**Cost Optimal Desalinated Water Production**

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Abstract

Industrial parks require a significantly large amount of water for industrial activities. The water requirement for these industries is fulfilled by using locally available freshwater sources like surface water, groundwater, external water diversion, reclaimed water, etc. Using these water sources for industrial demand stresses them for the demand satisfaction of other sectors. Due to different water sources having different costs of water generation, desalinated water can be one of the options for industrial water supply because of their abundance. Since desalination is a more cost-intensive water production process, it becomes mandatory to have cost optimal water production. This work proposes a Pinch-based, non-iterative graphical method to determine the cost-optimal water mix production to satisfy demand. The method determines the minimum subsidy required to meet overall water demand. A case study to demonstrate the applicability of the method is done.

**Keywords**: Optimization, Desalination, Pinch Analysis.

* 1. Introduction

Water, an indispensable resource for life, plays a vital role in sustaining ecosystems, supporting agriculture, and meeting the basic needs of human societies. As global population growth, urbanization, and climate change place increasing pressure on water resources, effective water management becomes paramount. Water management involves planning, developing, distributing, and conserving water resources to ensure equitable access, environmental sustainability, and resilience in the face of evolving challenges (World Bank, 2016). Water scarcity is expected to worsen with the current policy and climate change in developing countries (Tan and Foo, 2018). Pinch Analysis is used for systematic planning of resources, which was developed by Linnhoff et al. (1978) for heat exchanger applications. Later, its applications expanded to include the conservation of mass-separating agents (El-Halwagi and Manousiouthakis, 1989) and various material resources (Foo, 2012). Bandyopadhyay et al. (2009) later extended the concepts of Pinch analysis to address segregated targeting problems, proposed a decomposition method. Prabhakar and Bandyopadhyay (2023) extended the concept of Pinch analysis for decarbonization and proposed a graphical optimization method. Pinch Analysis has proven its versatility by tackling diverse engineering challenges across mechanical, chemical, process, energy, and environmental domains (Klemeš et al., 2018).

Industrial water demand is rising rapidly, posing a significant threat to water resources and exacerbating water scarcity in many regions due to the substantial amount of water required for manufacturing, cooling, and other operational needs. Climate change is further compounding the challenge by altering precipitation patterns and reducing the reliability of existing water supplies.

Desalination technologies offer a promising solution to mitigate the strain on conventional freshwater sources by converting seawater or brackish water into freshwater. However, implementing desalination comes with challenges, including high energy consumption, environmental impacts, and cost-intensive. Balancing the increasing industrial water demand with sustainable desalination practices is crucial for ensuring water security and minimizing adverse effects on ecosystems and local communities. Addressing the challenge of water desalination is crucial for enhancing water resource planning. Various quantitative methodologies, including game theory as demonstrated by Yamamoto et al. (2012) and input-output analysis as illustrated by Yang et al. (2015), have been employed to optimize policies in the realm of integrated water management.

In this work a new graphical methodology for determining the minimum desalinated water production needed for the satisfaction of demand is presented. The method also determines the minimum subsidy requirement to support the desalinated water production. The proposed method can be used as a planning too and can determine the maximum water demand that can be satisfied for a given subsidy. A mathematical optimization formulation to solve the above problem is also presented in the subsequent section which is used to verify the graphically obtained results. In subsequent section the mathematical optimization formulation is presented which is followed by graphical methodology and case study. At last conclusion is presented.

* 1. Mathematical Optimization Formulation

Let is the capacity of water produced, and the capacity factor be for the  th water source. Therefore, the total water produced by source annually is . The cost of water produced by  th source is and the total cost of water produced is . Similarly, be the water demand of  th sector. The capacity factor for the sector be and hence, it consumes annual water of while producing a fund of from the system. is the maximum acceptable price of the  th sector. is the amount of desalinated water produced and is subsidy provided to support the production of desalinated water. The primary objective is to determine the minimum subsidy required to support desalinated water production for the demand satisfaction of specified geographic regions. The mathematical equations for the optimization problem can be written as:

Minimize:

|  |  |
| --- | --- |
|  | (1) |

Constraints:

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

Equation (2) implies that the summation of the total freshwater produced and the water produced after desalination should satisfy the total water demands of various sectors. Similarly, equation (3) represents that the total subsidy provided for desalinated water produced should be either less than or equal to the difference of the total cost of water product and the total fund generated by water consumption by various sectors. In addition to these constraints, the capacity factors are non-negative, and their values should lie between 0 and 1.

* 1. Graphical Methodology

A new graphical method is proposed to determine the minimum subsidy required for desalinated water production to meet industrial demand. This method involves constructing a piecewise linear water production composite curve, which plots water production against its corresponding production cost (Figure 1a). The cost intensity, or the cost per unit of water production, is calculated for each water source, and these sources are then arranged in ascending order of their cost intensity. The water production composite curve is constructed to ensure the utilization of the least cost-intensive water sources first. The resulting cumulative water produced versus cumulative cost incurred curve represents the optimal sequence for utilizing water sources to meet the specified water demand while minimizing production costs.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Figure 1(a): Water demand composite curve (b) water production composite curve.

Similarly, a piecewise linear water demand composite curve is drawn to represent the relationship between water consumption and the cost of water consumption (as shown in Figure 1b). This curve is created by calculating the cost intensity (i.e., fund generated per unit of water consumed) for each water source and arranging the sources in descending order of their cost intensity. The resulting curve ensures that the highest cost-intensive water sources are used first for water consumption in the region. For every point on the composite curve of water, the fund generated by the water source is represented by the y-axis, and the x-axis represents the amount of water consumed.

To meet the water demand of a specific region, the water production composite curve (Figure 1a) is adjusted by shifting it vertically downwards. This shift is equivalent to the subsidy provided by the government. After this adjustment, the shifted water production composite curve and the water demand composite curve are plotted together on the cumulative water versus cumulative cost graph to determine the minimum subsidy provided to meet the industrial water demand. This process ensures the region's water needs are fulfilled while minimizing the subsidy required for desalinated water production.

The first point of intersection of both the shifted composite curves of water production and water demand composite curve gives the optimum solution to the problem (see Figure 2). This intersection point is called the Pinch point. The Pinch point ensures that the optimum mix of water is produced. The horizontal projection of the production composite curve represents the amount of water produced by the different water sources, which must satisfy the given water demand (as indicated by the horizontal projection of the water demand composite curve). Thus, the horizontal projections of the composite curve ensure that the water balance constraint is met. Likewise, the vertical projection of the composite curve corresponds to the cost for the system, ensuring that the fund balance constraints are satisfied.

Water Demand composite curve

Figure 2: Graphical solution for determining the minimum subsidy for desalinated water production.

The point of intersection of both the composite curves is called the Pinch point as it has similar characteristics to the classical Pinch point. The Pinch point splits the system into the below-pinch utilization region and the unused region. The below-pinch region contains all water-producing sources and demands that must operate at full capacity to meet the system's demands. The water sources and water demand that are not needed are included in the above-pinch region and can be shut down. The water production and water demand operate at partial capacity at Pinch Point. Following the golden rule of Pinch Analysis, transferring water across the Pinch point is not allowed.

* 1. Case Study

The case study is based on Qingdao, a city in Shandong Province on the east coast of  
China. It is one of the cities which suffers from water shortage issues. The case study is taken from Jia et al. (2019). The tabulated data in Table 1 represents the various sectoral demands for water and the acceptable cost of water paid by these sectors. Table 2 represents the water production capacities of various existing water sources. The total water demand from multiple sectors is 275 kt/d, and the total water produced by the existing sources is 210 kt/d. The remaining water demand is satisfied using desalinated water, and the cost of freshwater generated from desalination is 1.15 $/t. The objective of this case study is to find the cost-optimal water mix production for the satisfaction of the overall demand for water.

Table 1: Sectoral water demand and the cost of water (Jia et al., 2019).

|  |  |  |
| --- | --- | --- |
| **Sector** | **Water demand (kt/d)** | **Cost ($/t)** |
| Residential sector | 70 | 0.36 |
| Industrial sector | 150 | 0.65 |
| Commercial Sector | 45 | 0.94 |
| Others | 10 | 1.05 |

Table 2: Water production capacity and the corresponding cost of water production (Jia et al., 2019).

|  |  |  |
| --- | --- | --- |
| **Water sources** | **Capacity pf production (kt/d)** | **Cost ($/t)** |
| Ground water | 20 | 0.55 |
| Reclaimed water | 50 | 0.78 |
| Surface water | 50 | 0.43 |
| External diversion water | 90 | 0.72 |

Figure 3: Graphical solution for determining the cost-optimal water mix production to satisfy the overall water demand.

The production composite curve and the demand composite cure in Figure 3, drawn using the proposed method. The production composite curve is drawn according to the increasing cost per unit of water production. Similarly, the demand composite curve is drawn according to decreasing per unit of acceptable price. The production composite curve is shifted vertically downwards until it covers the total water demand. The amount of vertical downward movement gives the amount of subsidy to be provided for desalinated water generated. The point of intersection of both curves gives the optimum solution and is also called the Pinch point. The solution implies that after using the locally available resources completely, the seawater desalination fulfills the remaining water demand. Total water produced by desalination to satisfy the water demand of 65 kt/d at a generation cost of 74750 $/kt. The subsidy provided by the government is equal to 35550 $/kt. These results are identical to those reported by Jia et al. (2019), where the limiting composite curve is used to determine the minimum subsidy.

* 1. Conclusion

This paper introduces a novel non-iterative graphical targeting approach to optimize subsidies for desalinated water production. The method determines the minimum subsidy and desalinated water production necessary to meet demand requirements. The graphical outcomes obtained through the proposed technique can be verified using a mathematical formulation presented in the paper to ascertain the optimal subsidy. The applicability of this method is demonstrated through a case study presented focusing water scarcity of Qingdao city in China. The obtained results suggest that, at a generation cost of 74,750 $/kt, the desalination process produces a total of 65 kt/d of water to meet demand, with a corresponding government subsidy of $35,550/kt.

This graphical method, outlined in this paper, is adaptable to changes in water demand and subsidy levels, providing an optimal solution. It serves as a valuable planning tool for achieving cost-effective desalinated water production. In subsequent studies, the methodology could be expanded to incorporate considerations of energy consumption and environmental impacts in water supply planning.

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