c^{c}_{t,n} + c^{p}_{t,n} - c^{q}_{t,n} \quad \forall n = 1,2 \; ; \; \forall\, t = 1,..,7 \tag{13}$$

$$x_{t,1}\, \omega_{t,1} + x_{t,2}\, \omega_{t,2} \geq \Omega \quad \forall\, t = 1,..,7 \tag{14}$$

$$\omega_{t,1} + \omega_{t,2} = 1 \quad \forall\, t = 1,..,7 \tag{15}$$

$$x_{t,n},\ c_{t,n},\ \omega_{t,n},\ l_{t,n}\ ,\ \lambda_n\ ,\Omega, \Phi \in \Re \quad \forall n = 1,2 \; ; \; \forall\, t = 1,..,7 \tag{16}$$

Suppose that corresponding data is collected and fed into the model; then it turns the following format. The data are the cleaning / processing cost per unit volume for the first and second water sources is $c^{c}_{t,n} = \{2,10\}$, the pumping cost is $c^{p}_{t,n} = \{15,3\}$ and the positive cost (gain) arising from energy production is $c^{q}_{t,n} = \{0,32\}$. Constraint (13) has been applied to these cost data and corresponding costs obtained as $c_{t,n} = \{-20,17\}$. It is assumed that the cost components do not change over daily basis, therefore, they remain the same over the whole time period of 1 week (7 days). The daily demand is known to be as $d_t = \{150, 145, 152, 155, 148, 149, 150\}$ thousand tons, while the quality ratio is $\omega_{t,n} = \{0.65, 0.35\}$, the water quality limit value is $\Omega = 120$, and the lowest water levels are $\lambda_n = \{3000,10000\}$ thousand tons, which is worked out in a particular way and upper limits per $x_{t,n}$ calculated as $\{100, 80\}$ per day or $\{80, 100\}$. The model is revised as in the Eq: (17) – (22), which has turned into a very simplified form.

$$Z_{min} = \sum_{t=1}^{7} 17x_{t,2} - 20x_{t,1} \tag{17}$$

Subject to:

$$\sum_{t=1}^{7} x_{t,1} + x_{t,2} \geq 1049 \tag{18}$$

$$x_{t,1} \leq 80 \qquad \forall t = 1 \dots 7 \tag{19}$$

$$x_{t,2} \leq 100 \qquad \forall t = 1 \dots 7 \tag{20}$$

$$0.65\, x_{t,1} + 0.35\, x_{t,2} \geq 120 \qquad \forall t = 1 \dots 7 \tag{21}$$

$$x_{t,1},\ x_{t,2} \in \Re \qquad \forall t = 1 \dots 7 \tag{22}$$

This model has been solved using one of online linear programming tools [20] and the optimum results are tabulated in Table 2, where 2 variants of capacities are presented. The results suggest that the compelling effect of power production enforces the supply to be more allocated from DAM rather than Lake due to the benefits. However, the cleanness of untreated water and the mineral contents limits the supply from DAM completely.

Table 2: Optimum daily water supply from both Lake and DAM with different capacities.

T=7 *t*→	1	2	3	4	5	6	7
Demand (d_t) (1K ton/day)	150	145	152	155	148	149	150
Lake ($x_{t,1}$) (80K ton/day)	50	45	52	55	48	49	50
DAM ($x_{t,2}$) (100K ton/day)	100	100	100	100	100	100	100
Lake ($x_{t,1}$) (100K ton/day)	70	65	72	75	68	69	70
DAM ($x_{t,2}$) (80K ton/day)	80	80	80	80	80	80	80

4 DISCUSSIONS AND CONCLUSION

This paper presents an approach for handling water resource management for metropolitan area of a hypothetical middle-size city assuming that the water is supplied through a natural lake and a constructed dam. Due to characteristics of untreated water from each resource would be different, a decision is required to be made each time period to supply from one of the resources subject to the quality and capacity constraints. On the other hand, water supply from the constructed dam can also be used for power generation through hydro-power plant integrated into water supply facilities. This makes the problem more complicated in solving. Water resource management, as a typical activity of enterprises, includes two fundamental stages by its nature; planning and control. In this paper, we propose solutions for each stage, which makes our proposal a framework for water resource management. Planning stage is handled via optimisation models, which suggest optimum breakdown of supply from each resource assuring that the incurring cost, including energy consumption, remains minimum, and the power generation is conducted in its highest capacity. Once the planning is done, then the control of the real-time supply comes to the scene, which is proposed to be handled with a multi-agent-based approach.

A mathematical programming model has been developed for planning stage considering energy consumption as an active input for the cost of water supply. This is indicated as Constraint (5) in the original model, and then implemented further. It becomes inclusive in cost coefficients within the implementation stage and disappears in the later model. This is done for simplicity purposes, but can be kept as a function of decision variables, $f(x_{t,n})$, in another implementation. This will support the model with much more accurate planning results, subject to the significance of precision in planning figures. In addition, the daily capacity of each reservoir statically takes part in the model, where the daily level of water, and the volume of water flows/emerges in the reservoir is assumed to be constant in the model, Φ in Constraint (4). The constant parameter, Φ, can be redefined into a function to calculate the daily water add-up more realistically.

The model is a single optimisation model in which a single quality measure, which is cost it this case, has been considered. Further to this level, a multi objective model can be developed revising Constraint (4) and converting into another objective to sit alongside cost function. This is due to that energy saving and power generation should play more active role in optimisation process rather being treated as a standard constraint. The same logic applies to water quality, which is statically considered in the model. The quality of water can also be linked to more realistic estimation, and be adopted as another objective. These are future directions of this undergoing study yet to be investigated further.

The implementation provided for the generic model in Section 3.2 is based on very rough data generated for the proof-of-concept purpose, and not validated to suit real cases. The results tabulated in Table 2 are the optimum portions of water extraction from the resources. In both cases, the results found provide an optimum (minimum) cost inclusive of energy contribution. The amount of power generation can also be calculated once the functional relation power generation per unit of water volume is redefined.

The multi-agent-based model proposed for control stage is developed following the idea of IoT to be implemented for the case described in the scenario. The nodes of IoT have been extended with more decision-making components, which intelligently act, hence the model is turned into a multi agent system. It consists of two types of agents; operative agents and moderator agent. The operative agents are in charge of operations per geographical site connected to the rest of the system. Although the model is sketched conceptually, an implementation is yet to be completed as the research is actively undergoing. The results of the framework and the performances will be studied in other articles in the future.

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