An Agent-Based Modeling Approach to Integrated Groundwater Management in Oman

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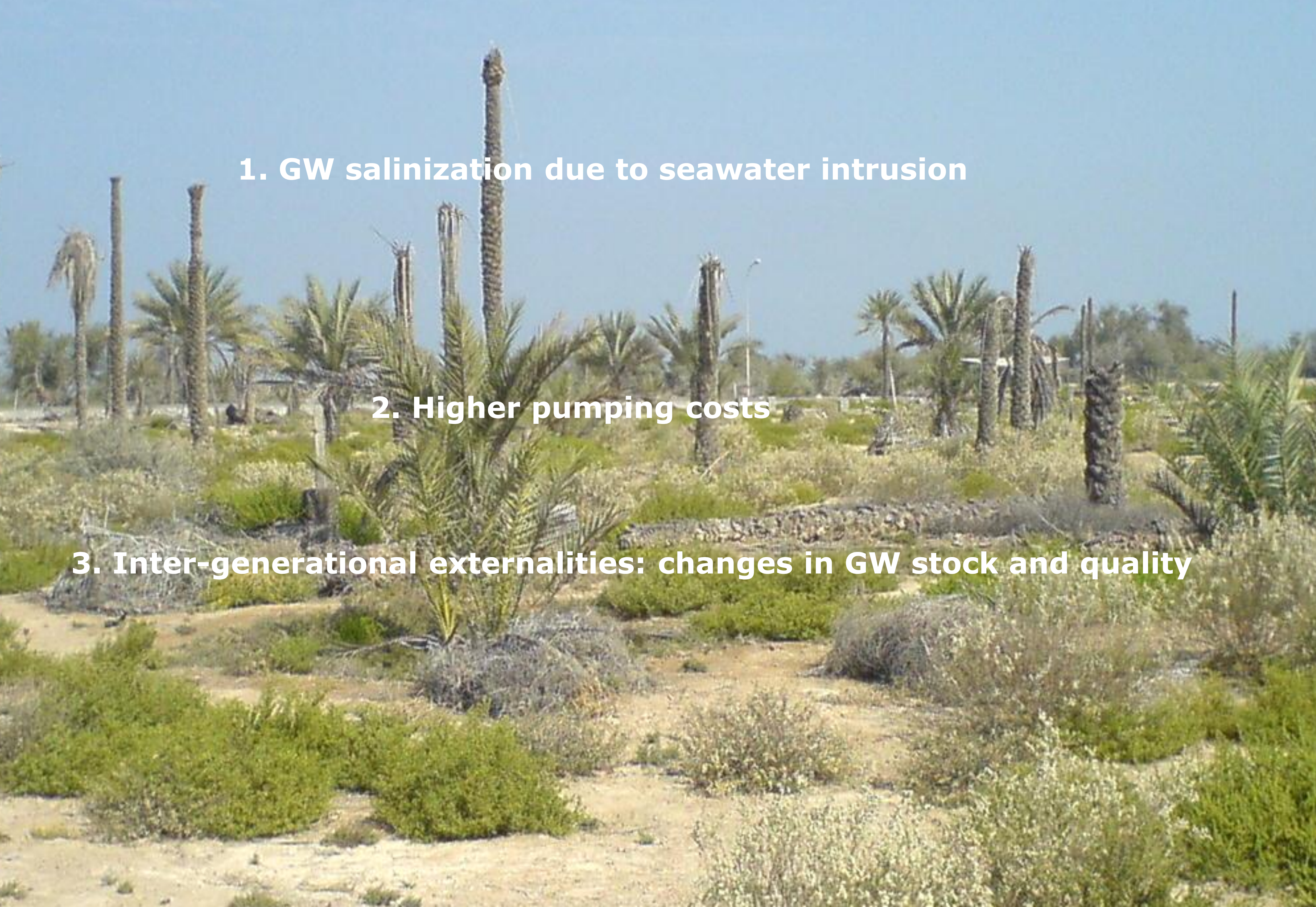
Consequences of over-pumping



1. GW salinization due to seawater intrusion
2. Higher pumping costs
3. Inter-generational externalities: changes in GW stock and quality

Oman's location

The Batinah Coastal Plain

Comprehensive Master Plan for Al-Batinah Coastal Area

Supreme Committee for Town Planning, Sultanate of Oman

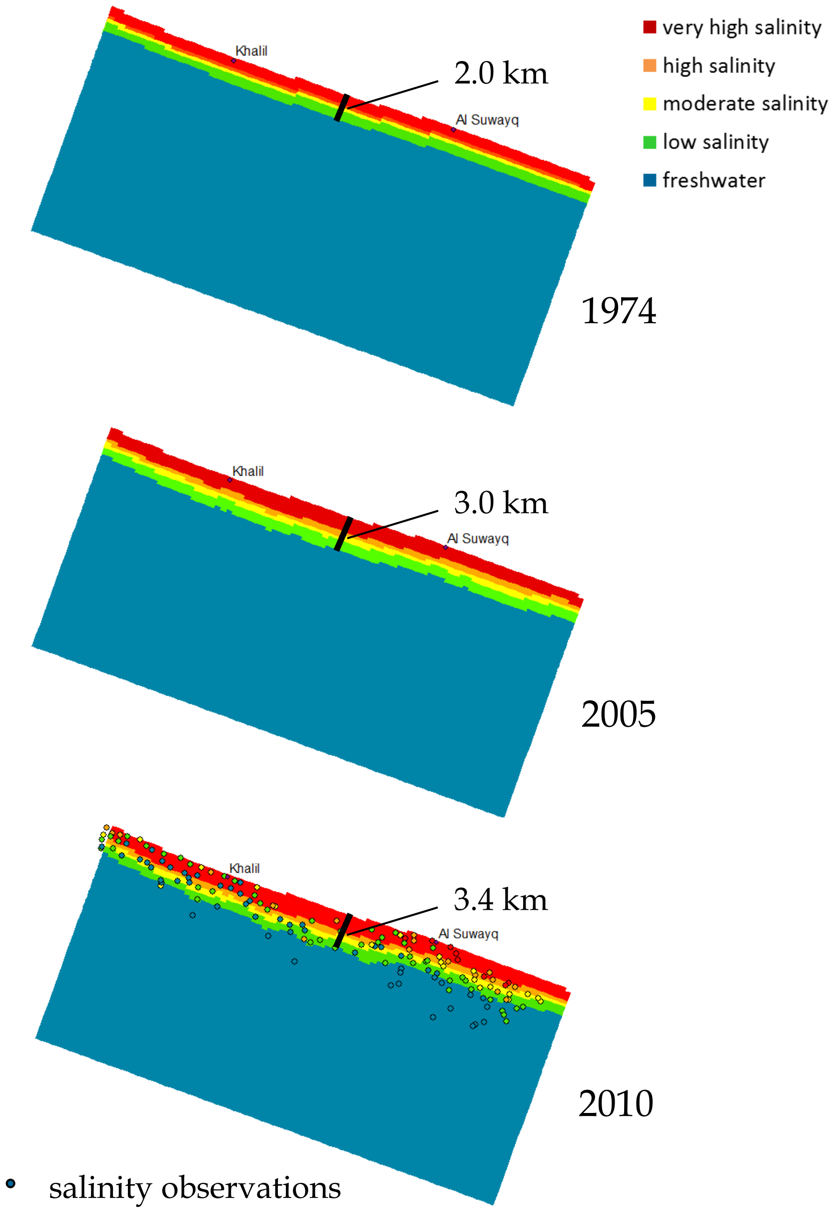
HMR Consultants,Oman - LEA Associates South Asia Pvt Ltd., India - Perkins+Will, USA

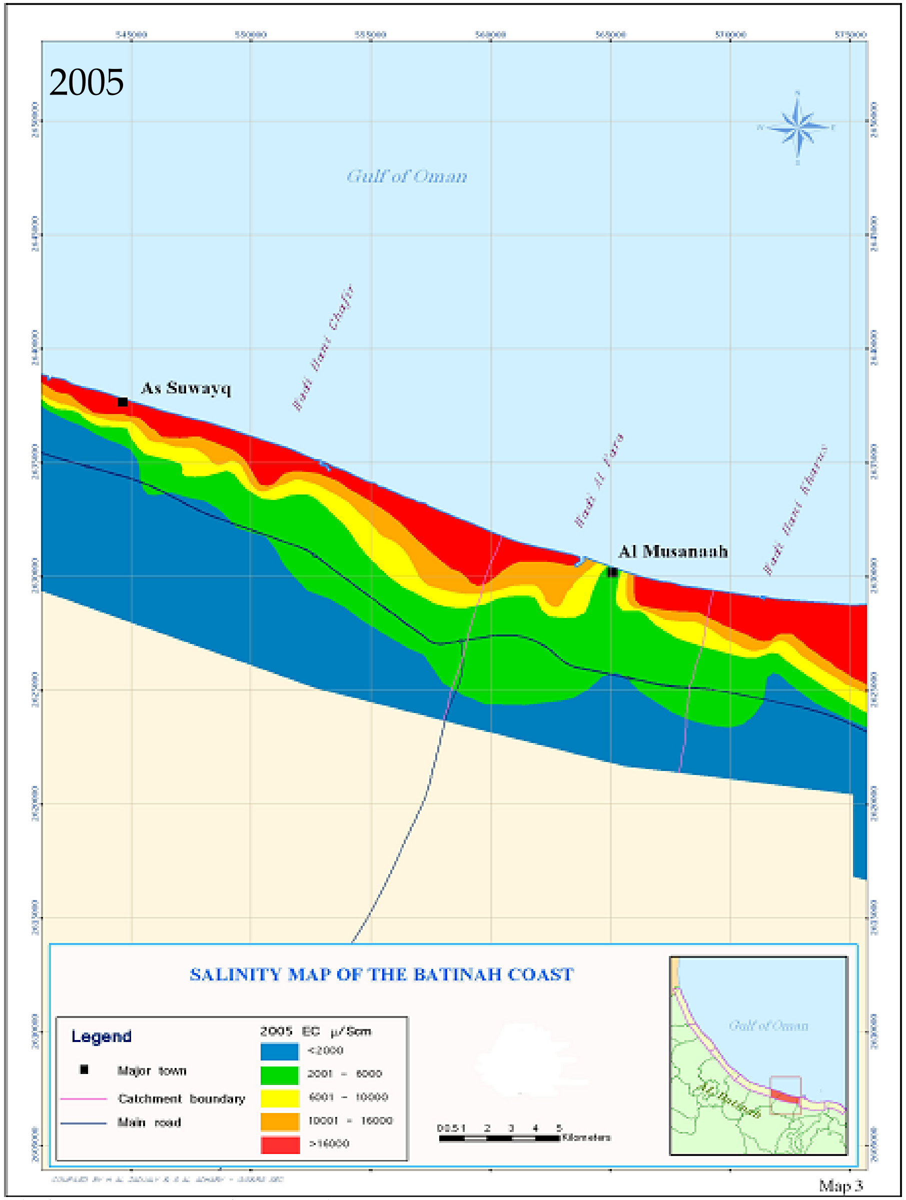
Agriculture Area Affected by Salinity Ingress

0 5 10 20 30 40 50 KM

June 2010

Observed Salinity 1974 - 2010





(Al Barwani & Helmi 2006)

Monitoring Groundwater Using Energy Water Smart Meters and Smart Irrigation

- 3 decades of efforts to address GW over-pumping and seawater intrusion
- Main measures adopted by the government since the 1990's:
  - a vast subsidy program of irrigation modernization
  - a freeze on drilling new wells
  - delimitation of several no-drill zones
  - a crop substitution program
  - re-use of treated wastewater and
  - construction of recharge dams
- But no major success to stop the salinization of the aquifers or water level drawdown

- In 1995 a regulation laid the ground for GW quotas
- Early studies suggested that:
  - cost of traditional flow metering was prohibitive and that cheating is easy
  - majority of Omani farmers have been found to be open to quotas, provided that:
    - groundwater remains free of charge
    - the quota covers the crops' water requirement
    - the quota is enforced without favoritism
- To overcome the major practical challenges of metering, smart electricity-water meters have been equipped with modems to facilitate GW use control and monitoring without creating a financial burden for the farmers and allowing for cheating detection
- 40 Farms were equipped since June 2013

Smart Water Meters Installed in 40 farms

Wireless Smart Irrigation System Developed

- Designing the appropriate quotas (soil type, crops…)
- Subjective decisions about when and how much to irrigate causing inefficiency
- Keeping cropped area while reducing pumping?

Date Palm Irrigation frequency	Bubbler/Drip system	Surface/Flood system
Once a Week	6%	
Twice a Week	47%	17%
After two days regularly	6%	
After one day regularly	6%	
Daily	35%	83%
Total	100%	100

Role of SI water on pumping and productivity?

- Wireless Automated SI System developed based on a network of moisture sensors, temperature sensors and electro-valves distributed at farm level.
- Tested in Lab and in Univ. Farm
- Cost: $3,600/ha. 1/5th of commercial cost
- Upgraded existing Drip/Sprinkler systems
  - 15 Farms equipped since august 2014
  - 8 farms with fert-igation system
- Objectives:
  1. How much groundwater could be saved?
  2. Labour saving
  3. Productivity improvement
  4. Feasibility, technical difficulties & adoption by farmers

Method

- A hydro-economic model that couples an aquifer MODFLOW-SEAWAT model and a dynamic profit maximization model using GAMS
- Long-term simulation-optimization
- Optimization model features:
  - Profit, crops, land and salinity are considered at farm-level in the model
  - Salinity is included in model via a Bayesian Inference Expectation
  - Can be run for different management institutions (non-cooperative, cooperative, regulatory interventions, …)
  - Relatively low run-time and high accuracy for a large-scale model

Model's size and computation

- A matrix with 2 Million Rows by 3.5 Million Columns and 20 Million Non-zero variables that is solved within 18 Minutes by GAMS.
- The SEAWAT also takes 27 Minutes to simulate the model for 60 years.
  - The model has 82 by 43 cells in 7 layers covering two main geological formations. An alluvium formation nearly 100 meter deep and the second is called upper fares with more 500 meters depth.

The Salinity Modeling in GAMS

- Optimization occurs in a separate environment from MODFLOW, the integration between MODFLOW and Optimization happens by a Surrogate Model which parameters are updated during the iterations that provide communication between Optimization and MODFLOW
- This Surrogate Model is basically a linear regression model of the following form:

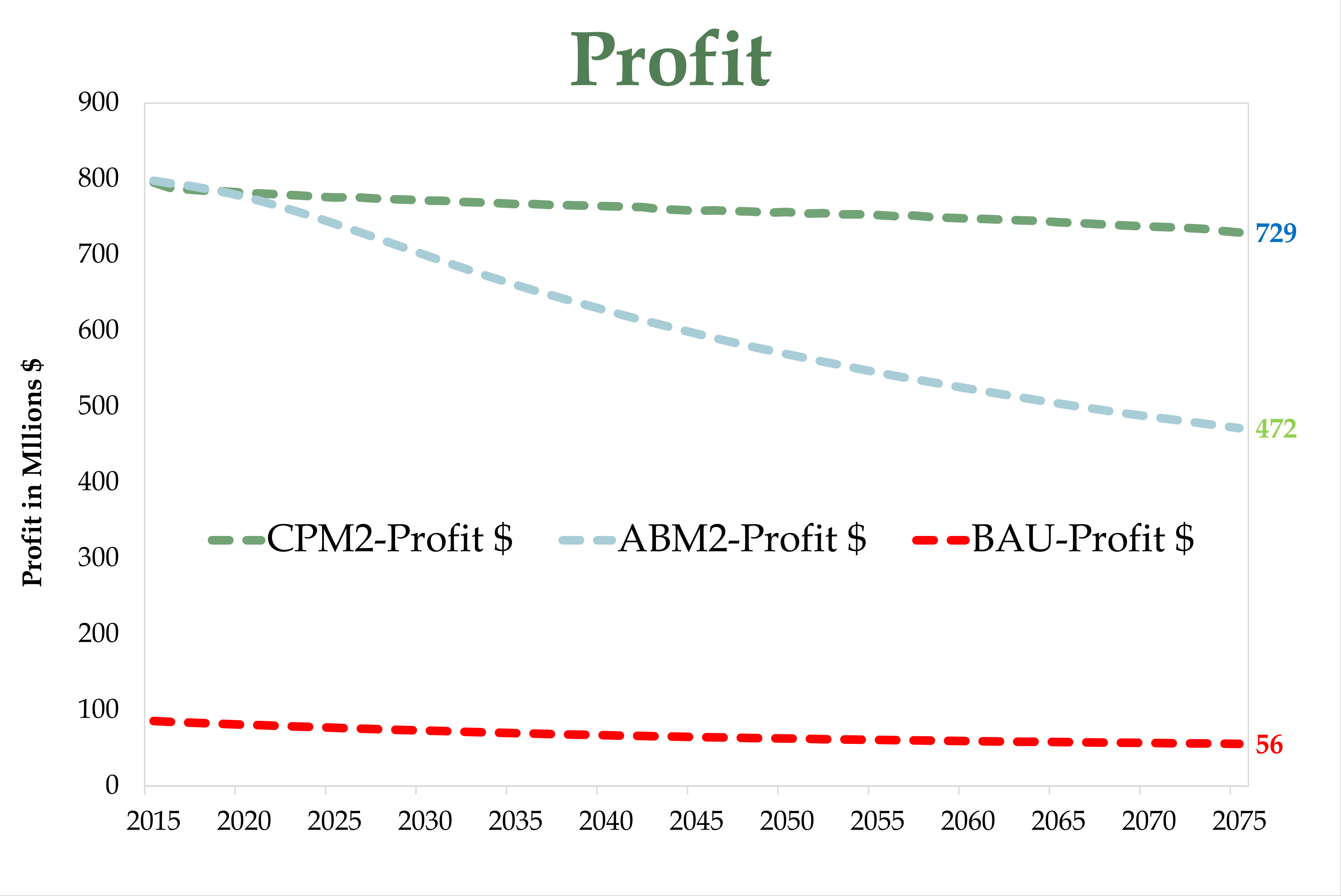
$$\Delta TDS_{i,j}^{y} = \beta_{i,j} \cdot \sum_{i,j} Q_{i,j}^{y} - \alpha_{i,j} \cdot NR$$

Some Tested Scenarios

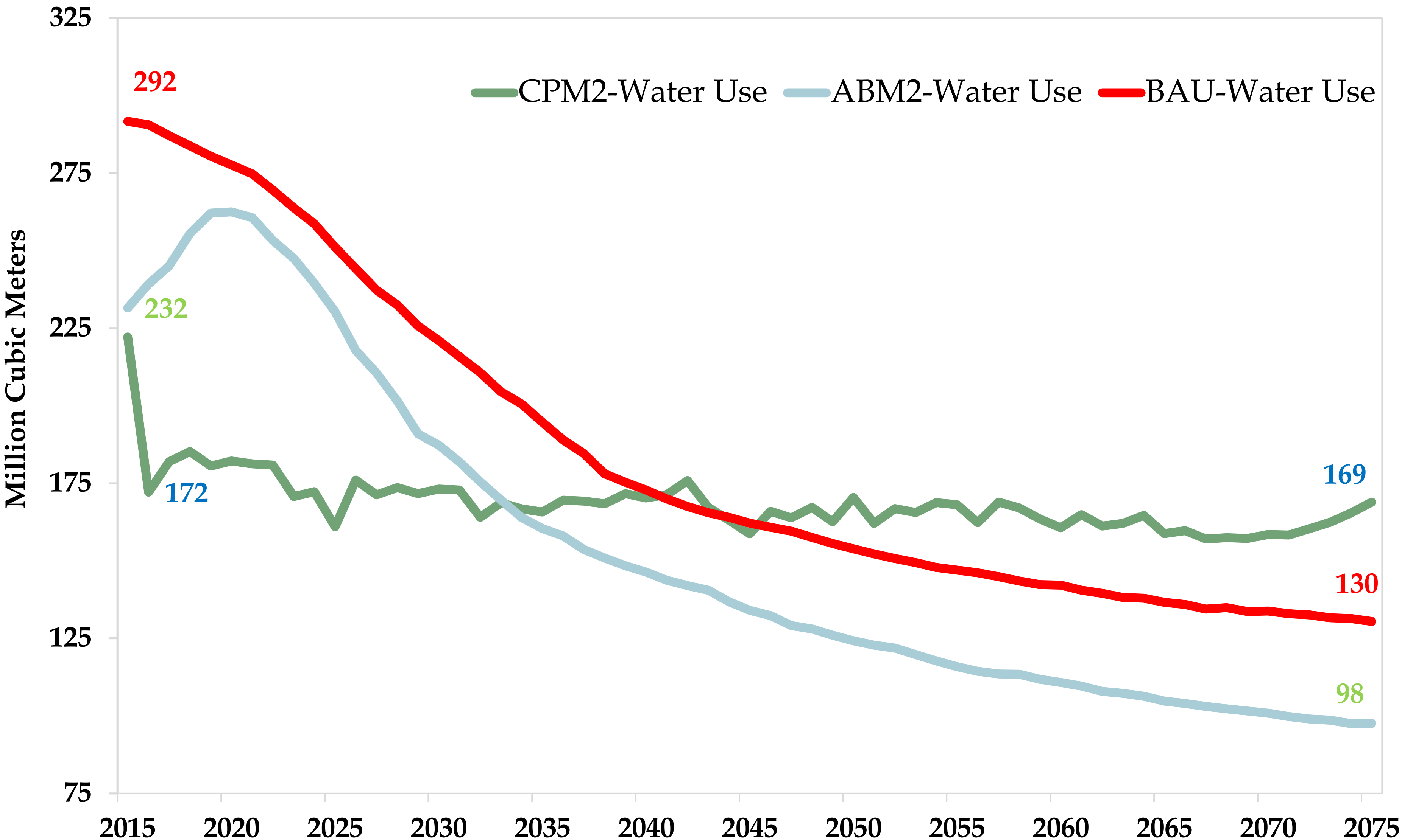
1. Business As Usual (BAU): current pattern and allocation of cropping continues without change (simulation)
2. Central Planner Model (CPM): Long-term optimization with "perfect foresight" into consequences of pumping on salinity [COOPERATIVE]
3. Agent Based Model (ABM): Annual profit optimization with ex-post partial information on salinity [NON-COOPERTIVE]
4. Exogenous Regulatory Interventions are being evaluated

The 3 first scenarios are analyzed under current irrigation system and fully converted irrigation system to modern

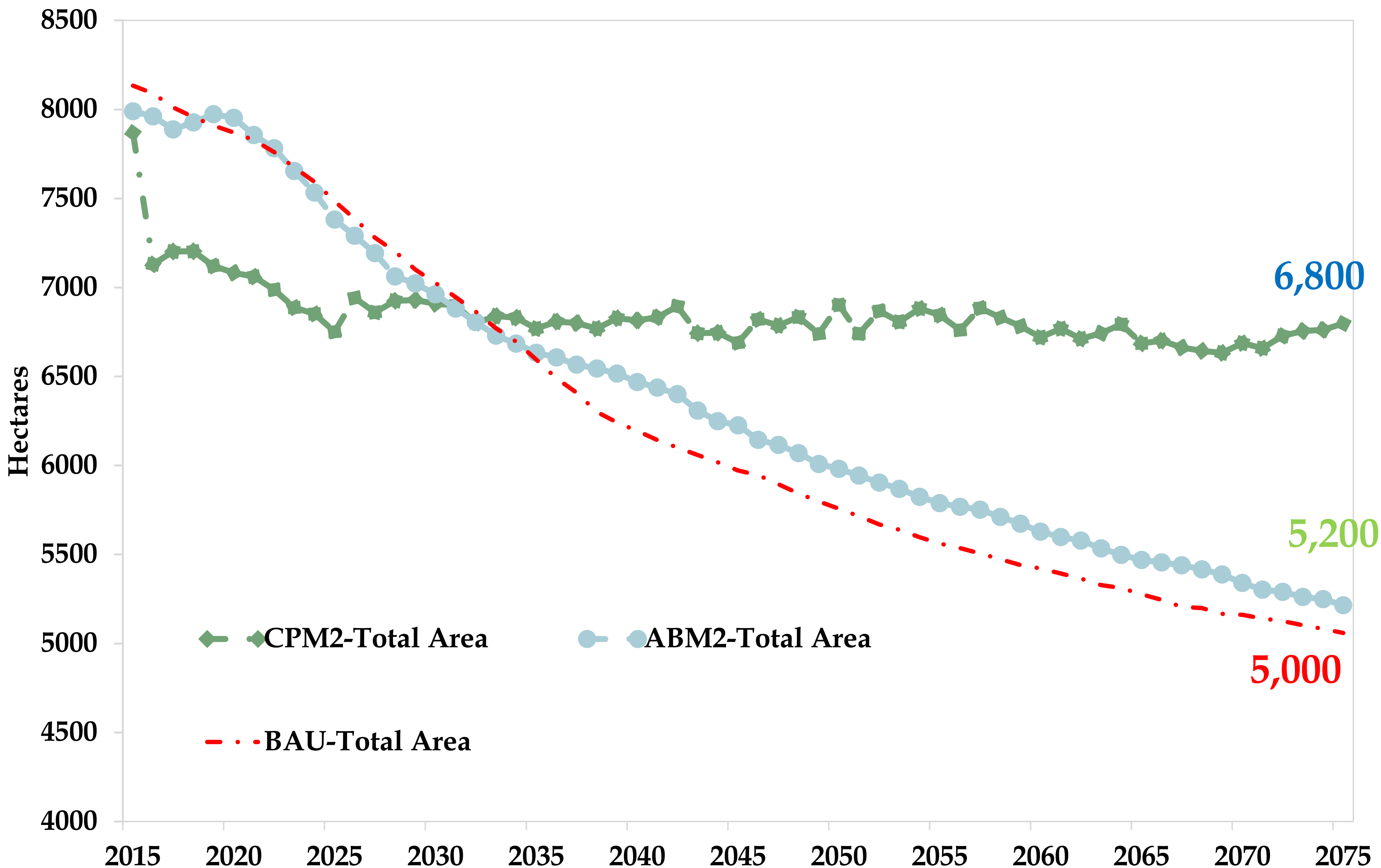
Results


Profit
Profit in Mllions $
900
800
700
600
500
400
300
200
100
0
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
CPM2-Profit $
ABM2-Profit $
BAU-Profit $
729
472
56

Water Pumping



Cropped Area

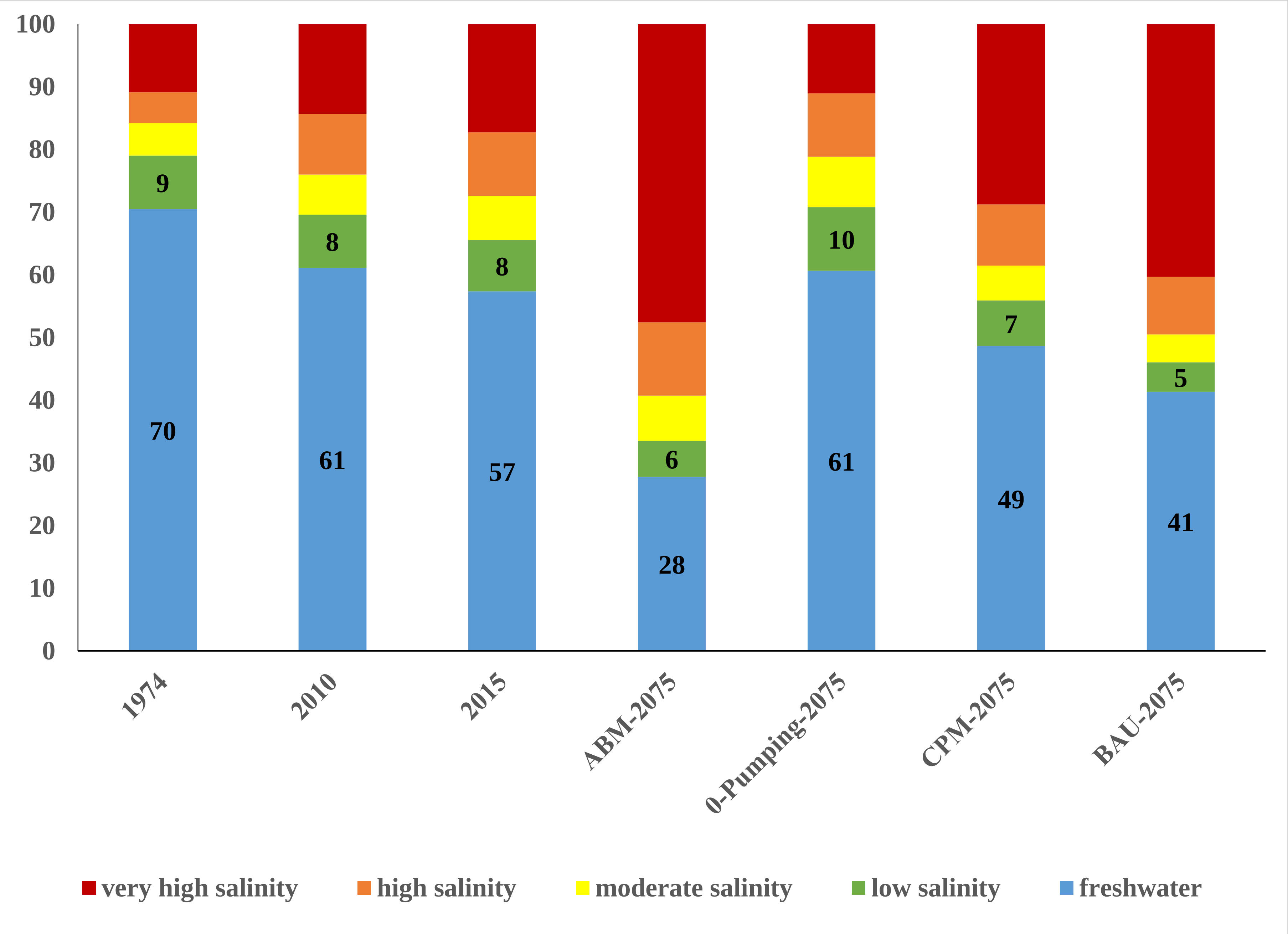


Lessons Learned

- Smart GW meters allowed online daily reading
  - at a low cost: $2/month communication cost
  - Resisted the high summer temperature 60° C.
  - Comparison of crop water requirement and pumping
  - Could be scaled up
- Low cost Smart irrigation system in place
  - Results will require one more year
    - How farmers will interact with the technology?
    - Maintenance and problem solving?
    - Water use efficiency per crop as SI allows daily measures of water use per crop
    - How fert-igation will affect productivity?
- Centrally planned model
  - 45% less GW pumping : "Sustainable Renewable Flow" = 170 Mm^3
  - ↗ 800% profit: there is room to improvement
  - Cropped area decreased from 8,100 to a cst 6,800 Ha

Lessons Learned

- Agent Based Model
  - Profit mimics the CPM for few years then keeps decreasing over the years: Agents have only ex-post on-farm information on salinity
  - Water use decreases compared to CPM from year 2045
    - after 2045, the salinity of groundwater in ABM gets so bad that the model can no longer use the water up to the CPM volume 170 Mm^3
    - Sustainable renewable flow is 91 Mm^3
  - Cropped area goes down to only 5,200 ha by 2075


100
90
80
70
60
50
40
30
20
10
0
9
70
8
61
8
57
6
28
10
61
7
49
5
41
1974
2010
2015
ABM-2075
0-Pumping-2075
CPM-2075
BAU-2075
very high salinity
high salinity
moderate salinity
low salinity
freshwater

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Bayesian Inference Model

The Salinity Model Specifications

- The TDS is total dissolved solids, the beta and Alfa are two unknown factors depending on location i and j and NR is yearly natural recharge
- The variation of TDS is modeled by the above equation which considers:
  - Salinity variation at one point is dependent on pumping in all points (The first term)
  - If there is no pumping then it is expected that salinity improves (the second term)
  - In NR the Natural Recharge to our modeled region is now 59 MCM per year
  - The parameters of this model (Alfa and Beta) are not fixed at first, they are updated and become more accurate by iterations
  - The Updating process is done by Bayesian Inference Method

The Bayesian Inference (Expectation) Model

- The process starts with an initial value then the parameters values are updated according to MODFLOW simulation results in each iteration,
  - Thus more info is produced about the salinity and pumping and the parameters get updated with more data leading to higher accuracey
- This simple Bayesian method considers the previous iteration value of the parameter and its current estimation and make and average of them as shown below:

$$\beta_{i,j}^{iter+1} = \frac{iter \cdot \beta_{i,j}^{iter} + \widehat{\beta_{i,j}}}{iter + 1}$$

  - Iter is the iteration, Beta is the parameter and the Beta-hat is the current estimation of Beta based on current simulation of MODFLOW

The Bayesian Inference (Expectation) Model

- The BIM instead of a simple regression parameter estimation is making use of the past and new data so all information is used according to Bayes assumption that future realization is relying on past observations.
- R^2 is used to compare the BIM-regression and MODFLOW. Due to nonlinearity in groundwater processes $R^2 = 0.7$ still good for predicting a nonlinear model by linear model.