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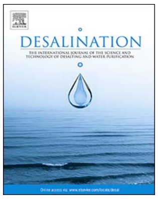

Desalination network model driven decision support system: A case study of Saudi Arabia

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ABSTRACT

This study aims to develop a network model driven platform that supports decision-makers to make well-informed decisions for the efficient water supplies, taking Saudi Arabia as a case study. The water/energy network analysis should be able to identify optimal locations for sustainable desalination infrastructure investments, accounting for the existing assets and the current investment plans. The geographical aspect of individual resource production and distribution can be quantitatively handled by a graph-theoretic approach. This study employs a new multicommodity network flow model called the INFINIT (interdependent network flows with induced internal transformation) model, which enables to address water-energy nexus issues and to optimize the flow of multiple resources as well as placement of new water/energy facilities at the individual facility level. The INFINIT model in this study formulates and solves mixed-integer linear programming (MILP) problems to minimize the designated multi-objective functions of the total cost and CO_2 emission. As a result of optimization, the Pareto-optimal solutions with different network flow topology and the downselected potential locations for new facilities are obtained. To effectively visualize alternative design and policy scenarios, two ways of visualization of the results are developed: a MATLAB-based graphical user interface and tabletop 3D map projection.

1. Introduction

The Kingdom of Saudi Arabia (KSA) is at the forefront of water desalination for human use. This is driven by the scarcity of renewable water resources. Indeed, with limited rainfall and excessive consumption, the major ground water aquifers are being depleted. A study in 1984 estimated that the storage of the main and secondary aquifers was 500 billion cubic meters and a study in 1996 estimated the amount to be 289.1 billion cubic meters [1]. Considering the reported consumption rates since then, the state of ground water resources in KSA is becoming unsustainable. Thus, water desalination in KSA is an indispensable strategic choice to secure potable water. Desalination is an energy intensive process. The energy required by those desalination plants are mainly supplied by oil and gas. Today, there is no use of nuclear energy or coal, and there is very limited use of renewable energy.

Growing demand on both water and energy due to the rapid population growth puts significant pressure on the current existing infrastructure [2]. This situation may lead to major problems for KSA if not tackled in an optimal manner. Drastic measures should be taken from either demand or supply side to put the state of water resources in a more sustainable path. On the supply side, large investments will be required in new water desalination and power generation plants and their accompanying infrastructure such as transmission and distribution systems. Planning a new infrastructure requires a better understanding of the current network of infrastructure as well as the dynamics of demand. Since infrastructure projects are usually expensive, decisions must be made with a full understanding of the effect of a new project on the overall infrastructure network.

This study aims to develop a network model based platform that supports decision-makers to make well-informed near-term and long-term decisions at a policy level for the efficient water supplies. While single facility analysis is very informative, the drive to use renewables as a primary energy source for desalination will likely impact the choice of both water and energy facility locations. The water/energy network model views a single plant as part of a larger network representing a region or spanning the entire KSA. Since desalination plants and power plants are increasingly connected together with water pipelines and electricity transmission lines, evaluating a standalone plant as a node in a larger network is compelling. The water/energy network analysis should be able to investigate and identify candidate locations for sustainable desalination infrastructure investments, accounting for the

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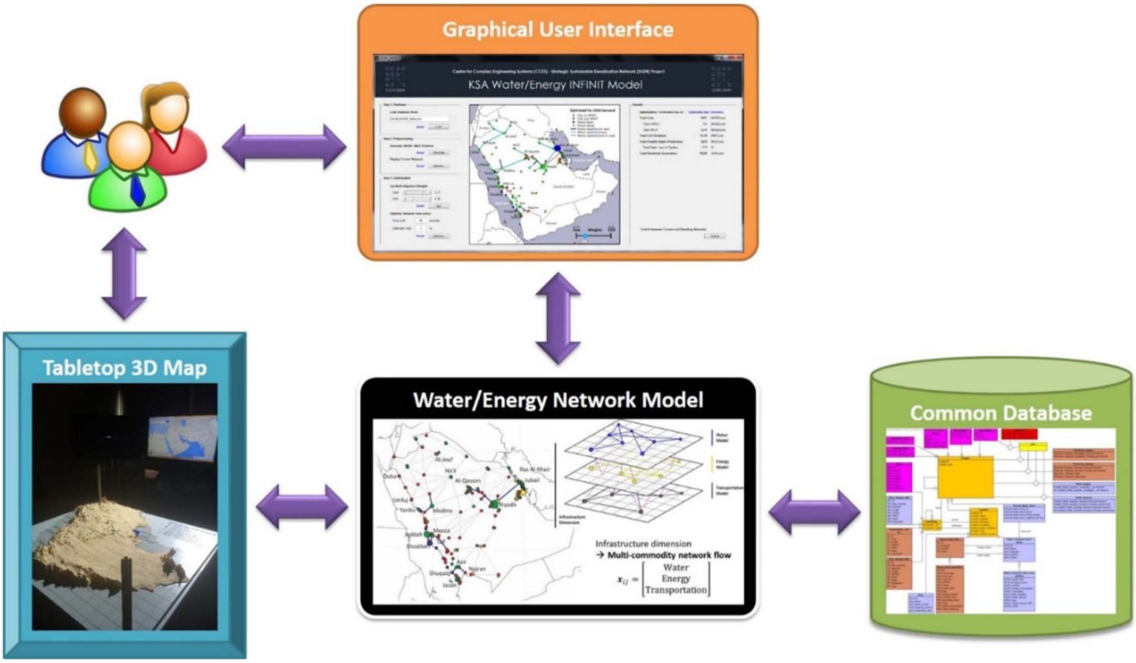

Fig. 1. Network model driven decision support system.

existing assets and the current investment plans.

In addition to the network model, due to the high degree of complexity of the problems being addressed, it is also important that the decision support system (DSS) is able to effectively visualize alternative design and policy scenarios. Fig. 1 illustrates the DSS proposed in this paper. Two ways of visualization of the results are developed: the MATLAB-based graphical user interface (GUI) and the tabletop 3D map projection. The DSS also includes a common database that covers all water and energy data needed for both supply and demand sides. This network model driven DSS will enable stakeholders to both evaluate and refine complex scenarios addressing the location of water and energy investments across KSA.

2. Related work

While a great deal of work has been done on optimizing the unit operations of a single desalination plant, little attention has been paid to optimizing the whole water supply chain network. Optimization of water supply chain considers higher level of strategic decisions about the optimal water supply and distribution to meet geographically dispersed demand nationwide. Kondili et al. proposed a linear programming optimization model for the optimal planning of complex water systems with multiple supply sources (desalination, ground reservoirs, dams, and water transfer) and multiple user demands (agriculture, industry, and urban and other sectors) [3]. However, this model only looks at the optimal matching between these sources and users without addressing a geographical network and its constraints. Al-Nory et al. proposed a mixed integer linear programming model to solve a water desalination supply chain problem as a network flow problem to provide decision makers with a set of investment alternatives comprising combinations of different desalination plant locations, capacities, technologies, and energy sources [4,5]. In this model, however, a simplified network with limited numbers of nodes and arcs was assumed in the analysis so that only obvious matching of the supply and demand locations occurred due to a limited tradespace. In addition, constraints on water transmission such as pumping energy and water losses (evaporation and leakage) are not given or only given through a unit flow cost. Also in this model, water-energy nexus issues cannot be addressed because of the decoupling of water layer from energy layer.

3. Water/energy network model

The water/energy network model discussed here views a single desalination/power plant as part of a larger network representing a region or the entire KSA. Since desalination/power plants are increasingly connected together with water pipelines and electricity transmission lines, the impact of evaluating a standalone plant versus evaluating that same plant as one of the nodes in a larger network will be interesting.

The geographical aspect of individual resource production and distribution can be quantitatively handled by a graph-theoretic approach. As shown in Fig. 2, since multiple interacting resources or "commodities" share the same network such as water (potable, non-potable, and waste water) and electricity, this problem can be modeled as a multi-commodity network flow problem. In this context, a new network flow modeling method was developed to optimize the flow of resources and placement of new facilities (and expansion or retirement of existing facilities) at the individual facility level [6,7]. This method, which is called the INFINIT (Interdependent Network Flows with Induced Internal Transformation) method, has demonstrated successful applications in different contexts [8,9].

3.1. INFINIT model

Before discussing the context-specific formulation, we present the basic form of the INFINIT model. The INFINIT model was created by combining two forms of generalization of the classical minimum cost flow problem: generalized flow problems, in which arcs might consume or generate flows, and multicommodity flow problems, in which multiple commodities share the same network. In INFINIT, the flow x_{ij} in arc (i,j) is split into two parts: $x_{ij}{}^{+}$ and $x_{ij}{}^{-}$, where $x_{ij}{}^{+}$ represents the outflow from node i and $x_{ij}{}^{-}$ represents the inflow into node j. Let $c_{ij}{}^{+}$ and $c_{ij}{}^{-}$ denote the cost per unit outflow and inflow, respectively. Using these notations, the INFINIT problem can be formulated as follows:

Minimize:

$$\mathscr{J} = \sum_{(i,j)\in\mathscr{A}} \left(c_{ij}^{+T} x_{ij}^{+} + c_{ij}^{-T} x_{ij}^{-}\right) \tag{1}$$

subject to: