Large Scale Infrastructure Design Using Evolving Networks

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ABSTRACT

This paper discusses the potential use of graph-theoretic framework in the context of large scale infrastructure design and management. Named as the Interdependent Network Flow with Induced Internal Transformation (INFINIT) model, it could be used to optimize the flow of resources and placement of new facilities (and expansion or retirement of existing facilities) at the individual facility level over multiple dimensions of geographical networks. This model can solve an optimization problem considering both spatial and temporal dimensions: a spatial dimension, where a new infrastructure should be invested at a given time; and a temporal dimension, when a new infrastructure should be invested. We apply the model to study the agriculture water system in Saudi Arabia and evaluate the concept of “Solar Desalination for Agriculture” at a national level. This framework takes into account key performance attributes such as cost, sustainability, optimality, strategic security and robustness as well as the ideal phasing and deployment of the network. These attributes span multiple dimensions such as spatial (network topology), temporal (multiple phases) and technical (available technologies) dimensions. The focus of this research is

to demonstrate the applicability of the INFINIT for modeling and assessment of agricultural water system in Saudi Arabia.

INTRODUCTION

Design of a large scale water system considers high level of strategic decisions regarding the optimal water production, supply and distribution to meet geographically dispersed demand nationwide that is changing overtime. The planning and governance of the water infrastructure become more difficult in regions with limited water resources, which rely on desalination due to shortage of rainfall and groundwater. In this context, the design of water as well as the required energy infrastructures is a major challenge as the power and desalination plants are increasingly connected to water pipelines and power lines. The design of a stand-alone facility may not be optimal if it is not considered as part of the whole network. The geographical aspect of the production and distribution of the resources can be addressed quantitatively using a network model following a graph theory approach. The network model should solve a spatial optimization problem, what and where a new infrastructure needs to be invested in order to satisfy the water demand, and also to answer the question when to invest given the evolving demand.

In order to address these challenges, we introduce in this paper a graph-theoretic framework called the Interdependent Network Flow with Induced Internal Transformation (INFINIT) model. A static version of the model was presented in Ishimatsu et al. (2017a) which can solve an optimization problem in spatial dimension, that is, where a new infrastructure should be invested at a given time. A time-extended version of the model is presented in this paper, which, in addition to the spatial dimension, addresses the temporal dimension answering the question of when a new infrastructure should be invested. Hence, the model can optimize not only snapshots of future infrastructure but also staged deployment of future infrastructure projects over time.

In order to illustrate the model, we present a case study addressing the agriculture sector in Saudi Arabia. Currently in 2017, agriculture water demand in the country is fully met through underground water resources. As the levels of depletion are not sustainable, one imaginable option is to use desalinated water for agriculture. Thus, we assess the concept of “Solar Desalination for Agriculture” at a national level. The INFINIT model can be used to optimize the flow of resources and placement of new facilities such as desalination plants and water pipelines (and expansion or retirement of existing facilities) over multiple dimensions of geographical networks. A first version of the study was presented in Doufene et al. (2016a).

In the following sections, after discussing related works, the presentation of our methodology and the INFINIT mathematical formulation, we present the case study addressing the water for agriculture system in Saudi Arabia. We discuss some results and conclude with perspectives.

RELATED WORK

Several works have been done in order to support decisions in terms of investment and expansion of new infrastructures. Following a system of systems thinking approach, Hall et al., (2014) presented a fast track assessment (FTA) methodology for analyzing national multi-sectoral infrastructure systems (energy, transport, digital communications, water, and waste) performance in the context of uncertain futures, incorporating interdependencies in demand across sectors. Applied to Great Britain, they demonstrated how different sectors are shaped by many of the same drivers such as those influencing demand (demography, economy) and energy prices. The FTA allows analyzing different scenarios across different infrastructure sectors. They advocated that understanding the interdependencies between different sectors is essential to minimize the risks of infrastructure failure.

Cardin et al. (2015) proposed a methodology based on design catalogs as a systematic process for identifying and evaluating improved infrastructure system designs. A catalog consists of a set of operating plans (an operating plan is a combination of design variables, parameters, and flexible decision rules to manage the infrastructure system in operations and over its lifecycle). These operating plans are created to suit uncertainty scenarios that are simulated and evaluated using lifecycle performance measures such as net present values, return on investment, internal rate of return metrics, etc. However, the authors advise to address an acceptable number of scenarios. Choosing different scenarios and parameters may lead to significantly different results and recommendations.

Adeptu et al. (2013) presented a functional and spatial system framework to model city infrastructure systems. This framework built on previous works on system decomposition (Alfaris et al., 2010), spatial topologies applied in geographic information system environments, and functional layers as referred to Tolone et al. (2004) and Grogan and de Weck (2012) aims at improving the system modeling process by taking into account the critical system interdependencies in the modeling framework as city systems do not operate in isolation. This modeling approach was used to design an integrated energy system model. This framework is appropriate for the representation of city infrastructure systems but do not support decisions in term of planning new investment and expansion giving the evolving demand of commodities.

From another perspective, Godau (1999) explained how the increasing complexity due to technical, economic, managerial, environmental, political, and social factors was changing infrastructure management. He discussed the issues when developing new engineering management system, and discussed evolving engineering management approaches and how they were related to the changing environment. His study suggests that the adoption of system thinking and holistic approaches to infrastructure management is the key to managing the increasingly complex interrelationships in order to overcome many of the shortages in the traditional approaches.

In the context of water management systems, particularly desalination for large scale utilization, many researchers addressed the techno-economic issues. Ghaffour et al. (2013) highlighted the desalination costing aspects and the influencing factors. His work focusses on the desalination technologies and energy consumption only, and do not consider the transportation issues.

Doufene et al. (2016b) presented a library of models addressing the solar desalination combination problem. The aim of this library is to help stakeholders compare technologies and systems at the facility level, including the role of solar-thermal and solar-electrical energy requirements based upon desalination technology choices. A key strategic issue is the degree to which renewable energy sources are dedicated and/or co-located with specific desalination facilities, including impacts on operational performance and flexibility - versus renewables that may be located elsewhere. The objective is to select the optimal output capacity, technology, and sub-system design specifications for a single desalination facility, in a certain location with its associated technical and environmental conditions. The transportation problem has not been addressed.

In order to address the problem of water supply over long term, Scarborough (2015) presented an interdisciplinary study for long term water supply planning. He compares dam and desalination costs (application in an Australian coastal city). Using system dynamics model combining economic, social and scientific variables, a sensitivity analysis suggests that over a longer time horizon, desalination provides a more viable, cost effective and secure bulk water supply alternative when compared to building large rain-dependent dams. Even if the study discusses the problem of supply, it does not consider water transportation cost while it is paramount when studying the water system at a large scale, connecting many disconnected production and consumption assets.

In the context of Saudi Arabia, the growing water and energy demand puts more pressure on the current existing infrastructure (MoWE, 2013), leading to a need for large investments in new water desalination and power production plants and their accompanying infrastructure such as transportation, distribution, and storage systems. Planning a new infrastructure requires a good understanding of the current network of infrastructure, and a good understanding of the dynamics of demand. Infrastructure projects are usually expensive (SSDN, 2015; SIPS, 2013 and 2015) and decisions must be made with full understanding of the effect of new projects on the overall infrastructure network. These spatial decision-making problems require the decision-makers to assess different alternatives along multiple dimensions in order to choose the best alternative. Spatial decision problems involve indeed a large set of feasible alternatives often evaluated by different individuals, based on multiple and frequently conflicting evaluation criteria, involving policy priorities, trade-offs, and uncertainties as explained in Jankowski (1995).

Kondili et al. (2010) 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). However, this model looks only at the optimal matching between these sources and users without addressing a geographical network and its constraints. Al-Nory et al. (2013, 2014) 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. 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.

In order to address these shortcomings, we present in this paper the INFINIT model. As a static version of the model was presented in Ishimatsu et al. (2017a) which can solve an optimization problem in spatial dimension, that is, where a new infrastructure should be invested at a given time, we focus in this paper on a time-extended version of the model, which, in addition to the spatial dimension, addresses the temporal dimension answering the question of when a new infrastructure should be invested. The model then can optimize staged deployment of future infrastructure projects over time. We apply the model to study the potential use of solar desalination to supply agriculture in Saudi Arabia.

METHODOLOGY

The INFINIT model employs a graph-theoretic framework, which was first introduced as the generalized multi-commodity network flow (GMCNF) model in Ishimatsu (2013a). This model has demonstrated successful applications in different contexts (Chale-Gongora et al., 2014; Ishimatsu et al., 2012, 2013b, 2016, 2017a; Khiyami et al., 2016a). As shown in Figure 1, the model can be used to optimize the flow of resources and placement of new facilities (and expansion or retirement of existing facilities) at the individual facility level over multiple dimensions of geographical networks. The basics of the INFINIT model are described in detail in Ishimatsu (2017a and 2017b). This paper is focused on using this model to address the concept of Solar Desalination for Agriculture.

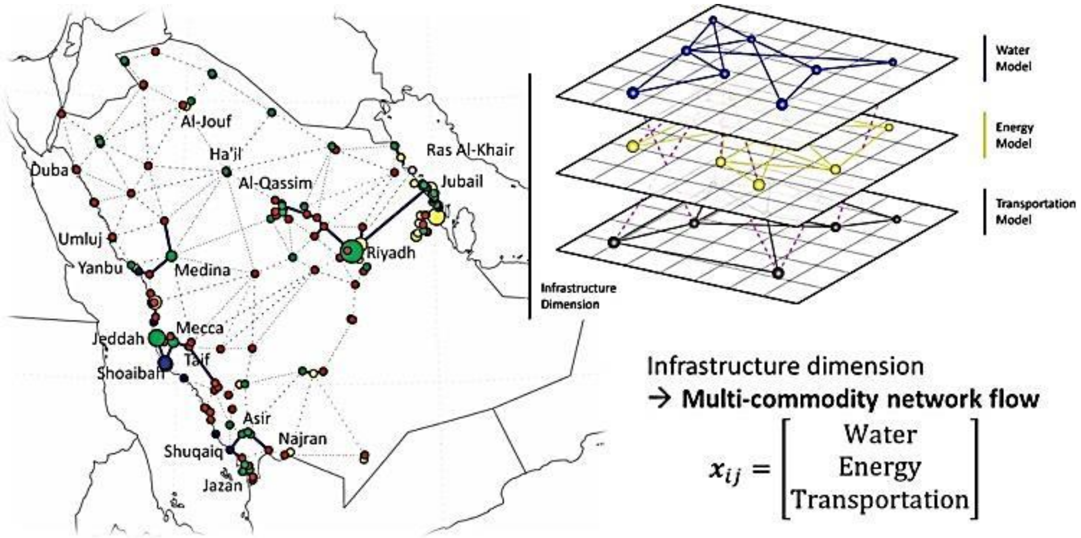

Figure 1. KSA multi-dimensional infrastructure network.

Overview of INFINIT Mathematical Formulation

In this paper, the INFINIT model defines three sets of decision variables: (1) flow amount on arc (i, j), denoted by $\boldsymbol{x}^{\pm}_{ij}$, (2) capacity expansion of arc (i, j), denoted by $\boldsymbol{y}_{ij}$, and (3) a binary variable representing whether arc (i, j) is used/invested or not, denoted by $\boldsymbol{z}_{ij}$. The mathematical formulation of the INFINIT problem is presented below:

Minimize:

$$\mathcal{J} = \sum_{(i,j)\in\mathcal{A}} \mathcal{J}_{ij} \qquad \text{(eq.1)}$$

subject to:

$$\sum_{j:(i,j)\in\mathcal{A}} \boldsymbol{A}^{+}_{ij}\boldsymbol{x}^{+}_{ij} - \sum_{j:(j,i)\in\mathcal{A}} \boldsymbol{A}^{-}_{ji}\boldsymbol{x}^{-}_{ji} \leq \boldsymbol{b}_i \quad \forall\, i \in \mathcal{N} \qquad \text{(eq.2)}$$

$$\boldsymbol{B}_{ij}\boldsymbol{x}^{+}_{ij} = \boldsymbol{x}^{-}_{ij} \quad \forall\, (i,j) \in \mathcal{A} \qquad \text{(eq.3)}$$

$$\boldsymbol{l}_{ij}^{+} \leq \boldsymbol{x}_{ij}^{+} \leq \boldsymbol{u}_{ij}^{+} + \boldsymbol{y}_{ij} \quad \forall\,(i,j) \in \mathcal{A} \qquad \text{(eq.4)}$$

$$\boldsymbol{0} \leq \begin{bmatrix} \boldsymbol{x}_{ij}^{+} \\ \boldsymbol{x}_{ij}^{-} \\ \boldsymbol{y}_{ij} \end{bmatrix} \leq \mathcal{M}\boldsymbol{z}_{ij} \quad \forall\,(i,j) \in \mathcal{A} \qquad \text{(eq.5)}$$

$$\boldsymbol{z}_{ij} \in \{0,1\} \quad \forall\,(i,j) \in \mathcal{A} \qquad \text{(eq.6)}$$

where $\mathcal{J}_{ij}$ is a contribution from arc (i,j) to the overall objective function in the form of a weighted linear sum of $\boldsymbol{x}_{ij}^{\pm}$, $\boldsymbol{y}_{ij}$, and $\boldsymbol{z}_{ij}$, $\boldsymbol{b}_i$ denotes the net supply/demand vector at node i, $\boldsymbol{l}_{ij}$ and $\boldsymbol{u}_{ij}$ represent the lower bound and the capacity of arc (i,j), respectively, and $\mathcal{M}$ is a sufficiently large number for the so-called big-$\mathcal{M}$ method. $\boldsymbol{A}_{ij}^{\pm}$ is called a *flow equilibrium matrix*, and $\boldsymbol{B}_{ij}$ is called a *flow transformation matrix*. Since $\boldsymbol{z}_{ij}$ is binary, this problem falls into the category of mixed integer linear programming (MILP). See (Ishimatsu, 2017a and 2017b) for more detail.

Time-Evolving Network

The INFINIT model formulated by Eqs. (eq.1)-(eq.6) is a static network flow model, in which the flow is optimized with respect to a given snapshot of supplies and demands. A static INFINIT model can solve an optimization problem in spatial dimension, that is, *where* a new infrastructure should be invested at a given time. However, it does not answer the question of *when* it should be. Since demand must be satisfied each year (not only once) and a facility, once built at a certain time, operates during its lifetime of a few decades from then, the problem to be solved is not a one-time optimization. The INFINIT model must be extended to the temporal dimension so that it can optimize not only snapshots of future infrastructure but also staged deployment of future infrastructure projects over time. In other words, the transition of network topology occurs in a staged manner, not at one time.

The basic idea of the time-expanded network is that it contains a copy of a static network (nodes and arcs) for each discrete time step. Figure 2 takes a simple time-expanded network as an example, which consists of two desalination plant nodes i and j and a city node k for three discrete time steps of 2010, 2020, and 2030. Desalination plant i is online in both 2010 and 2020 but supposed to be retired by 2030. Node j is a candidate location for a new desalination plant. Therefore, loop (j, j) and arc (j, k) do not exist but can be constructed if invested. The demand for water in city k must be satisfied somehow in each of 2010, 2020, and 2030.

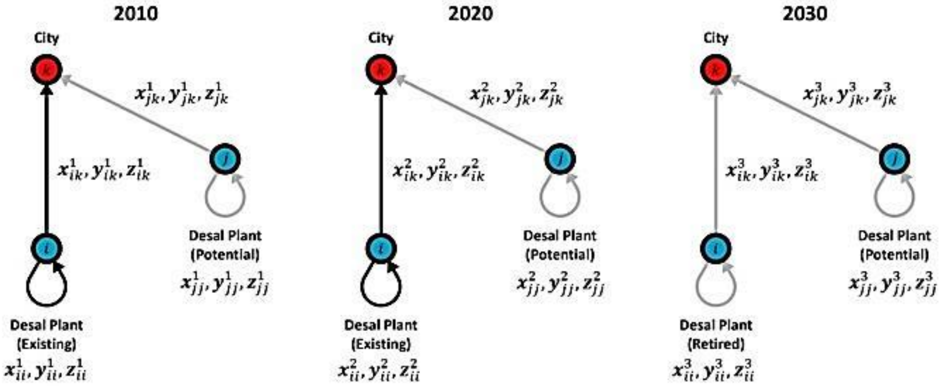

Figure 2. Time-expanded decision network for temporal dimension.

The objective function should be evaluated as a whole. Therefore, instead of Eq. (eq.1), the objective is to minimize:

$$\mathcal{J} = \sum_{t\in\mathcal{T}} \sum_{(i,j)\in\mathcal{A}} \mathcal{J}_{ij}^{t} \qquad \text{(eq.7)}$$

where the superscript t represents the value at time step t. The constraints (eq.2), (eq.3), (eq.5), and (eq.6) hold the same form but must be satisfied at each time step. However, since a facility built at a certain time operates during its lifetime over multiple time steps, the constraint (eq.4) needs to be changed as follows:

$$\boldsymbol{l}_{ij}^{t} \leq \boldsymbol{x}_{ij}^{t} \leq \boldsymbol{u}_{ij}^{t} + \sum_{\substack{t-\Delta_{ij} \leq \tau \leq t \\ \tau \in \mathcal{T}}} \boldsymbol{y}_{ij}^{\tau} \quad \forall\, t \in \mathcal{T}, (i,j) \in \mathcal{A} \qquad \text{(eq.8)}$$

where Δ_{ij} denotes an entire lifetime of the facility. What this means is that the overall capacity at time step t is the original capacity $\boldsymbol{u}_{ij}^{t}$ plus the sum of the capacities that have been added to this facility since $t - \Delta_{ij}$. By this modification, neighboring time steps are indirectly connected through facility lifetime. As for the selection of time step size, the smaller it is, the higher fidelity the results can be. But if it is too small (e.g., 1 year), the downside is that it requires considerable computational effort. Considering KSA has issued 5-year development plans, we can pick 5 years as a reasonable time step size. Assuming a 30-year lifetime for any added desalination capacity at a certain site i, water production in 2050, for example, at this facility is written as:

$$\boldsymbol{x}_{ii}^{2050} \leq \boldsymbol{u}_{ii}^{2050} + \boldsymbol{y}_{ii}^{2020} + \boldsymbol{y}_{ii}^{2025} + \boldsymbol{y}_{ii}^{2030} + \boldsymbol{y}_{ii}^{2035} + \boldsymbol{y}_{ii}^{2040} + \boldsymbol{y}_{ii}^{2045} + \boldsymbol{y}_{ii}^{2050} \qquad \text{(eq.9)}$$

Note that $\boldsymbol{u}_{ii}^{2050}$ is a capacity that is pre-existing (known before optimization) even if no new capacity is added between 2020 and 2050. Therefore, $\boldsymbol{u}_{ii}^{2050}$ does not include a new decision on $\boldsymbol{y}_{ii}^{2020}$ through $\boldsymbol{y}_{ii}^{2050}$. If a currently existing facility at this site is supposed to be retired before 2050, or if there does not exist a facility at this site, then $\boldsymbol{u}_{ii}^{2050} = 0$.

This time-evolving INFINIT MILP model is able to determine where a new facility should be established both in spatial and temporal dimensions. After optimization, the Pareto-optimal solutions with different network flow topology are obtained. If the result shows that a new infrastructure is not invested in the same site as an existing facility, then it implies that the site should be closed before or at the end of its current lifetime. This would suggest an optimal strategy for staged transition of infrastructure network.

CASE STUDY

In its effort to diversify its economy, Saudi Arabia initiated a huge agricultural reform initiative in the seventies, providing interest-free loans to farmers, giving land grants, subsidizing energy, and purchasing certain strategic crops from farmers. This government support led to a swift development of the agricultural sector that used to be labor intensive, into a more mechanized and efficient one (MoEP, 2010). Agricultural land area grew from around 400 thousand hectare in 1970 to peak at around 1,600 thousand hectare in the mid 1990's (Figure 3). Since then, agricultural land area has been in a declining trend (SAMA, 2013). It is apparent from Figure 4 that agriculture contribution to GDP peaked at above 6% in the late 80's and 90's. Agriculture contribution declined steadily in the 2000's until it reached 3% in 2012 (SAMA, 2013). The steady decline in agriculture's share of GDP is attributed to the higher growth of other components of GDP (Figure 4).

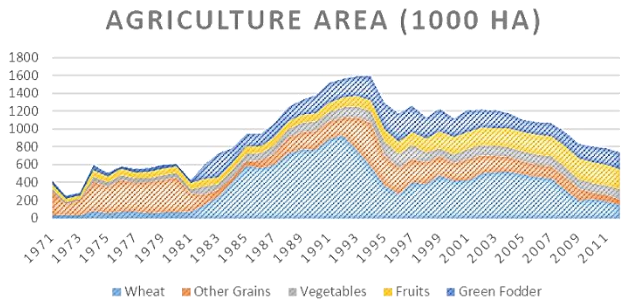

Figure 3. Historical agricultural land area showing major crop families, national (SAMA, 2013).

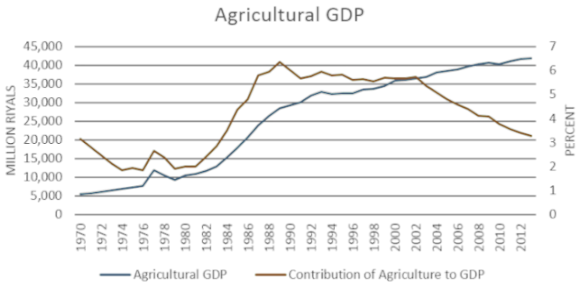

Figure 4. Agricultural GDP and contribution of agriculture to overall GDP, national (SAMA, 2013).

One of the goals of developing the agricultural sector is to achieve food security. At some point, Saudi Arabia exceeded the point of self-sufficiency and started exporting wheat. The government acknowledged the severe consequences of the unbound expansion in agriculture on the limited water resources; underground water being the sole supplier of water for agricultural activity is being depleted in faster rates than what was accounted for. In the mid 2000's, the government started regulating agriculture, limiting the number of new water well permits, banning the exportation of fodder, stopping permits to grow fodder, and shutting down its wheat purchasing program in an eight year process, reducing its purchases by 12.5% annually to stop purchasing wheat in 2015 (MoEP, 2010). Agricultural activities vary across different regions of Saudi Arabia; Figure 5 shows the distribution of the irrigated areas across Saudi Arabia.

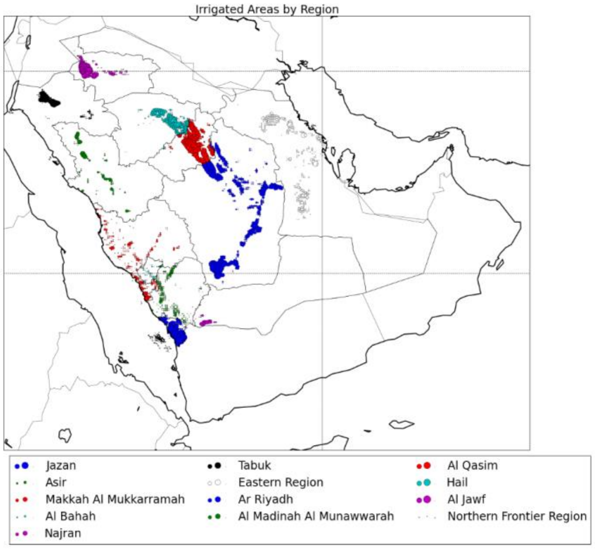

Figure 5. Regional distribution of irrigated areas across Saudi Arabia. (FAO, 2015)

Agricultural water demand constitutes 83% of the total water demand, and the remaining 17% is municipal and industrial water demand (MoWE, 2013) (Figure 6). Presently, agricultural demand depends almost exclusively on groundwater reserves, while industrial and municipal demand is met from a combination of groundwater and seawater desalination (MoWE, 2013). The water cost that farmers pay is almost only the cost of energy needed to pump water from the ground up, and they usually rely on energy resources that are heavily subsidized by the Saudi government (SIPS, 2013 and 2015). This makes water costs marginal and there is no incentive to invest in water efficient irrigation systems.

Due to limited rainfall and excessive consumption, the major groundwater aquifers are being depleted. A study estimated the storage of the main and secondary aquifers in 1984 to be around 500 billion m3 and a study in 1996 estimated the amount to be 289.1 billion m3 (Al-sheikh, 1997). Taking into consideration the reported consumption rates since then, the state of groundwater resources is unsustainable (UN-FAO, 2009), and measures should be taken from either demand or supply side (or both) to put the state of water resources in a more sustainable path.

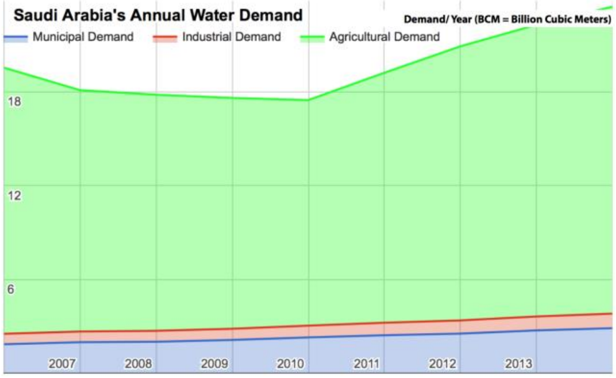

Figure 6. Saudi Arabia Water Demand 2007-2013 (SSDN, 2015)

The major goal of the policies outlined earlier is to reduce the rate of depletion of groundwater, as those levels of depletion are not sustainable; one imaginable option is to use desalinated water for agriculture. To evaluating the concept of “Solar Desalination for Agriculture”, we use the INFINIT model as explained in the following section.

Application of INFINIT

Prior to running INFINIT, we clustered the irrigation areas in KSA into 27 “Agricultural Zones” based on the map of irrigated areas, and then we approximated the water requirements for each of those zones based on historical national agricultural water demand, and the statistics on crop types in each region. To optimize the water strategy for agricultural demand and municipal demand simultaneously in the INFINIT framework, agricultural zones should be added to the baseline network described earlier (see Figure 1) as demand nodes. Figure 7 places the 27 agricultural zone nodes in the water infrastructure network as of 2010. It can be seen from the relative size of the demand nodes that the agricultural demand is much larger than the municipal demand. Potential arcs are also added in the database, connecting the geographical centers of the agricultural zones and nearby nodes so that the INFINIT model can choose the network configuration to supply water to each of the agricultural zones.

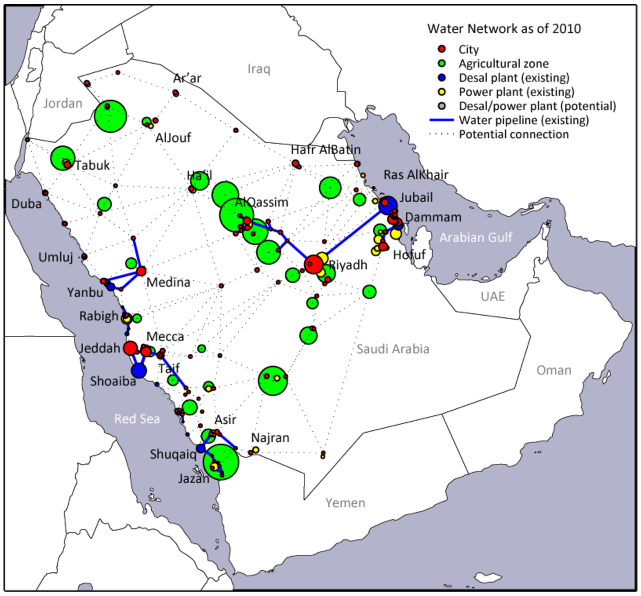

Figure 7. Agricultural zones used; size of circles indicate water demand.

Using this initial data, we performed three sets of computation with a different assumption about groundwater availability relative to agricultural demand: (1) 100% available, (2) 50% available, and (3) 0% available. In case (1), for example, if an agricultural zone needs some amount of water, that same amount is assumed to be available from groundwater at this site. Note that while groundwater is available up to 100% of the demand in terms of capacity, it does not necessarily force the use of groundwater. On the other hand, case (3) assumes no reliance on groundwater in any agricultural zone. Therefore, all the agricultural demand must inevitably be satisfied by desalination (no other water source is considered in this paper).

Figure 8 plots the Pareto-optimal solutions of each of the three cases that were obtained by varying the weights between cost and CO_2 emission. The groundwater availability becomes limited, the Pareto-front moves to upper right (higher cost and emission). Comparing the red and blue dots implies that a full transition from groundwater to desalinated water for agriculture requires additional costs on the order of 1,000 billion USD over 40 years at most, which is roughly approximated to be an average of

25 billion USD per year. Likewise, a full transition from groundwater to desalination also produces additional CO_2 emissions on the order of 1,000 million metric tons over 40 years at most, which is translated into an average of 25 million metric tons per year. Note that this is a rough estimate as a whole and does not consider the detailed costs that will be incurred in adjusting each of the agricultural zones to a major infrastructure change.

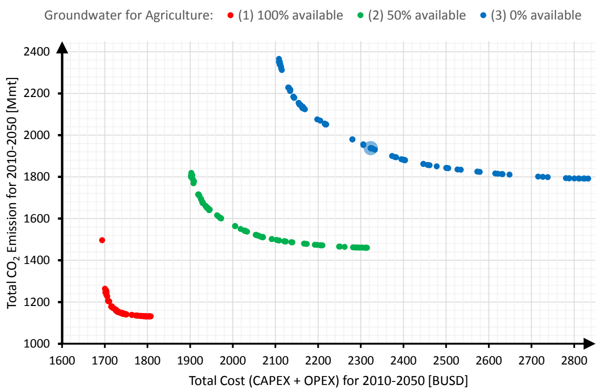

Figure 8. Groundwater vs. desalination for agriculture: Pareto-optimal solutions.

For reference, Figure 9 shows the resulting networks of case (3) cost 50% – CO_2 50% (corresponding to the light blue circle in the upper right of Figure 8). The 2050 water network in Figure 9 eventually constitutes a nationwide trans-peninsula pipeline network connecting the east and west coasts. Table 1 lists the annual cost and CO_2 emission.

Table 1. Desalination for agriculture; case (3) resulting cost and CO_2 for each period (2010-2050): cost 50% – CO_2 50%.

Period	2010-2014	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050		Overall
Total Cost (BUSD/year)	61.6	41.5	65.5	52.3	50.1	52.8	62.9	63	75.2		2323.4
CAPEX (BUSD/year)	26.6	2.6	23	6.5	1.4	1.2	7.9	4	12.8		378.7
OPEX (BUSD/year)	35	38.9	42.5	45.8	48.6	51.6	55	59	62.4		1944.7
Total CO2 (Mmt/year)	34.3	38.2	42.3	45.6	48.5	55.1	55.1	59.2	64.4		1937.8

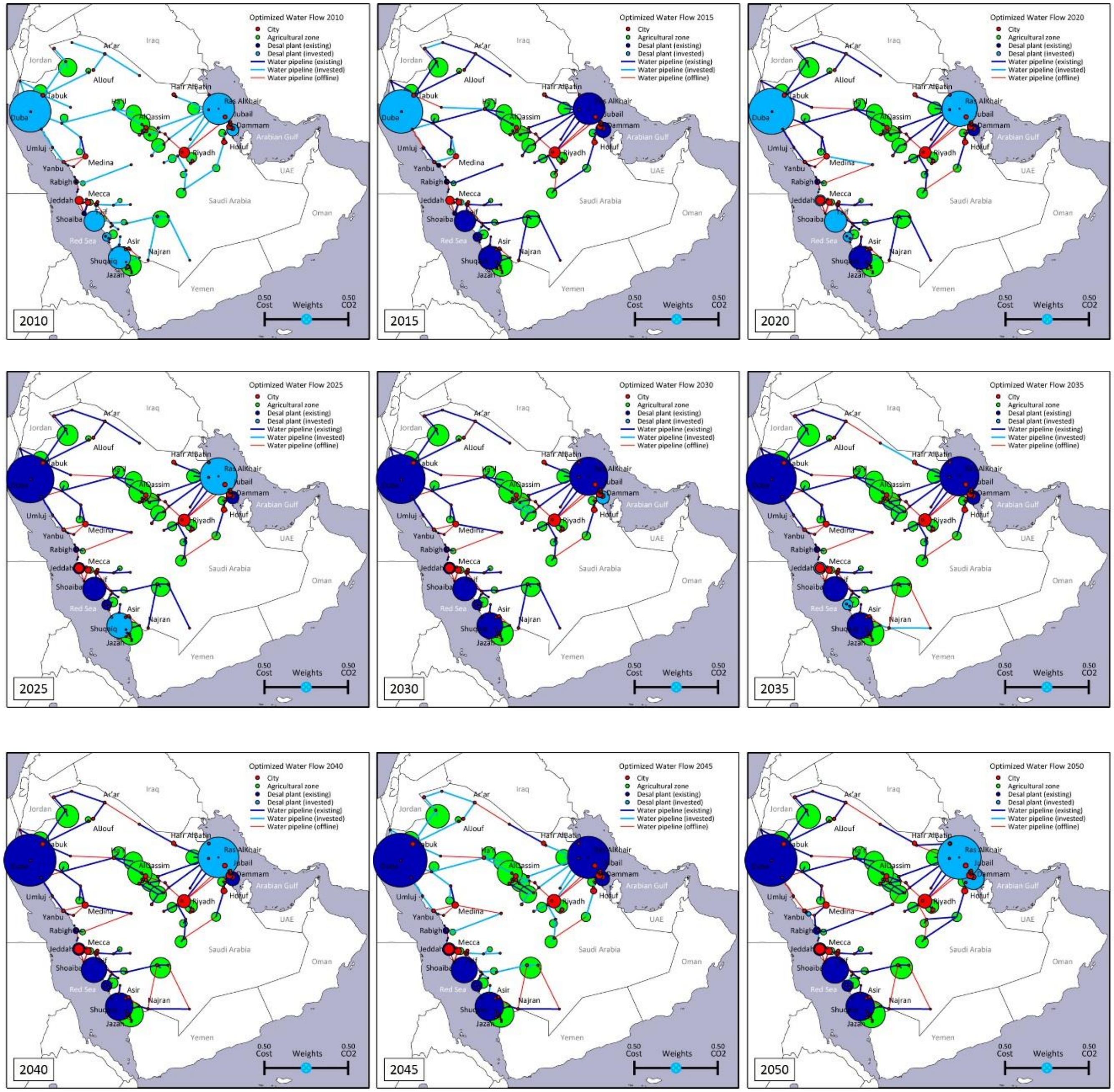

Figure 9. Desalination for Agriculture: resulting network from 2010 to 2050 cost 50% – CO2 50%.

Discussion and study limitations

The cost associated to water desalination for agriculture under the model assumptions is prohibitively high. Agriculture contribution to GDP in 2012 is slightly less than 45 Billion Saudi Riyal ($12 Billion) (SAMA, 2013). The results suggest that we need triple that amount ($35 Billion) as operational costs. There are many ways to reduce those expenses. One approach is to reduce overall agricultural water demand by using higher efficiency irrigation systems, and focusing on crops with less water requirements. Experimenting with unconventional agriculture is an option, for instance, indoor hydroponic agriculture using light emitting diodes as a substitute for sunlight is claimed to save 90% of water requirements in agriculture (SIPS, 2015). Another approach is to reduce water transportation costs by shifting agricultural activity closer to the coast. Doing so is subject to the availability of arable lands within proximity to potential locations of desalination plants, etc.

Where and how large the next desalination investment should be is dependent on our knowledge of the availability of groundwater resources. Al-sheikh (1997) shows estimates of groundwater reserves of only 289 billion m3 at 1996, but consumption in the period of 1996-2013 proved that estimate wrong (SIPS, 2015). It is obvious that there is a need for more detailed understanding of the state of groundwater to make well-informed decisions. Such an understanding would enable Saudi Arabia to better plan its seawater desalination infrastructure. Demand side measures should be taken as well. Excessive groundwater withdraws for agriculture will lower groundwater levels and degrade quality leading to more energy requirements to deliver groundwater to demand points. Excessive extraction of groundwater is associated with increased financial costs. Lower groundwater levels would add more energy demand for extraction from deeper wells. Deeper wells cost more to be dug, and water quality degrades significantly with excessive groundwater withdrawal (Al-sheikh, 1997; Morris et al., 2003). Also, the state of the groundwater is based on limited available data with a large degree of uncertainty.

This is due to the fact that estimating exact figures of groundwater levels is a difficult and uncertain task. We could end up either overestimating or underestimating groundwater levels with a significant margin of error. More studies are needed to better evaluate the current state of groundwater levels to make plans that are more reliable for the future.

Also, in addition to water supply management, other factors on the demand side should be taken into account in order to build a comprehensive model to support decision-making on agricultural water allocation and other agricultural policy actions. There are four major parameters that play a major role in estimating water requirements: climate, soil, crop choice and irrigation management. Those parameters determine crop yield and water needs among other agricultural performance indicators. Such will allow to investigate the effect of a broader set of parameters on agricultural water demand; for example, we can investigate the effect of different irrigation methods or the variation of the cultivated crop types on water demand.

One major limitation of this paper is its choice of time horizon. As a first phase of our study, we use a 5-year time step as an example to make predictions over a 30-year time frame. Significant sources of uncertainty may occur during this timeframe such as: political change, climate change, drought, floods, resource availability change, changes in population demographics, changes in demand and water use patterns, changes in technological capabilities, etc. At this stage of our study, some of the uncertainties can be addressed within a probabilistic framework with smaller time step. However, given the high uncertainty surrounding national infrastructure projects, sophisticated investment analysis techniques are required. The flexibility of infrastructure systems could be addressed through real options that include the possibility of change in the planning and design stages in order to allow the infrastructures to get by future uncertainties. A literature review of academic works discussing real options technique is presented in (Martins et al., 2015). Another methodology addressing the flexibility in water distribution system design under uncertain future water demand is illustrated in (Basupi and Zoran, 2015). However, in our study, we are not emphasizing the uncertainties and specific results but we are emphasizing the design framework.

CONCLUSION

This paper introduces the INFINIT model in order to design large scale infrastructures. This generalized multi-commodity evolving network flow model can solve an optimization problem in spatial dimension, that is, where a new infrastructure should be invested at a given time. In addition to the spatial dimension, it can answer the question of when a new infrastructure should be invested. Hence, the model can optimize not only snapshots of future infrastructure but also staged deployment of future infrastructure projects over time.

In order to illustrate this model, the paper discusses the concept of “Solar Desalination for Agriculture” in the context of the Kingdom of Saudi Arabia. The objective is not to emphasize specific results, but to demonstrate one way of evaluating this concept from an infrastructure network perspective. Using the INFINIT model, the case study highlights many alternatives, factors and issues to be addressed in the context of desalination for agriculture. The problem could be addressed as an energy-water-food nexus topic which explains its complexity and the necessity of studying it following holistic systems engineering approaches.

The INIFNIT model is novel in a sense that the facility sizing and the conduit network planning can be done concurrently over the water-energy coupling problem. The INFINIT framework is helpful in translating the complex (more than single-phase) network problem to a mathematical problem (MILP in this case).

In order to consolidate this study, a much more realistic pipeline cost model is under development to capture not only distance and diameter, but also quality and tunnel options. The study could be extended in order to perform a network analysis with different levels of investment budget constraints to see how the optimal solution would change. Finally, as it is important to explore the representation of partially degraded operation of the system, the authors address the problem of infrastructure resilience in a related work Khiyami et al. (2016b). In this associated study, the authors discuss how to evaluate quantitatively the resilience of water systems. They illustrate the approach with a notional case study of a portion of Saudi Arabia’s desalination network. The current approach provides a starting framework upon which to improve for an advanced assessment of resilience in water infrastructures.

Next, we will attempt to identify a list of guidelines and best practices in order to support policy makers` decisions for a long term planning through scenario analysis and multidisciplinary optimization, by looking at both demand and supply sides. A particular emphasis will be on the consideration of solar desalination and waste water treatment as well as different irrigation scenarios for more sustainable agricultural system. Reforming agriculture by taking actions determine what crops are the most suitable for Saudi Arabia's water balance, determining the amount of cultivated land area, and using more efficient irrigation methods are among the candidates for policy reform. Following comprehensive socio-technical system engineering approaches, the purpose is to build a decision support platform aiming at the assessment of key capabilities and constraints of the current Saudi national water system. A first version of the platform is presented in Doufene et al. (2017). The ultimate goal is to support decisions in term of investment in new infrastructures over time (location and deployment) taking into account uncertainty, addressing internal changes (population and economic growth, etc.) as well as potential external changes (international trade market and natural environmental constraints, etc.)

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