A Risk-Based Evaluation of Policies for Sustainable Water System Design in the Kingdom of Saudi Arabia

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ABSTRACT

Stakeholders in the Kingdom of Saudi Arabia are concerned about the sustainability of the country's water system. The Ninth Development Plan (2009-2014) formulates a number of policy directives to make the water system more sustainable. Assessing whether these policies can improve the degree of sustainability of the water system is a challenge because it is linked with many economic sectors, and characterized by a high degree of uncertainty. Conventional techniques of assessing water system performance do not reveal system wide impacts of water system policies, either on the supply- or the demand-side.

This paper presents an approach and some preliminary results in evaluating policies to assess their degree of sustainability. A multi-generational comprehensive wealth framework captures the notion of sustainability across the economy, which the analysis applies partially for water system assessment. By including uncertainty formulations in a system dynamics model, the analysis provides a risk-based view of water system performance showing that policy impacts under uncertainty are likely to be very different than those expected in deterministic planning scenarios.

Keywords: water, policy, infrastructure, uncertainty, planning, sustainability

1. INTRODUCTION

This paper presents an approach and some preliminary results in evaluating policies for sustainable water system design in the Kingdom of Saudi Arabia (KSA). Uncertainty analyses integrated with a system dynamics formulation provide a risk-based view of water system performance in KSA.

Stakeholders in the Kingdom of Saudi Arabia, an arid environment with fast depleting non-renewable groundwater resources, are concerned that existing water system performance is unsustainable in the long-run (MoWE, 2010; Ninth Development Plan, 2009). Agriculture is historically the largest end use - about 85% of total water demand over the last decade - followed by municipal consumption (10%) and industry (5%) (see Figure 1). Agricultural demand is met almost entirely through groundwater extraction, much of it from non-renewable or fossil water. Groundwater extraction further supplies one half of municipal demand while desalination, an expensive and energy intensive technology, supplies the other half. End-use magnitudes and supply types both vary significantly by region, as a result of water resource availability, economic activity, geography and climate. Policymakers are also asking the important question of how to allocate natural water resources and supply side infrastructure capacity to different end-uses. For these reasons, the Ninth Development Plan (2009 – 2014) states that the Kingdom's high-level objective is to "**develop, conserve and ensure rational utilization** of natural resources, particularly **water**, protect the environment and develop environmental systems within the context of sustainable development". The Plan thus envisions that key policy stakeholders in KSA will coordinate actions to implement a number of demand- and supply-side policies (Table 1) to make the KSA water system "more sustainable".

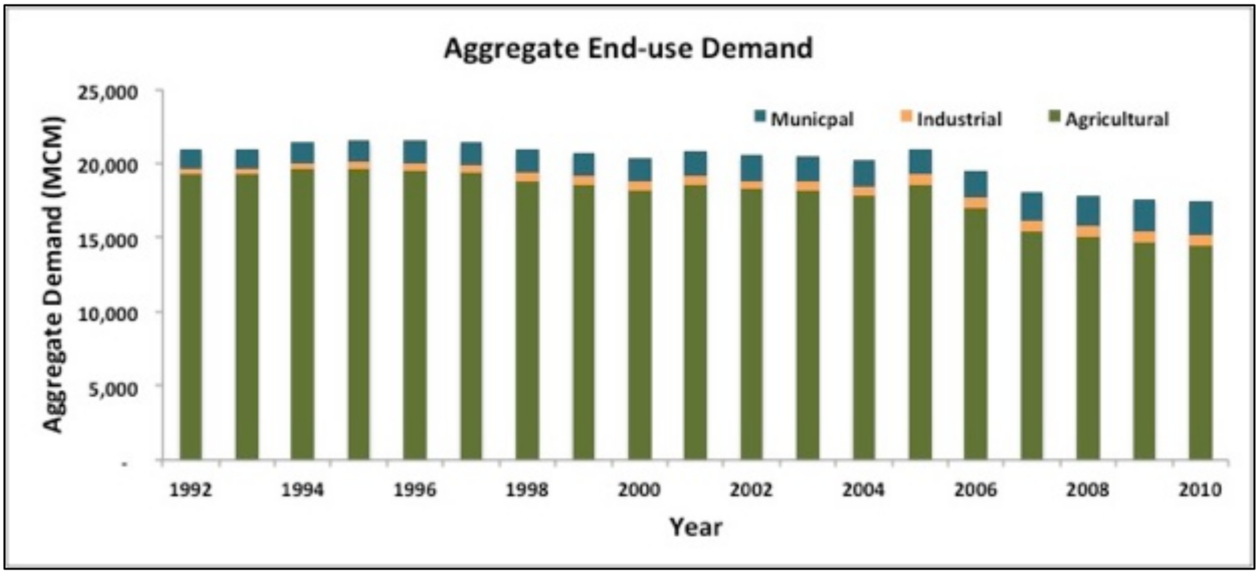

Figure 1. End-use demand in the Kingdom of Saudi Arabia (1992 – 2010)

Data: Estimates based on World Bank, AQUASTAT, KSA Central Department of Statistics and Information, and KSA Ministry of Water and Electricity (MoWE) (accessed March 2013)

Measuring or otherwise analyzing the degree of sustainability of the KSA water system is a complex research and policy challenge because of (a) many linkages and dynamics between the water system and other related systems, (b) the high degree of uncertainty in important demand- and supply-side factors, and (c) the limitations of conventional techniques that do not allow for capturing system wide impacts. For example, a direct agricultural policy such as reducing the production of wheat is an indirect water demand-side policy. Agricultural demand (million cubic meters per year – MCM / year) decreased by 25% between 1992 (19, 300 MCM/year) and 2010 (14,400 MCM/year), as a consequence of reducing wheat production, and improvements in irrigation efficiency and other agricultural practices. However, crop yields in part depend on variable surface water and groundwater resources; unavailability of these resources constitutes a risk of shortfalls in meeting demand. While the magnitude of water supplied to agricultural demand is measurable *post hoc*, policymakers are actually interested in assessing *ex ante* the potential consequences (both benefits and costs) of not meeting agricultural demand or reallocating supply to other end uses, using a comparable metric. In other words, while the reductions in demand from curtailed wheat production in the example above are known, the combined effect on the economy of conserved groundwater and reduced wheat production compared to any counterfactual is not assessed.

These imperatives call for a technique for evaluating policies by measuring trade-offs between supplying water for different end uses and the associated benefits and costs in the context of various risks affecting the KSA water system. Trade-offs can be described in the form of some specific policy directives or actions, as summarized in Table 1. For instance, 'what is the effect of reducing agricultural demand at 3.7 % / year?' Some examples of risks affecting the water system, and potential socio-technical policy levers for managing or mitigating those risks are listed in Table 2. The policy evaluation exercise should strive to understand the effect of risks, and prioritize the use of one or more levers for managing them.

Table 1. Water system policy directives in the Ninth Development Plan (2009 – 2014)

Source: Ninth Development Plan, Ministry of Economy and Planning (MEP)

Demand-side Policies

- Increasing the reuse of treated wastewater to about 50%
- Reducing demand for water for agricultural purposes at a rate of 3.7 % / year
- Increasing consumption of water for municipal and industrial uses by 2.1% / year and 5.5 % / year, respectively
- Adding 600,000 new household water connections and 15,000 kilometers of networks, bringing water distribution service to 88% of the population
- Adding 700,000 new wastewater connections and 12,000 kilometers of wastewater networks, bringing service coverage to 60%

Supply-side Policies

- Increasing the storage capacity of dams by 85%, from about 1.35 billion cubic meters in 2009 to about 2.5 billion cubic meters in 2014
- Doubling the capacity of desalination plants from 1,048 to 2,070 million cubic meters
- Increasing the proportion of treated wastewater to about 50% of consumption for municipal purposes
- Providing a 20% strategic emergency stockpile of water annually in major cities

Table 2. Examples of Demand- & Supply-side risks affecting the water system and available socio-technical levers

	Uncertain factors that create system risks	Potential socio-technical levers for managing risks
Demand-side		
Municipal	Population growth (persons)	Per Capita Demand (LCD)
Agricultural	Precipitation & evapotranspiration (mm/yr)	Crop-type & production (yield)
Industry	Economic water intensity (MCM /GDP)	Industry-type (capacity)
Supply-side		
Groundwater	Recharge rate (MCM/yr);	Withdrawal rate (MCM/yr)
	Unknown non-renewable supply (MCM/yr)	Water collection (MCM/yr)
Treatment	Water for resuse (MCM/yr)	

The rest of the paper is structured as follows. Section 2 describes the conceptualization of sustainability used for measuring trade-offs. Section 3 provides an overview of the preliminary integrated uncertainty-system dynamics model. Section 4 presents preliminary results.

2. ASSESSING SUSTAINABILITY

This work borrows the general framing of sustainability as a measure of multi-generational, comprehensive wealth presented in Arrow et al (2012). The thrust of this approach is to "ask whether the society under study is functioning well enough to ensure that some measure of intergenerational well-being does not decline." While the analysis in this paper does not use Arrow et al (2012)'s mathematical formulation directly, its overall logic is explained as a context for the calculations in this paper.

The approach uses a weighted sum of capital asset stocks as a measure of an economy's wealth, with shadow prices as weights. The economy is considered sustainable if its wealth is non-decreasing in time at constant shadow prices at any point in time. Mathematically, wealth *W* is formulated as (Arrow et al, 2012):

$$W(t) = r(t)t + \sum p_i(t)K_i(t)$$

where W(t) is wealth at any instant in time

r(t) is the shadow price of time (time is treated as an asset)

$K_i(t)$ is the capital asset stock

$p_i(t)$ is the shadow price of capital asset K_i

This formulation of wealth is multi-generational because W(t) can be re-expressed as a value function V(t) of intergenerational wellbeing such that a change in well-being over time is:

$$\Delta V(t) = r(t)\Delta t + \sum p_i(t)\Delta K_i(t)$$

where economic development is defined to be sustainable if $\frac{dV}{dt} \geq 0$.

Using this formulation directly and comprehensively requires estimates of asset stocks and consumption shadow prices of natural resources, population, infrastructure, health, etc. Empirical work prior to and including Arrow et al (2012) has demonstrated the use of similar formulations applied to various economies (Dasgupta and Maler, 2000; Dasgupta, 2001; Arrow et al, 2004, World Bank, 2011). In the case of the KSA, our current limited understanding and lack of data on the various capital stocks precludes the use of Arrow et al (2012)'s framework.

The preliminary analysis here therefore uses a partial formulation of multi-generational comprehensive wealth, viz. accounting for groundwater as the main (natural resource) capital asset and GDP as the basis of the economy's wellbeing. Further, instead of measuring both asset stocks and changes to stock value, only changes in stock value are recorded. Further work will make efforts to broaden the number of stocks and calculate shadow prices more systematically.

Changes in groundwater capital value (GWV) are calculated using the opportunity cost of the alternative per unit (for ex. desalination \$ / cubic meter) to meet demand and the incremental amount of water consumed or conserved (million cubic meters) (see National Research Council, 1997). The change in GDP as a result of unmet demand is calculated using a GDP elasticity of water demand (Strzepek et al, 2008). The change in GDP is traded off with value of groundwater conserved to give a measure of 'net return to GDP (NR_GDP)', a value function of intergenerational wellbeing:

$$NR\_GDP_i(t) = \Delta V_i(t) = \Delta GDP_i(t) - \Delta\, GWV_i(t)$$

In this formulation, the reduced water system (instead of comprehensive economy) is sustainable if

$$\sum_i \int_0^s NR\_GDP_i(t)\, e^{-r(t)t} dt \ \geq 0$$

across all the capital stocks 'i' being considered, where r(t) is the discount rate. In other words, the *change* in wellbeing is sustainable if the net present value of net return to GDP across the asset stocks is non-negative. The revised framing is that sustainability is thus a *relative* measure of multi-generational wealth of the system along different performance trajectories.

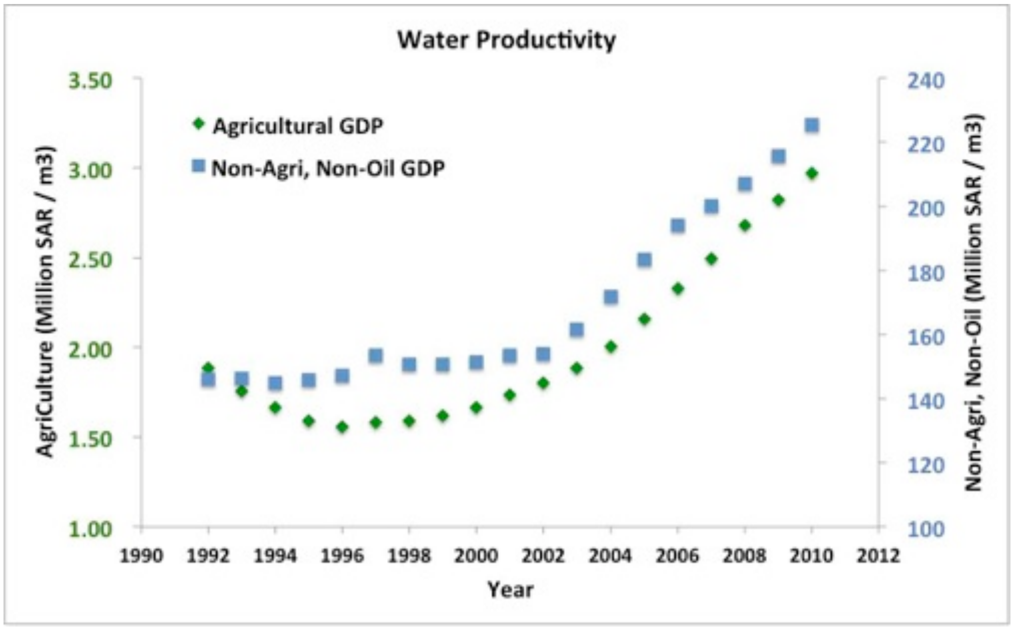

Figure 2. Comparison of water productivity of Agricultural and Non-Agricultural, Non-Oil economic sectors

Data: KSA Central Department of Statistics and Information (2013)

Empirical data on historical 'returns to GDP' measured in the form of water productivity suggest that this formulation will be useful in demonstrating trade-offs of supplying water to different end-uses. Water productivity is the marginal contribution to GDP of unit supply of water to a particular economic sector. Figure 2 compares the water productivity of water supplied to agriculture and the non-agricultural, non-oil sectors of the Saudi economy. The returns to GDP of meeting demand in the non-agricultural, non-oil sector are two orders of magnitude higher than meeting agricultural demand. Other things equal, reallocating constrained water supplies from agriculture to other sectors should therefore make the KSA water system *more* sustainable. This intuition can be examined in more detail through a model of the KSA water system.

Sustainability as a relative measure requires a reference scenario or benchmark against which different performance trajectories can be evaluated. Perturbations or shocks to the system result in deviations from the reference trajectory, allowing for the calculation of the traded off net returns. Perturbations to GDP and groundwater consumption (or conservation) are introduced using uncertain demand factors, integrated with a system dynamics model of the KSA water system.

3. INTEGRATED UNCERTAINTY-SYTEM DYNAMICS MODEL

A system dynamics model of the KSA water system was developed in the AnyLogic modeling environment. At the highest level, the system is expressed as a 'Demand' sub-system, informing a 'Supply' sub-system. In this initial version of the model, feedback to Demand primarily consists of information about supply-side constraints (such as desalination and treatment capacity) and tariffs, so that supply-side resources can be appropriately allocated to the various end-uses. Figure 3 shows a high level overview of the model.

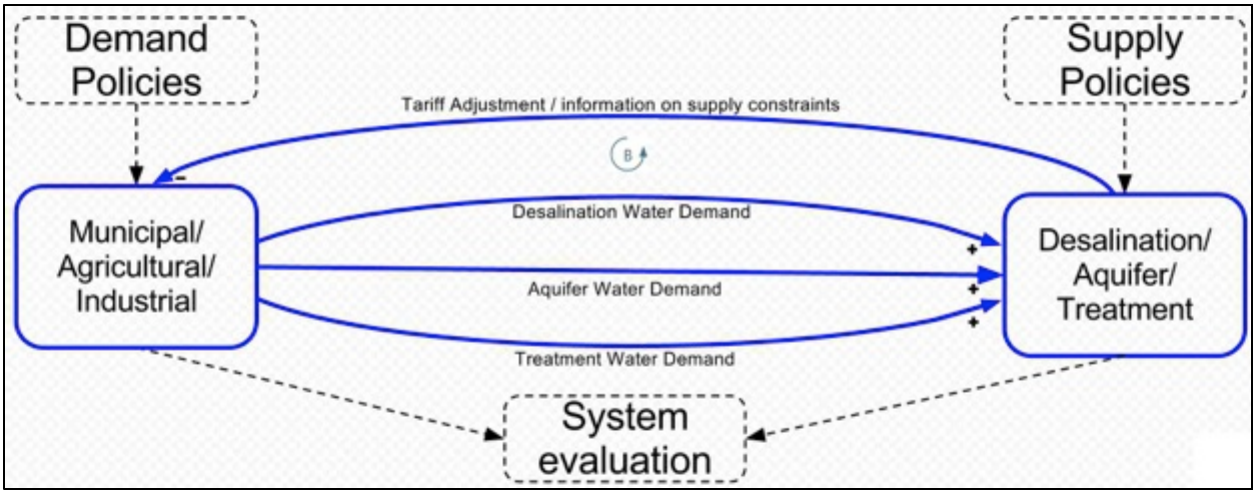

Figure 3. Overview of the integrated uncertainty-system dynamics model for KSA Water System

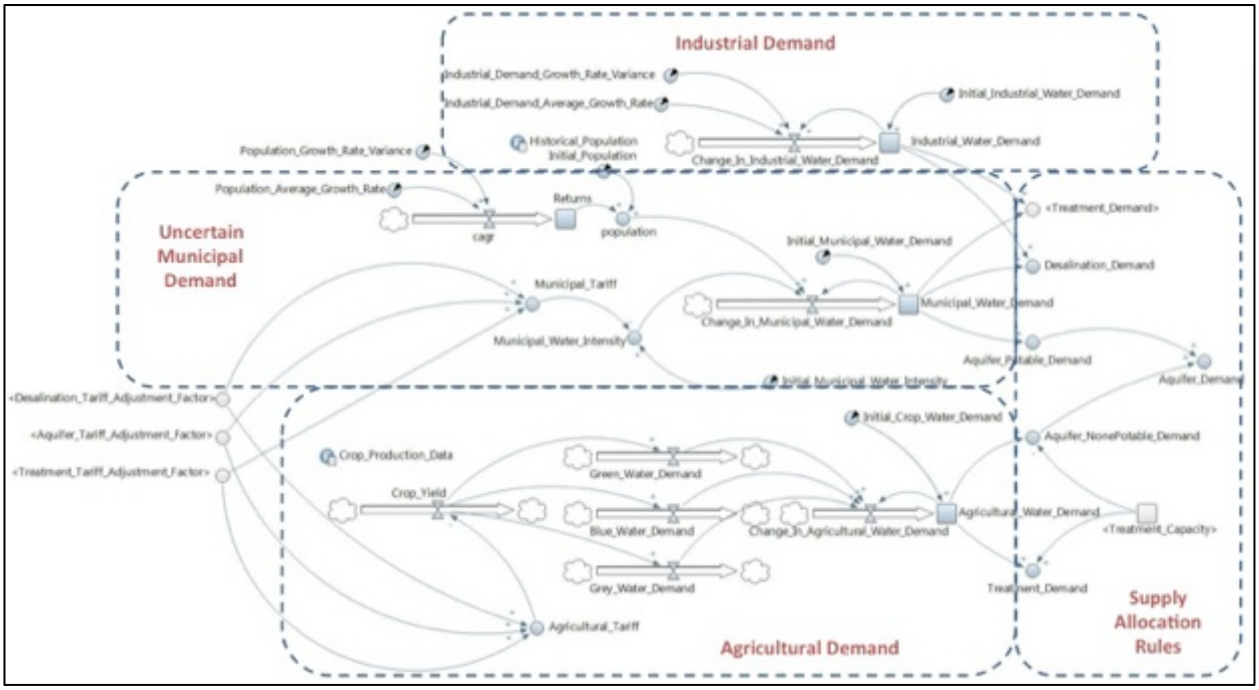

Figure 4. Disaggregated 'Demand' sub-system with deterministic agricultural & industrial demand, uncertain municipal demand, and supply allocation rules

The 'Demand' system is further disaggregated into agricultural, municipal, and industrial demand, the three main end use categories in KSA. Figure 4 shows the disaggregated 'Demand' sub-system. Although variable in reality, agricultural demand (85% on average, historically) is treated deterministically, since this end use is defined by structural policies governing crop-type and production targets. Industrial demand (5%) is also deterministic and treated similarly. On the other hand, municipal demand (10%) is not currently constrained or influenced in any way. Uncertainty on the demand side is therefore introduced primarily through the municipal sector. Supply-side resources are then allocated to end-uses through allocation rules based on supply-side constraints.

Uncertainty in municipal demand is simulated using the following procedure, which can be extended to other capital stocks in future versions of the model. Since municipal demand is a function of population, to simulate uncertainty in a stock variable such as population, consider:

$$R(t_i) = m + v * \tilde{\varepsilon}_i$$

and

$$R(t_i) = ln\left(\frac{P(t_i)}{P(t_{i-1})}\right)$$

where

R(t)	is the instantaneous return in population i.e. growth rate per time period (%/year)
m	is the drift, or expected growth rate per time period (%/year)
v	is the volatility, or standard deviation of growth rate per time period (%/year)
ε	is a standard normal random variable, ~N(0,1)
P(t)	is the instantaneous population (or any other stock variable) (physical units, ex.persons)

Thus, the cumulative return over a time horizon is given by

$$R(t_0, t_i) = \sum_{1}^{i} R(t_k)$$

and the population (or stock) value at any time t_i

$$P(t_i) = P(t_0) * e^{R(t_0,t_i)}$$

Any variable that is a function of the instantaneous stock value can utilize this quantity. However, municipal water demand, which is assumed to be a linear function of population (liters per capita day), may have its own inherent variability. This is formulated as:

$$D(t_i) = P(t_i) * \tilde{d}_i$$

where

d_i	is the random liter per capita day value, for ex. d ~ Normal (230 LPCD, 10 LPCD)

Municipal demand thus takes a joint probability distribution as calculated by the model, which would otherwise have been difficult to estimate because of sparse water demand data. This formulation is depicted in the uncertain municipal demand portion of Figure 4.

The ‘Supply’ sub-system is in turn disaggregated into three main supply sources desalination, treatment and groundwater. Desalination draws seawater (unlimited) for purification into potable water for municipal demand; however, desalination capacity is limited in the near term in the absence of a policy allowing for additional capacity addition. Treatment transforms used/waste water into potable and non-potable water for agricultural and municipal uses. Potable demand is first met by available potable groundwater, and then by desalination. Agricultural demand is first met by treated water, and then by available non-potable groundwater (mostly fossil water). The desalination component of the model is shown in Figure 5.

Of the supply-side resources, desalination and treatment are treated deterministically since their capacity is know based on existing data. However, groundwater stocks are inherently uncertain because of the difficulty in estimating fossil water stocks and variable recharge rates for shallow aquifers. Uncertainty is introduced into the supply-side of the model through groundwater availability.

To simulate variability in a natural resource stock such as groundwater, consider:

$$GW(t_i) = GW(t_{i-1}) + rc(t_i) - pump(t_i)$$

where

GW(t)	is the instantaneous value of the stock
rc(t)	is the instantaneous recharge rate
pump(t)	is the instantaneous withdrawal rate

Thus volatility in the stock value is driven by stochastic variation in both the recharge and withdrawal rates. The recharge rate RC can be parameterized based on empirical data, or assumed to be log-normally distributed, for example. On the other hand, withdrawal rates are determined endogenously in the model. Since municipal demand (shown above) is uncertain, groundwater withdrawals will also vary stochastically.

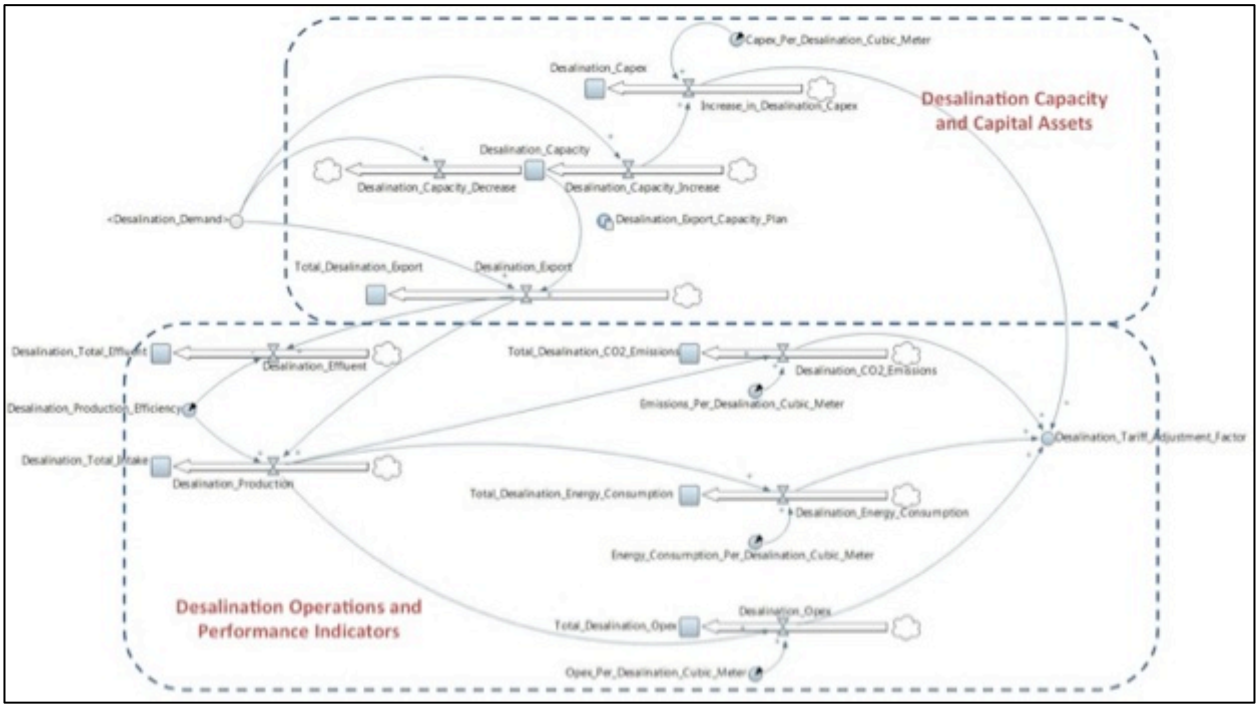

Figure 5. Desalination component of the model

4. PRELIMINARY RESULTS

The preliminary results demonstrate how uncertainty affects the KSA water system, and the nature of impacts that could be expected.

Population growth is the main uncertain driver affecting demand-side of the KSA water system. Figure 6 below shows a deterministic growth path where population grows at an assumed rate of 2 % / year. Although this is similar to the historical trend – population grew at an average rate of 3 % - between 1994 and 2010 – the growth rates were volatile. Growth rates ranged between 2.5 % and 5 % /year, with a standard deviation of 0.84 % / year. The integrated uncertainty-system dynamics model simulates uncertain population growth, as shown by the two sample paths (dashed lines) in Figure 6. While both have an expected growth rate of 2% / year, simulated volatility in growth rate demonstrates very different growth paths.

Uncertain population growth interacts with uncertain per capita demand to result in a joint probability distribution of municipal water demand. When the uncertainty-based model is used in a Monte Carlo simulation with 1000 iterations, distributions of demand (and other variables) at various points in time are obtained. Figure 7 shows that there is only a 10% chance that municipal demand will be as high as 2600 MCM/year in 2015. In 2035, the probability of municipal demand being less than 3500 MCM is less than 10%, but expected (or median) demand is as high 3700 MCM/year. The probability distributions are wider further out in time, showing that demand becomes more risky over time.

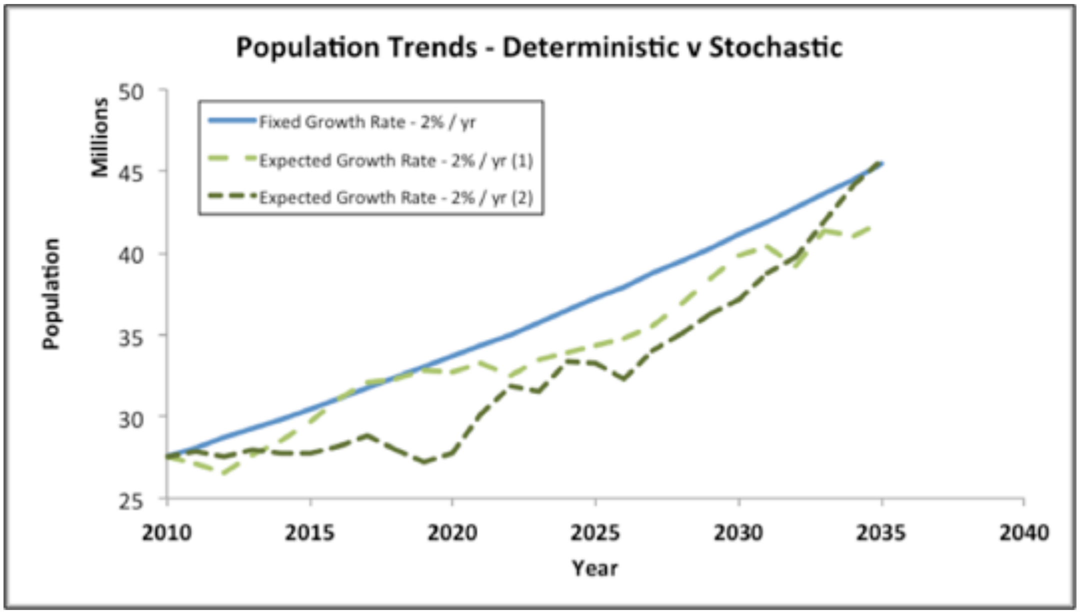

Figure 6. Different population growth paths for the same assumed expected growth rate in the simulation

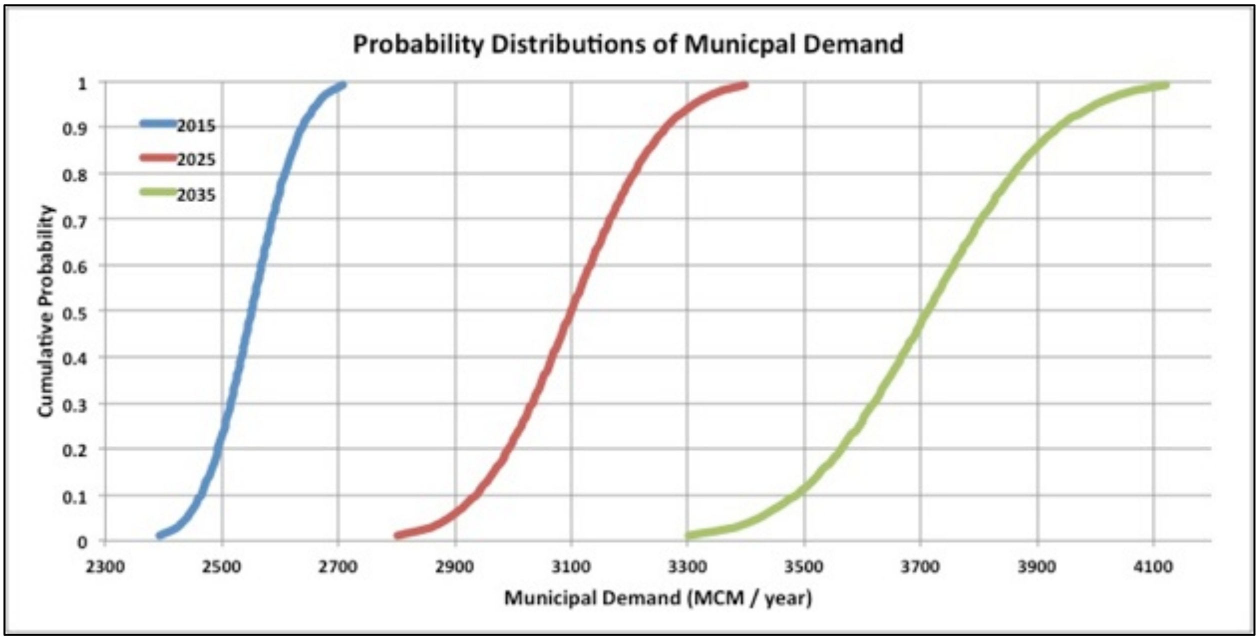

Figure 7. Probability distributions of municipal demand in 2015, 2025 and 2035

Water produced from desalination plants in KSA is supplied to municipal demand. On average, about half of municipal demand is met by desalination, and the rest by groundwater. Since demand is uncertain, desalination capacity use varies widely. Figure 8 shows desalination output distributions corresponding to the municipal demand profiles in Figure 7 above. If the full desalination build out envisioned in the Ninth Development Plan is accomplished by 2015, desalination capacity will be severely underutilized, while groundwater will continue to be withdrawn to meet 50% of municipal demand.

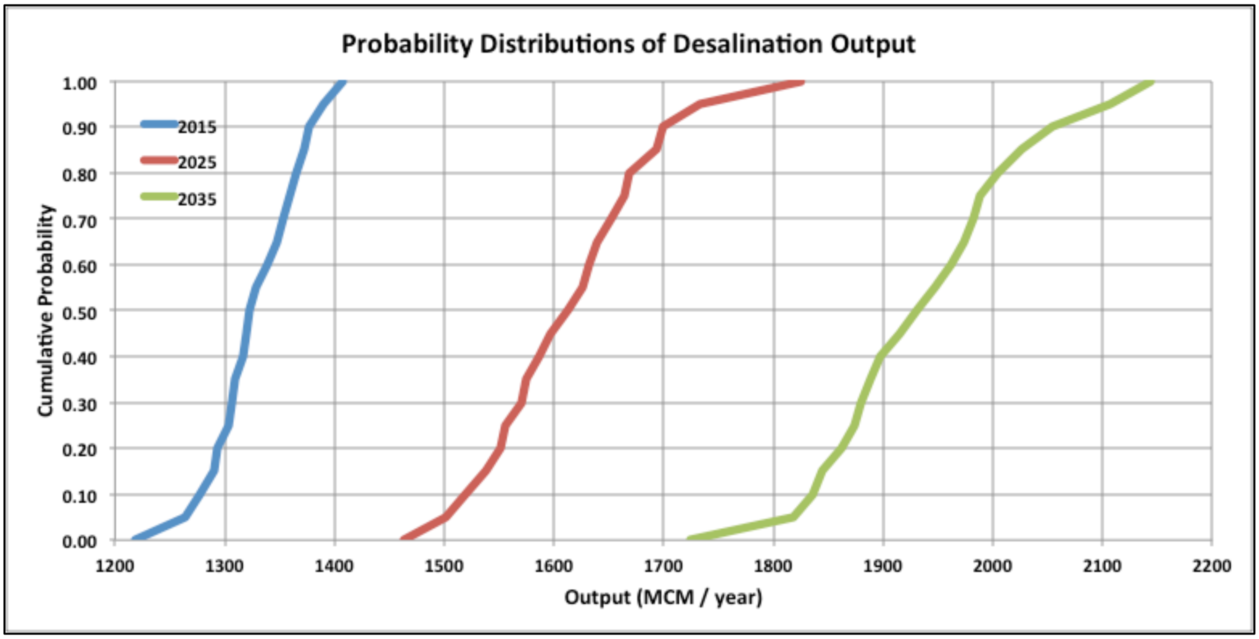

Figure 8. Probability distributions of desalination output to meet municipal demand in 2015, 2025 and 2035

Groundwater supplies meet almost all of the agricultural demand in KSA, along with about half of municipal demand as discussed above. Planned reductions in agricultural demand interact with uncertain municipal demand to give uncertain withdrawal amounts. Figure 9 shows the results of groundwater withdrawals in the Monte Carlo simulation. Although withdrawal estimates are identical at the start and narrowly spaced in the near term, the confidence intervals show that estimates become less accurate over time.

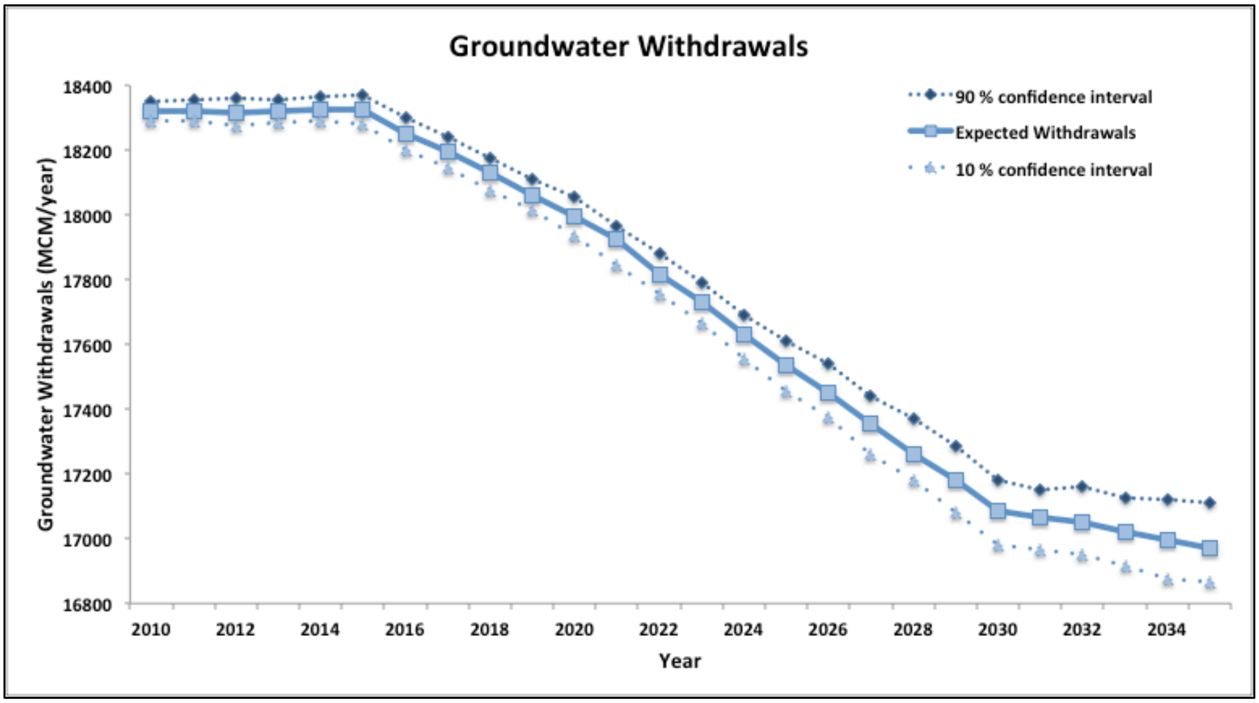

Figure 9. Groundwater withdrawals over time with agricultural demand reduction under uncertainty

The KSA water system experiences a welfare loss in the event that demand is unmet – either because of policy decisions or shocks to the supply side of the system such as a drought, desalination plant outages, etc. Figure 10 shows how GDP is path dependent. The solid dashed lines are the forecasted return to GDP as a consequence of meeting demand fully (under demand uncertainty). The dashed lines show a deviation of GDP from the forecasted path in the event that 20% of demand is unmet on average. While GDP may revert to the forecasted path if supplies are available the welfare loss as a result of unmet demand is irreversible.

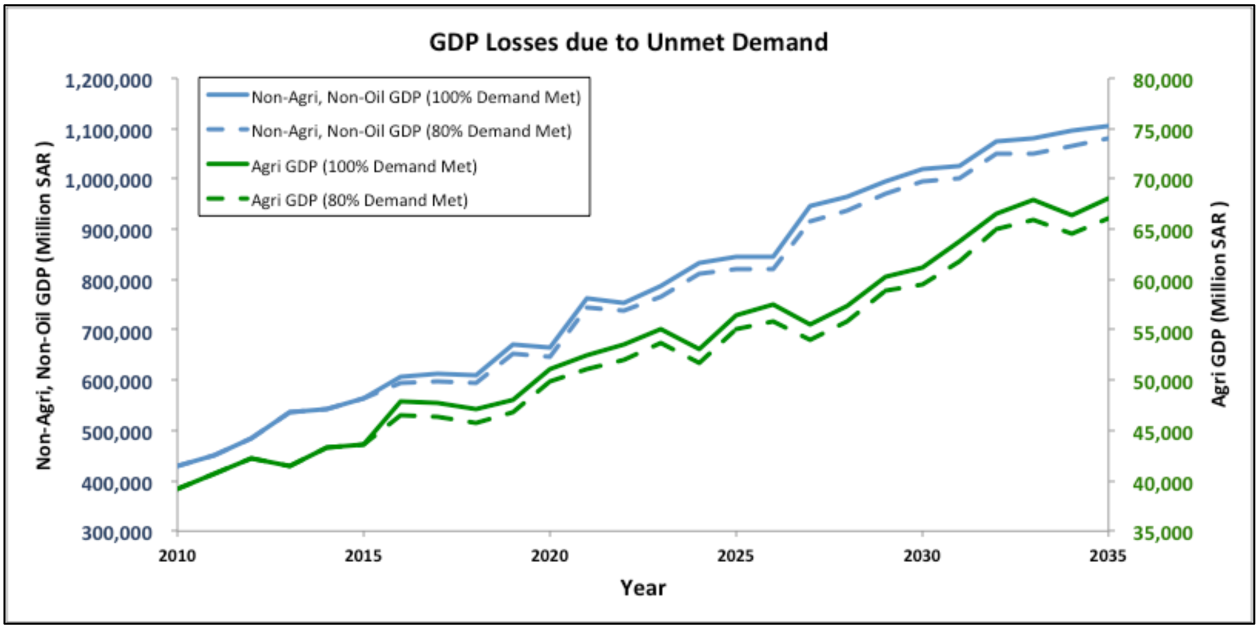

Figure 10. Comparison of GDP losses due to unmet demand in Non-agricultural, Non-Oil and Agricultural sectors

5. CONCLUDING REMARKS

While the preliminary results here show how the KSA water system performs under uncertainty, the analysis will further develop and implement the sustainability formulation as the main next step. Further next steps include broadening the sustainability metric to include other social and environmental indicators that capture system performance dimensions such as emissions, water-energy nexus, and other externalities.

So far, the results have shown that the various water system policies envisioned in the Ninth Development plan are likely to have highly variable impacts, perhaps very different from those expected by policymakers under deterministic planning scenarios.

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