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

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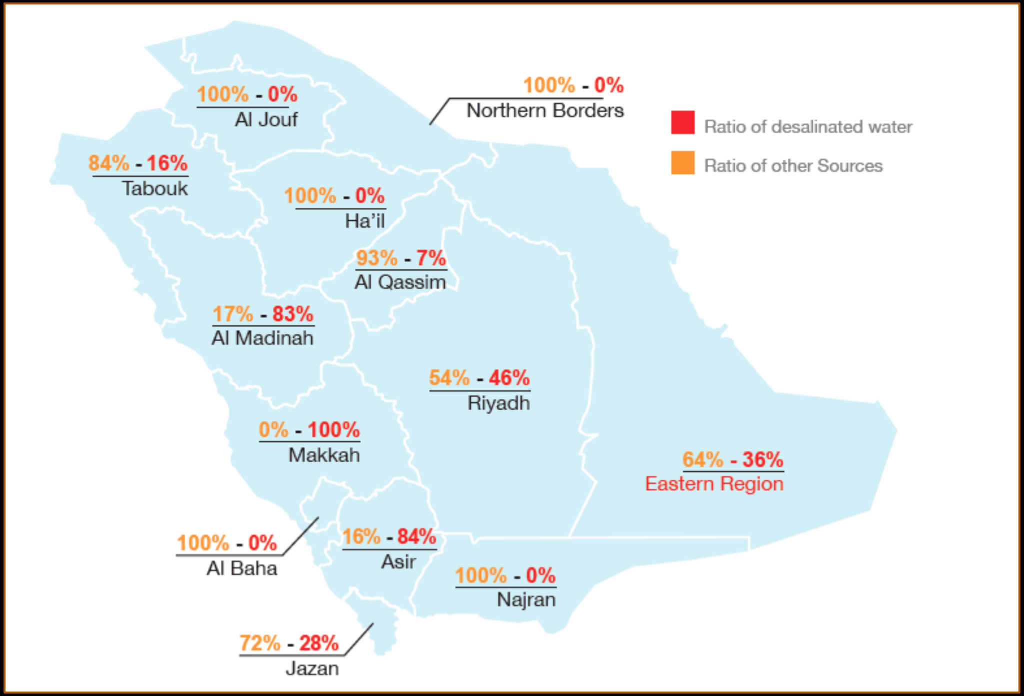
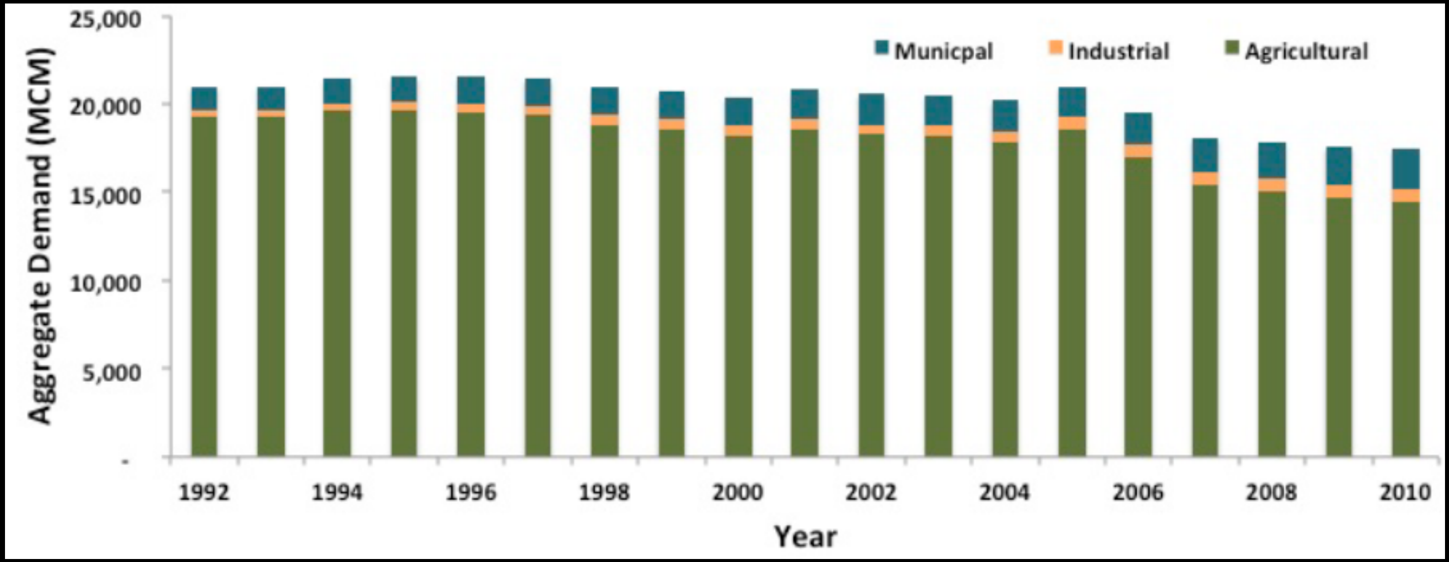
Designing a Sustainable Water System

- Average water level decline of 2 to 3 m / year in non-replenishable aquifers **(FAO 1996)**
- Approx. 50 % of water supplied is desalinated **(MoWE 2010)**





Presentation Outline

• Motivation	Sustainable water system design
• Research Question	Evaluating policies under uncertainty
• Case context	Saudi Arabia
• Approach	Integrated uncertainty + system dynamics
• Analysis	Multi-attribute performance over time
• Implications	Policy prioritization

Research Question

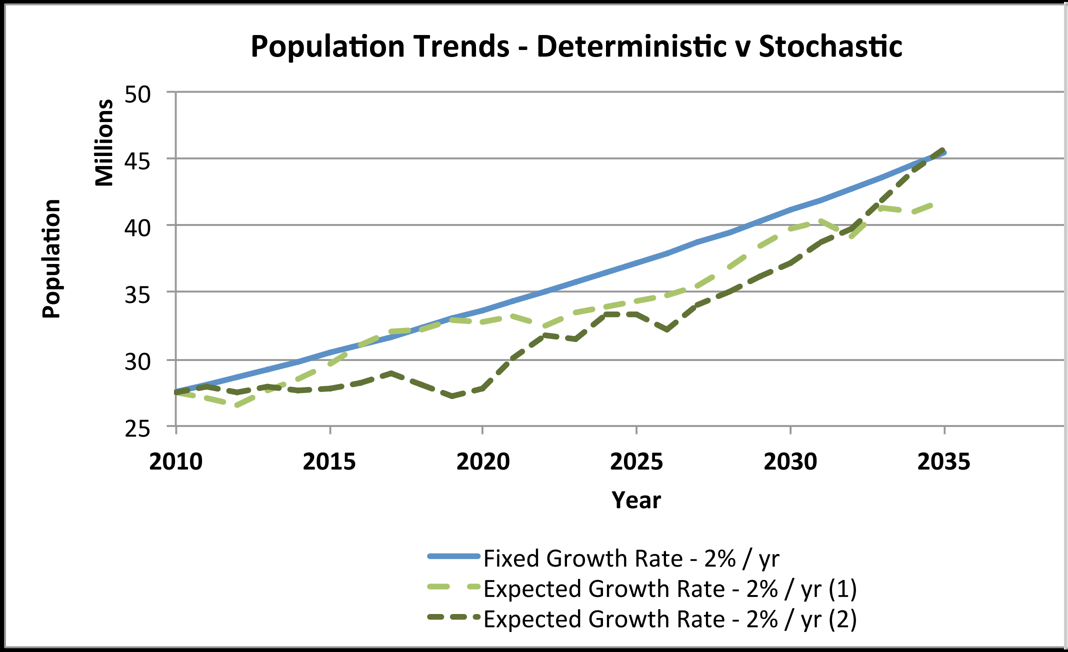
How do different investment and operating policies alter the trajectory of system performance over time and under uncertainty?

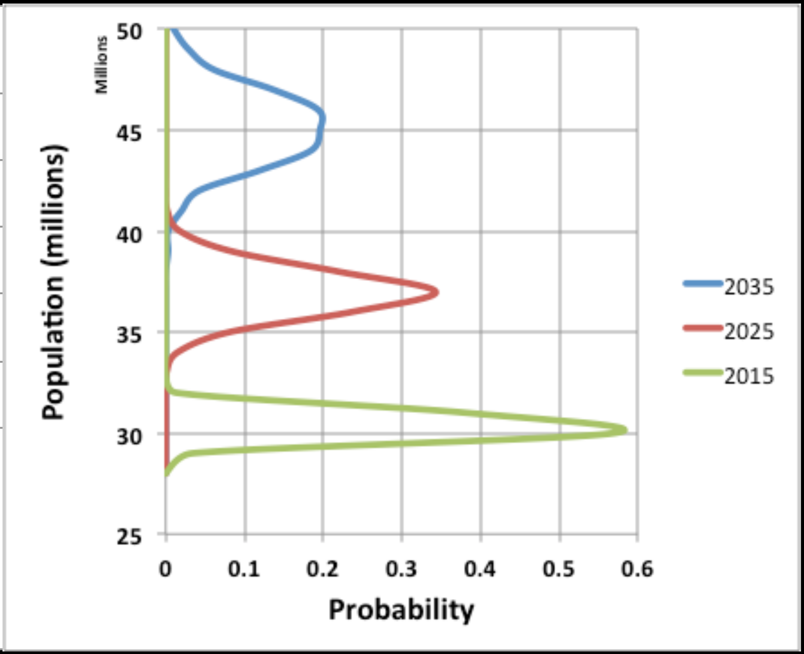
Sustainability and Trade-offs

- Sustainability is defined as a measure of *multi-generational, comprehensive wealth* **(Arrow et al. 2012, UNU-IHDP 2012)**
- '*Multi-generational*' – time is an important factor
- '*Wealth*' – natural resources and infrastructure have socioeconomic value
    - May be quantified, but not straightforward
    - But value varies with time and circumstances-> an implicit discount rate!
- '*Comprehensive*' – wealth can increase or decrease in a number of ways
    - Ex. by consuming water for agriculture, industry
    - Trade-offs between low value and high value uses
    - Both total value and pathways are important!
- Sustainability is thus <u>a relative measure of system performance across alternative pathways</u> of consuming and generating valuable resources **(El Serafy 2013)**

Water System Planning under Uncertainty

- Long-term planning assumes forecasts for water system services **(de Neufville & Scholtes 2011, Qi & Chang 2011)**
- Forecasts can be deterministic or stochastic
- Example: Municipal water demand depends on varying population growth (persons) and per capita demand (LCD)





KSA Water System Risks – and Policies

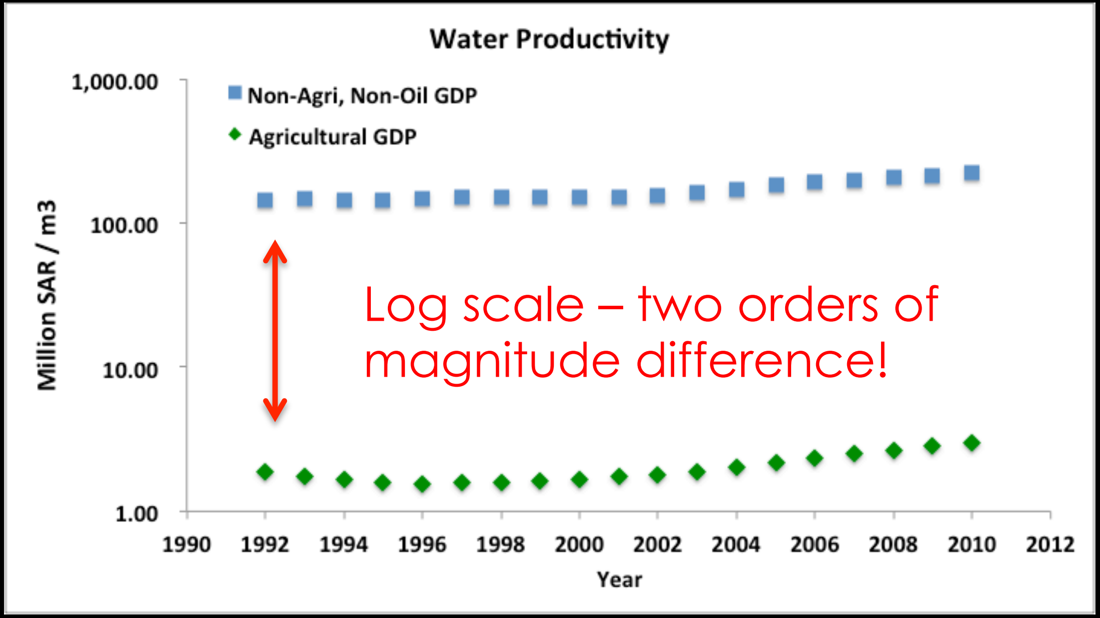
	Uncertain Drivers	Potential Socio-technical Levers
Demand-side		
Municipal	Population growth (persons)	Per Capita Demand (LCD)
Agricultural	Precipitation & evapotranspiration (mm/yr)	Crop-type & production (yield)
Industry	Economic water intensity (MCM / GDP)	Industry-type (capacity)
Supply-side		
Groundwater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

Assessing System Performance

- System performance can be compared using Key Performance Indicators (KPIs)
  - Economic: ex. annual system costs, contribution to GDP
  - Environmental: ex. CO_2 emissions, volume of effluents
  - Equity: ex. demand shortfalls, health impacts
  - Technical: ex. desalination output, % water treated

Valuing Water Resource Productivity

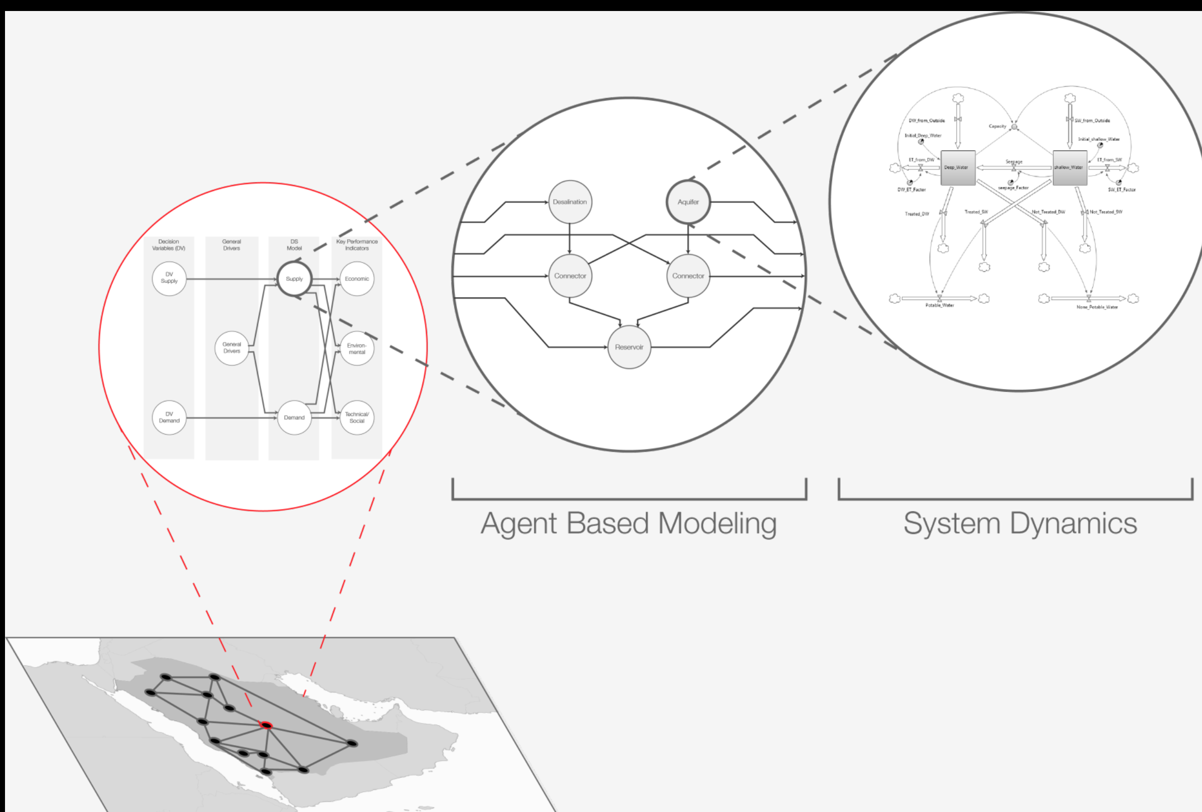
- Water is one of many inputs in agriculture and economic activities
- Contribution to GDP of these activities is an indicator of the socio-economic value of water
  - Imprecise indicator: many interactions and links between water and other inputs (ex. water, electricity, fertilizers and labor in agriculture)
  - Partial indicator: many aspects of the social value of water are not 'priced' /valued in to GDP ex. health benefits
- However, GDP is a reasonable proxy for measuring 'wealth' over time
- KSA water productivity in terms of GDP is two orders of magnitude higher in non-agri, non-oil sectors, than in agri sector



High Level Architecture

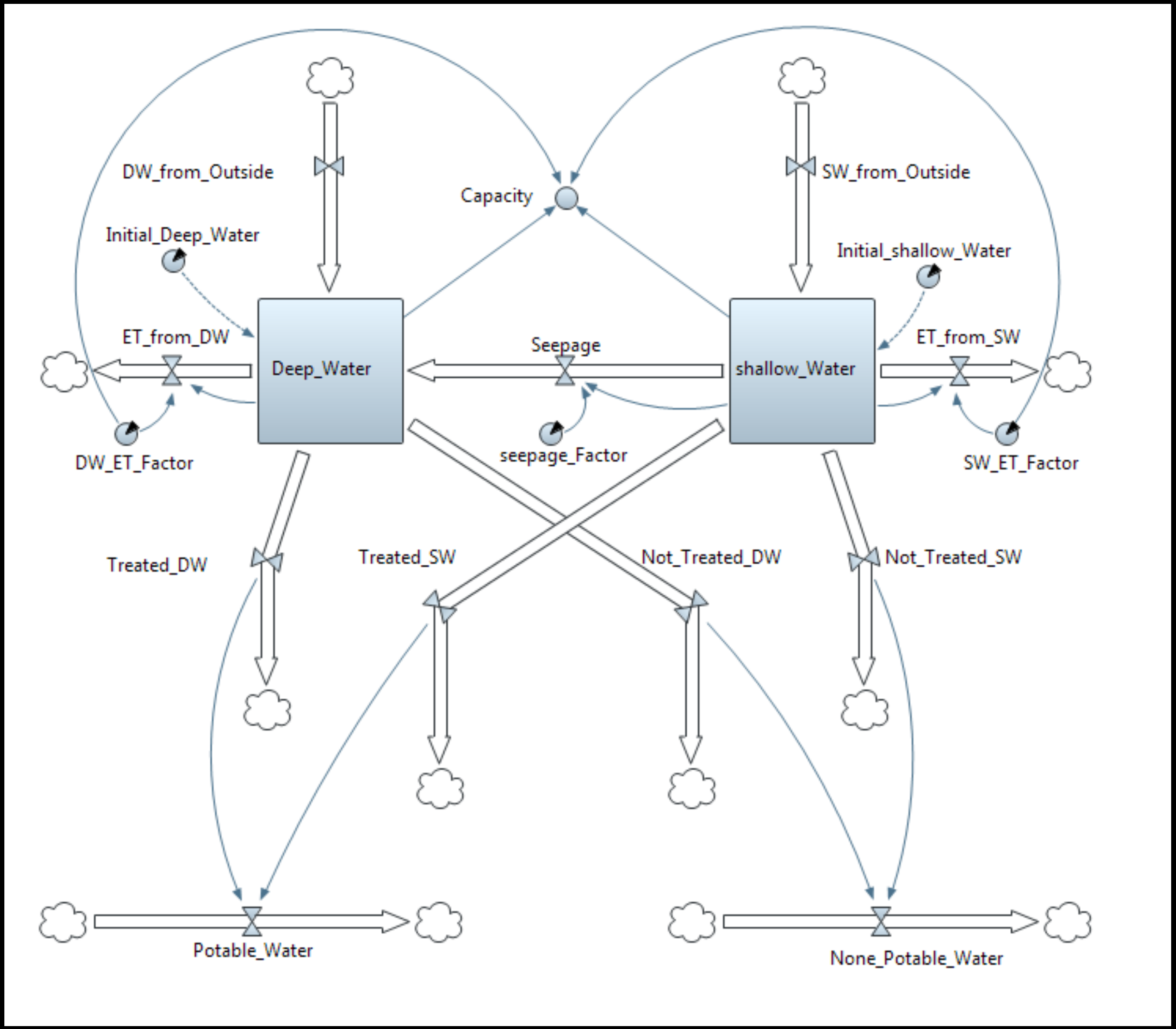
Scenarios are studied using an Integrated Uncertainty-System Dynamics model

- Multidimensional Hierarchically Integrated Framework (MDHIF) implemented in AnyLogic ™ **(AlAbdulkareem et al 2013)**



- System dynamics model nested in agent-based hierarchy **(Borschev & Filippov 2004, Schieritz & Milling 2003)**
- "Fuzziness" in parameters to introduce stochastic variation **(Altunkaynak et al 2005)**
- Monte Carlo simulation **(Khatri & Vairavamoorthy 2009)**

Example: Groundwater sub-system

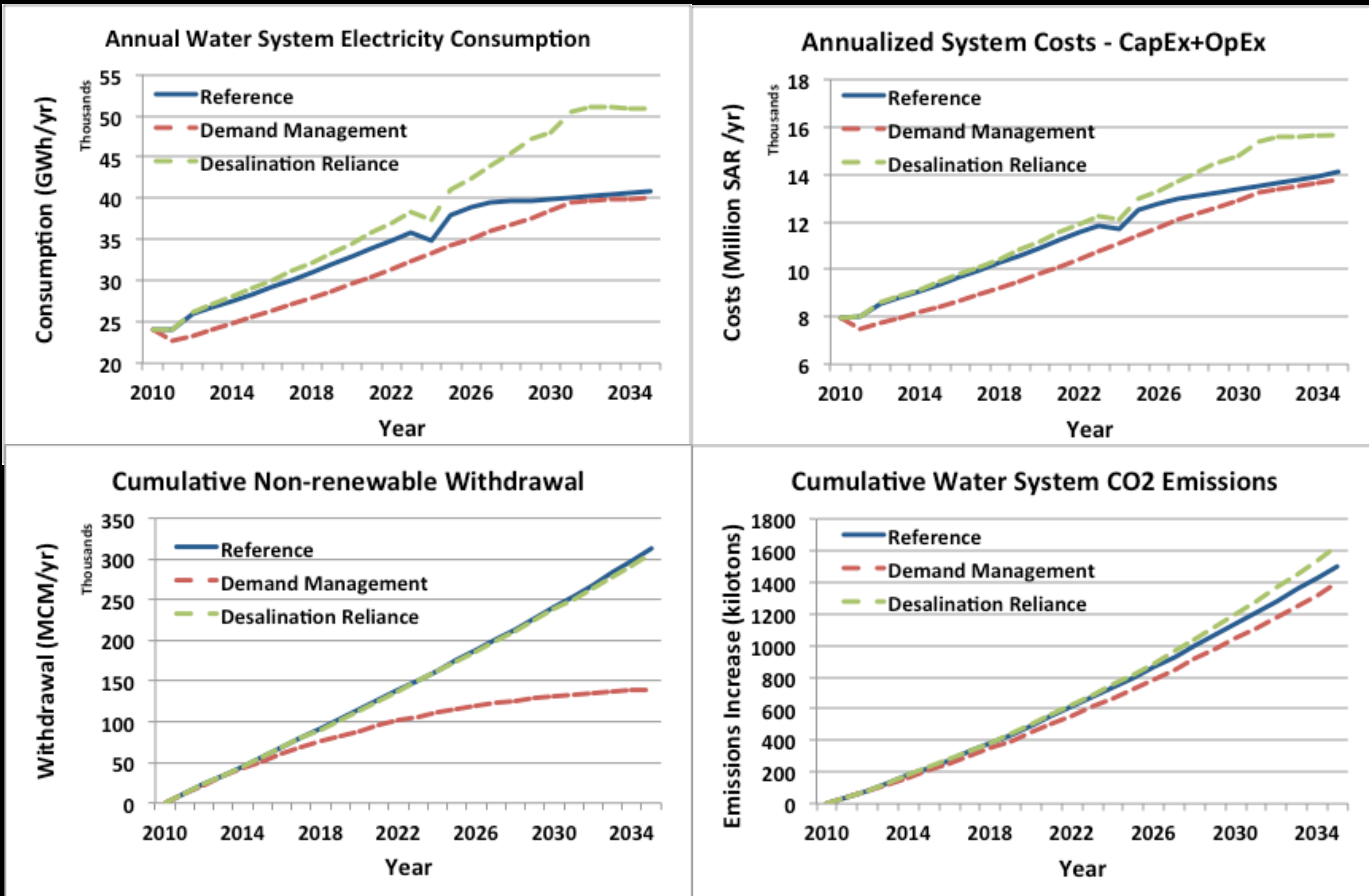


Deterministic Scenarios

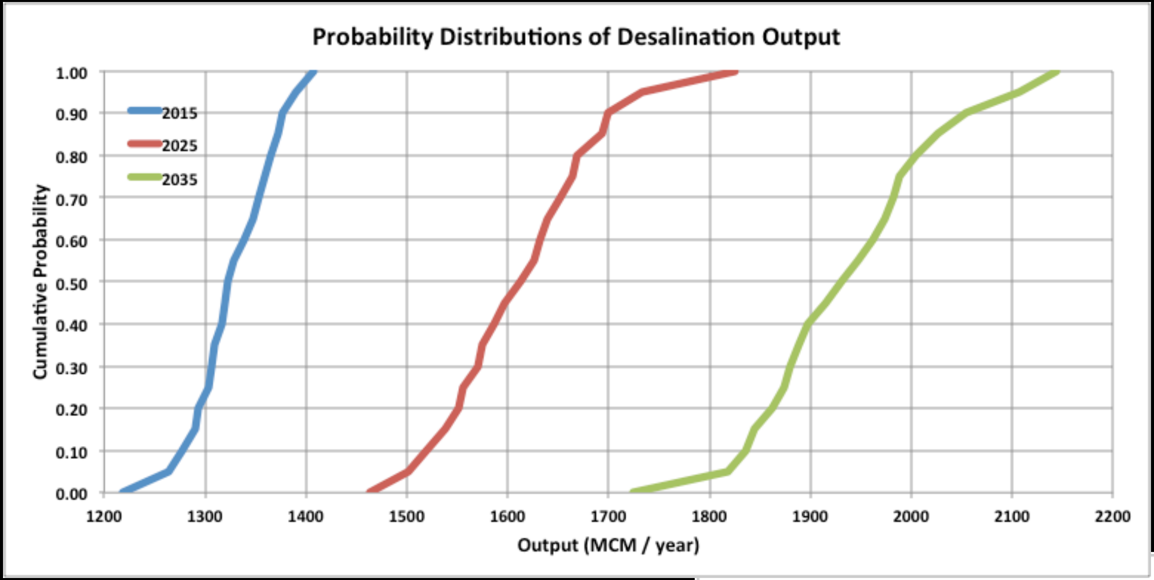
- Deterministic scenarios for initial exploration (2010 – 2035; 25 year horizon)
  - Reference Scenario - a benchmark scenario to indicate the status quo
    - Average per capita demand – 230 LPCD
    - Population growth – 2% / year
    - Agricultural consumption grows at 2010 levels
    - Desalination meets 50% - 60% of municipal demand
  - Demand Management – actively influence demand-side changes
    - agricultural demand reduces by 3.7 % / year
    - Average per capita demand reduces by 10 % from 230 LPCD to 210 LPCD
    - Treatment and reuse of wastewater increases by 1.5 % / year
  - Desalination Reliance – supply-side infrastructure addition
    - 80% of municipal demand to be supplied by desalination
    - Desalination capacity and conveyance infrastructure added

Analysis

Demand Management is Dominant Strategy



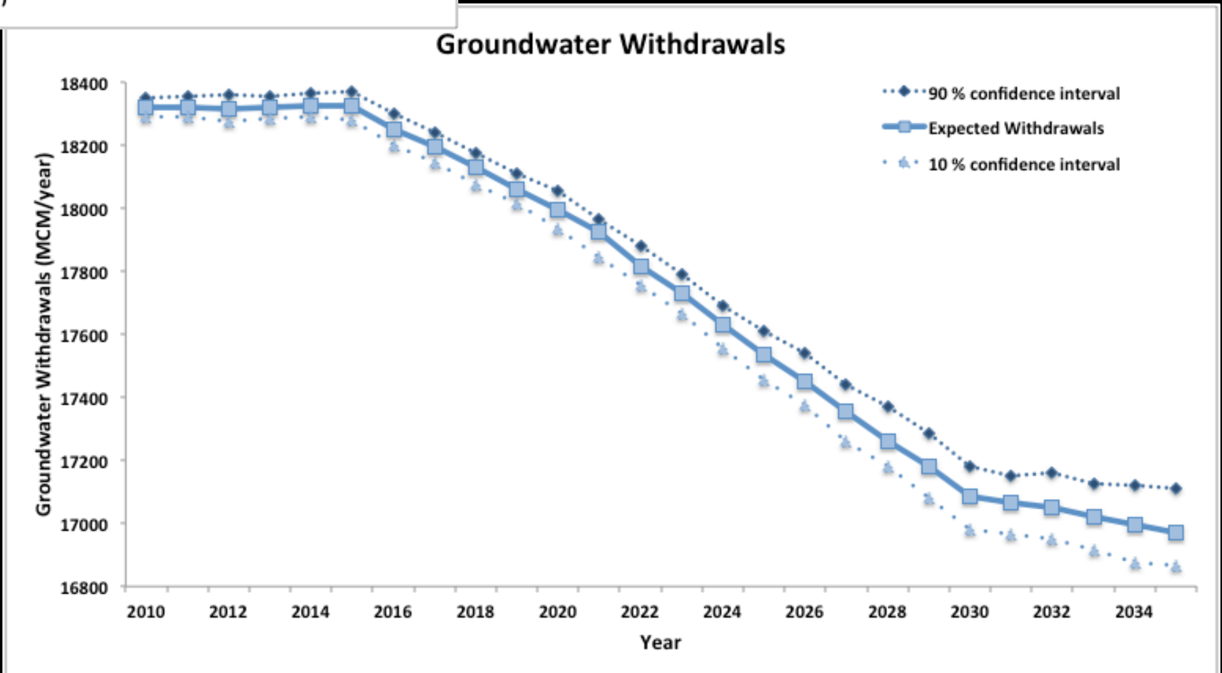
Including Uncertainty



=> High probability that existing desalination capacity is underutilized under uncertain demand

Variations in recharge rates and agricultural, municipal withdrawals make net groundwater levels uncertain

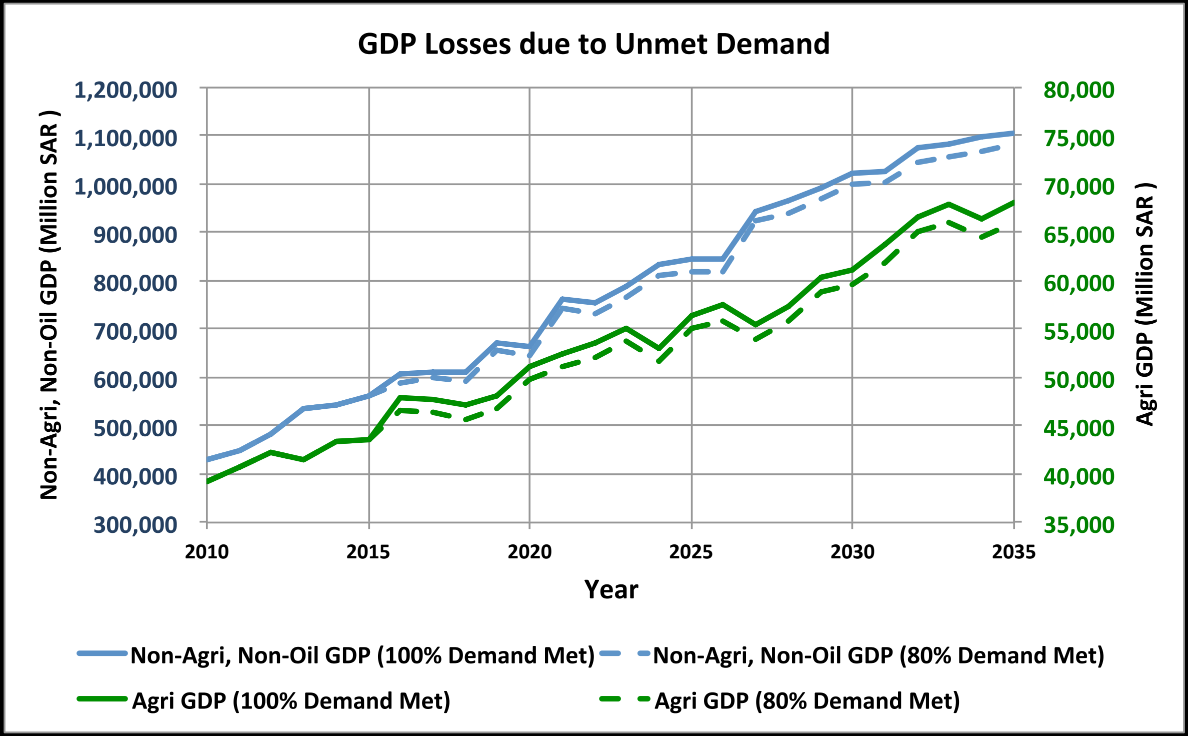
=> need to include variability in policy formulation



Valuing Water Use Trade-offs

- The economic return to water use is different for different sectors, implying different GDP elasticities to demand (ex. 20% reduction in supply to Agriculture -> 1% reduction in GDP – vs 2% for Non-agri, non-oil GDP)

- Economic return to water use exhibits path dependence – ex. depletion or contamination of an aquifer for a few years may restrict ability to meet demand in future



Prioritization of Policy Levers

- Valuing end-use trade-offs differentiates high-value end uses from low-value
- High-value end uses tend to be those with high water productivity / low water intensity
- Influencing demand reductions (conservation) mitigates the pressure to always meet it, even if high-value end use
- Alternatively, reducing water intensity (efficiency) allows for supply to high-value end use with same water budget
- Uncertainty analyses help show variability of policy impact

Potential Socio-technical Levers

Per Capita Demand (LCD)

Crop-type & production (yield)

Industry-type (capacity)

Withdrawal rate (MCM/yr)

Water collection (MCM/yr)

References

- AlAbdulkareem, A., Alfaris, A., Sakhrani, V., AlSaati, A., de Weck, O. (2013). Multidimensional Hierarchically Integrated Framework for Modeling Complex Engineering Systems. Accepted to the 2013 Complex Systems Design and Management conference.
- Altunkaynak, A., Özger, M., & Çakmakci, M. (2005). Water consumption prediction of Istanbul city by using fuzzy logic approach. Water Resources Management, 19(5), 641-654.
- Arrow, K., Dasgupta, P., Goulder, L., Mumford, K., Oleson, K. (2012). Sustainability and the measurement of wealth. *Environment and Development Economics* 17, 317-353.
- Borshchev, A., & Filippov, A. (2004). From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. In Proceedings of the 22nd international conference of the system dynamics society (No. 22).
- de Neufville, R., & Scholtes, S. (2011). Flexibility in engineering design. MIT Press. Cambridge.
- El Serafy, S. (2013). Macroeconomics and the Environment: Essays on Green Accounting. Edward Elgar Publishing.
- FAO.(1996). Country-case study: Water policy reform in Saudi Arabia.
- Khatri, K. B., & Vairavamoorthy, K. (2009). Water demand forecasting for the city of the future against the uncertainties and the global change pressures: case of Birmingham. In Proceedings of the World Environmental and Water Resources Congress, Great Rivers (pp. 5173-5187).
- Ministry of Water and Electricity (MoWE). (2010). Annual Report 2010. Kingdom of Saudi Arabia.
- Qi, C., & Chang, N. B. (2011). System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts. Journal of environmental management, 92(6), 1628-1641.
- Schieritz, N., & Milling, P. M. (2003). Modeling the forest or modeling the trees. In Proceedings of the 21st International Conference of the System Dynamics Society (pp. 20-24).
- UNU-IHDP and UNEP (2012). Inclusive Wealth Report 2012: Measuring progress toward sustainability. Cambridge University Press, Cambridge.