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Water Resources Management under Uncertainty (WRMuU)

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Philosophy and Attitude

- We recognize, we admit and we allow that decisions (political/public as well as private) are taken with a subjective attitude (bias). This is particularly true for decisions under conditions of uncertainty, which are difficult to grasp and understand, decisions whose consequences are uncertain.
- And still, we strive to provide the DMs and society with tools that expose the meanings of uncertainty and the consequences of making decisions under uncertainty, so decisions can be made with “open eyes” and result in minimum future regret.

Outline

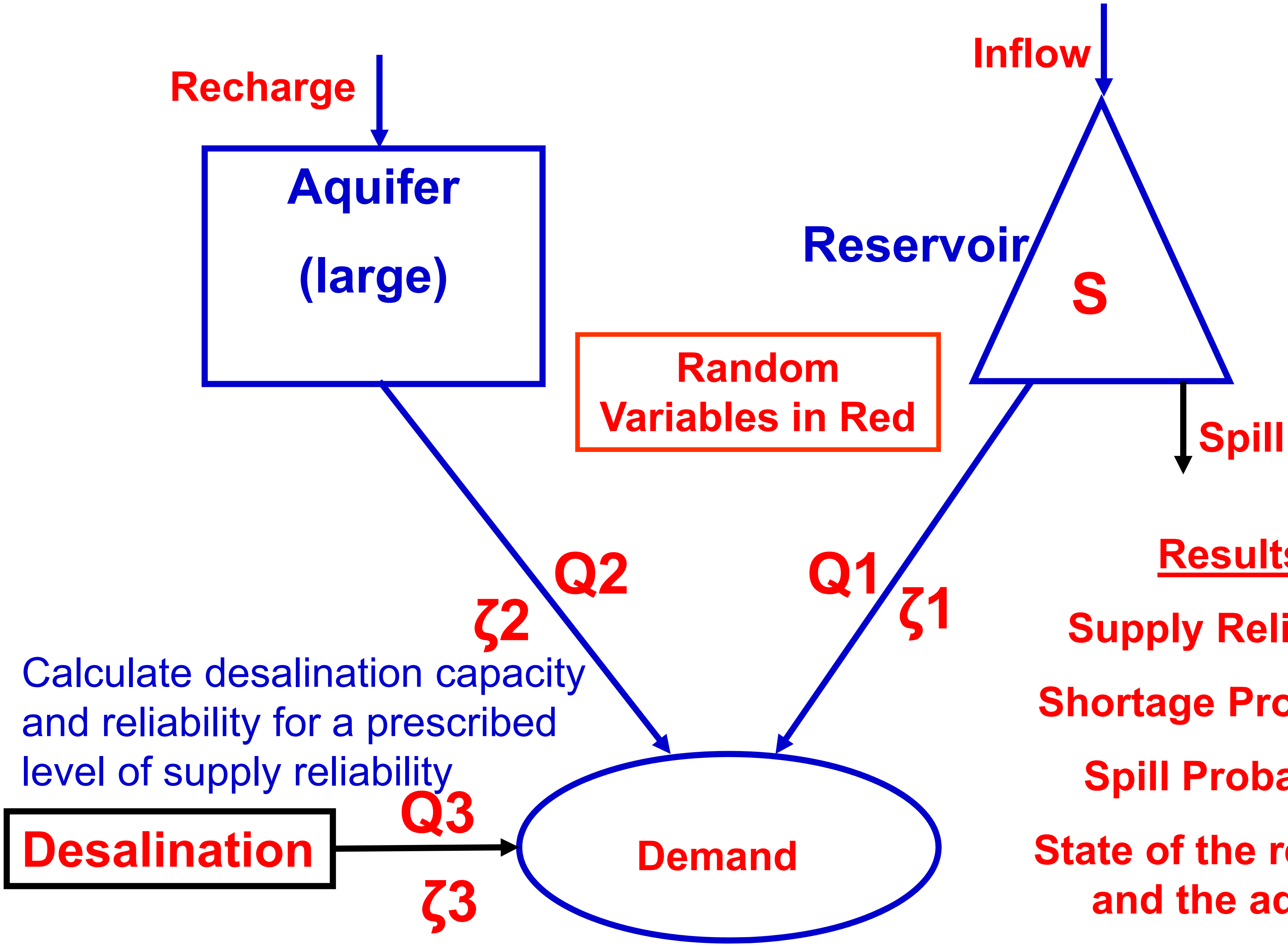
- Focus on regional water supply systems
- Examples of practice in 1980s and 1990s
- Recent methodologies & optimization models
- Some more recent applications

Regional Water Supply Systems

- Systems that connect consumers to sources through man-made facilities
- Management of: the sources, consumer demands, the distribution systems (planning, design, operation)
- Sources: river (clean, polluted), aquifer (fresh, brackish), wastewater (treatment plant), sea water (desalination)
- Demands: urban, irrigation, industry, nature and the environment
- Time horizons: minutes … days … years …decades

Uncertainties and Consequences

- Sources of uncertainty: hydrology, component failures, demands, performance of system components or their ensemble, costs and benefits, laws and regulations, politics, international conditions (e.g., water agreements, WTO)
- Desired outcomes: water quantity, quality, area cultivated, species protected, population served, income, net benefit
- Negative results: loss of service, shortage, loss of species, financial loss, loss of professional reputation, loss of political position



Random Variables in Red

Calculate desalination capacity and reliability for a prescribed level of supply reliability

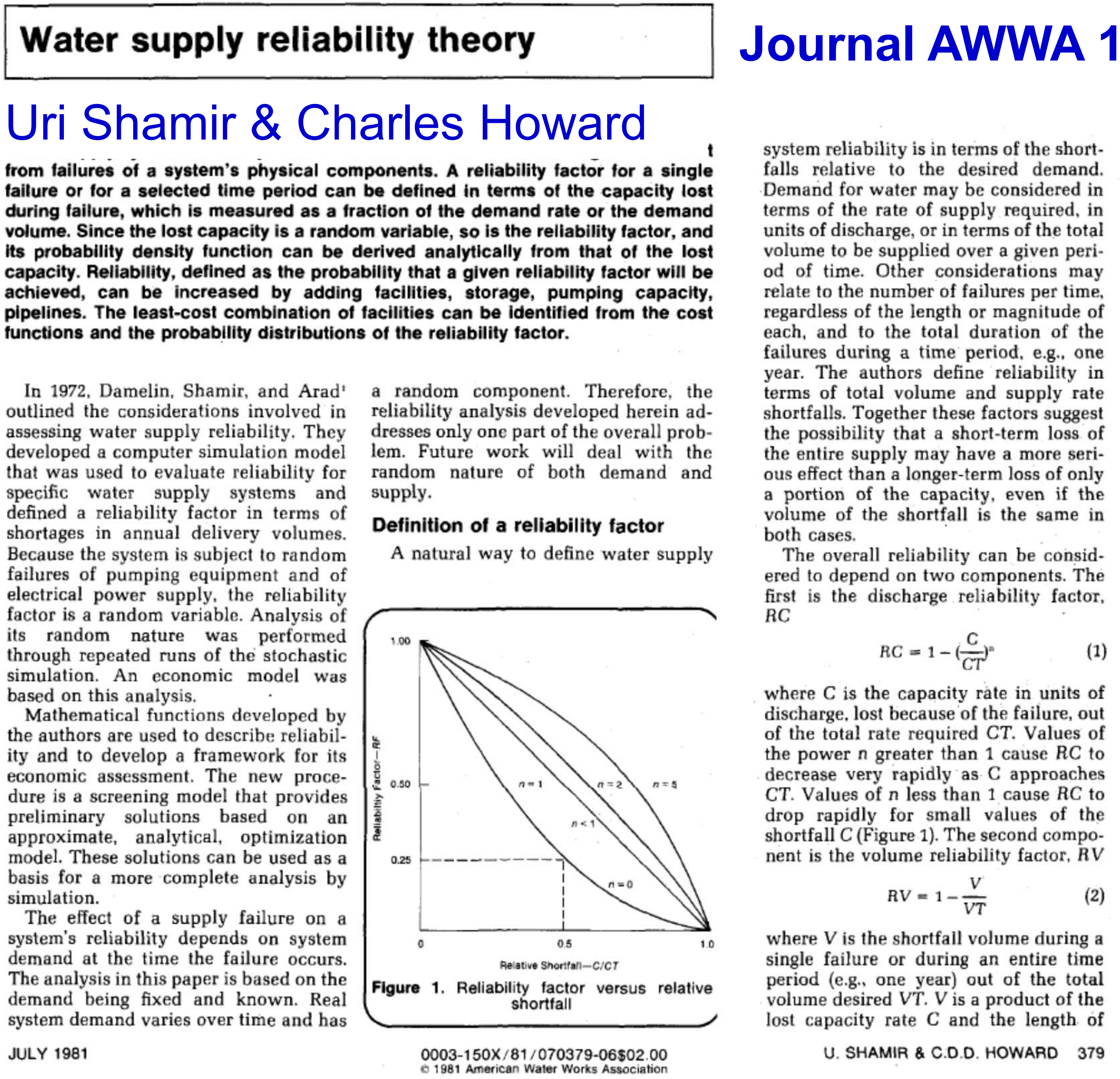
Results:

Supply Reliability

Shortage Probability

Spill Probability

State of the reservoir and the aquifer



Water supply reliability theory

Journal AWWA 1981

Uri Shamir & Charles Howard

from failures of a system's physical components. A reliability factor for a single failure or for a selected time period can be defined in terms of the capacity lost during failure, which is measured as a fraction of the demand rate or the demand volume. Since the lost capacity is a random variable, so is the reliability factor, and its probability density function can be derived analytically from that of the lost capacity. Reliability, defined as the probability that a given reliability factor will be achieved, can be increased by adding facilities, storage, pumping capacity, pipelines. The least-cost combination of facilities can be identified from the cost functions and the probability distributions of the reliability factor.

In 1972, Damelin, Shamir, and Arad[1] outlined the considerations involved in assessing water supply reliability. They developed a computer simulation model that was used to evaluate reliability for specific water supply systems and defined a reliability factor in terms of shortages in annual delivery volumes. Because the system is subject to random failures of pumping equipment and of electrical power supply, the reliability factor is a random variable. Analysis of its random nature was performed through repeated runs of the stochastic simulation. An economic model was based on this analysis.

Mathematical functions developed by the authors are used to describe reliability and to develop a framework for its economic assessment. The new procedure is a screening model that provides preliminary solutions based on an approximate, analytical, optimization model. These solutions can be used as a basis for a more complete analysis by simulation.

The effect of a supply failure on a system's reliability depends on system demand at the time the failure occurs. The analysis in this paper is based on the demand being fixed and known. Real system demand varies over time and has a random component. Therefore, the reliability analysis developed herein addresses only one part of the overall problem. Future work will deal with the random nature of both demand and supply.

Definition of a reliability factor

A natural way to define water supply system reliability is in terms of the shortfalls relative to the desired demand. Demand for water may be considered in terms of the rate of supply required, in units of discharge, or in terms of the total volume to be supplied over a given period of time. Other considerations may relate to the number of failures per time, regardless of the length or magnitude of each, and to the total duration of the failures during a time period, e.g., one year. The authors define reliability in terms of total volume and supply rate shortfalls. Together these factors suggest the possibility that a short-term loss of the entire supply may have a more serious effect than a longer-term loss of only a portion of the capacity, even if the volume of the shortfall is the same in both cases.

Figure 1. Reliability factor versus relative shortfall

The overall reliability can be considered to depend on two components. The first is the discharge reliability factor, *RC*

$$RC = 1 - \left(\frac{C}{CT}\right)^n \quad (1)$$

where C is the capacity rate in units of discharge, lost because of the failure, out of the total rate required *CT*. Values of the power *n* greater than 1 cause *RC* to decrease very rapidly as C approaches *CT*. Values of *n* less than 1 cause *RC* to drop rapidly for small values of the shortfall *C* (Figure 1). The second component is the volume reliability factor, *RV*

$$RV = 1 - \frac{V}{VT} \quad (2)$$

where *V* is the shortfall volume during a single failure or during an entire time period (e.g., one year) out of the total volume desired *VT*. *V* is a product of the lost capacity rate *C* and the length of

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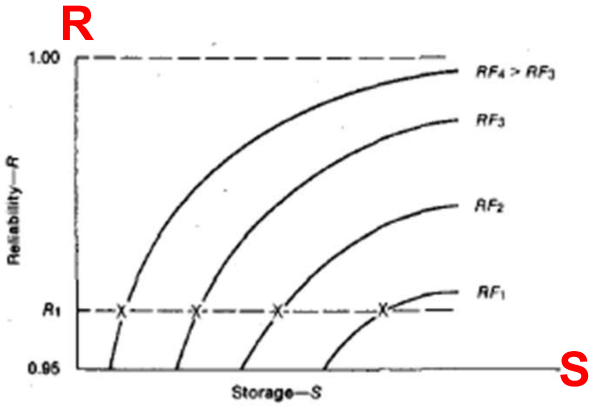

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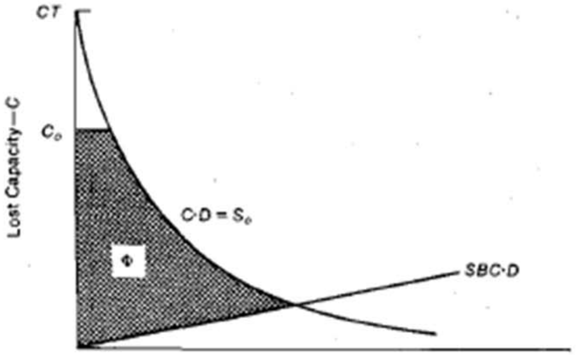
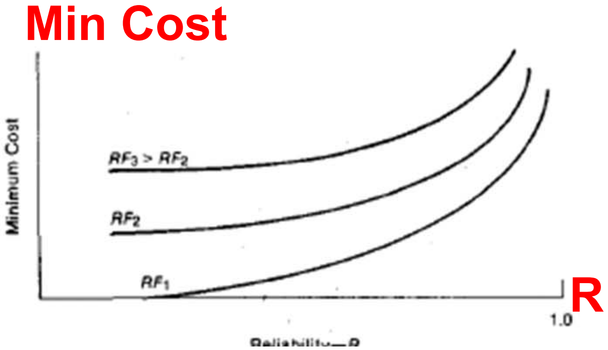
Effect of Storage on Reliability



Trade-off between Storage and Standby Pumping Capacity for given Reliability, and Min Cost path



Minimum Cost curves vs Reliability

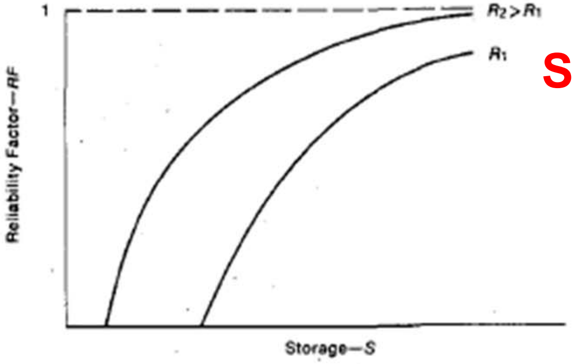


Figure 11. Effect of storage on the reliability factor

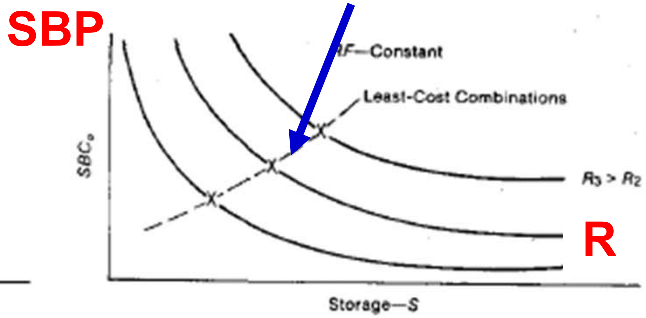


Figure 13. Trade-off between storage and standby pumping capacity to achieve a given reliability for a fixed reliability factor

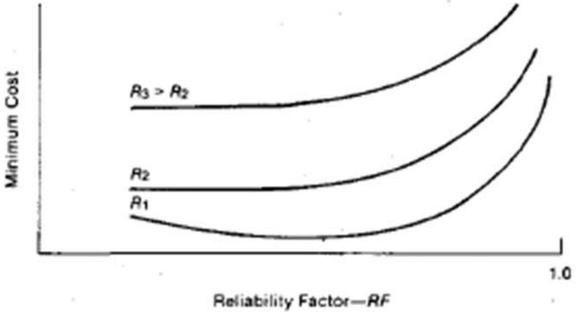


Figure 15. Minimum curves for reliability factor

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FOR
SEATTLE WATER DEPARTMENT

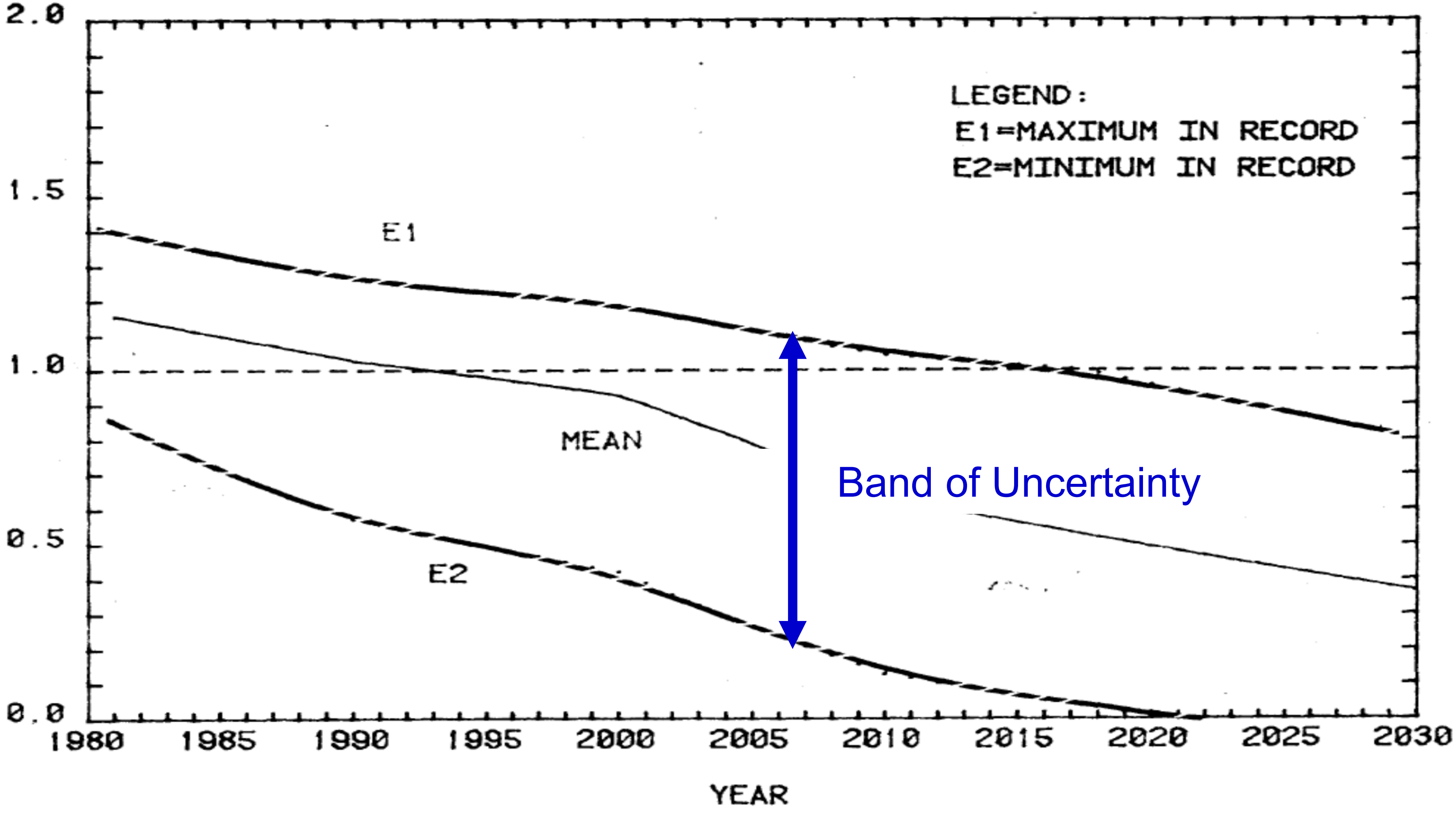
Water Supply Reliability and Risk
City of Seattle – 1984

Charles Howard and Associates Ltd.

WATER SUPPLY
RELIABILITY AND RISK

MAY, 1984

Charles Howard & Associates Ltd.
Professional Engineers



Seasonal Reliability - No Further Source Development

Economic Cost of Shortages in the Wet Months

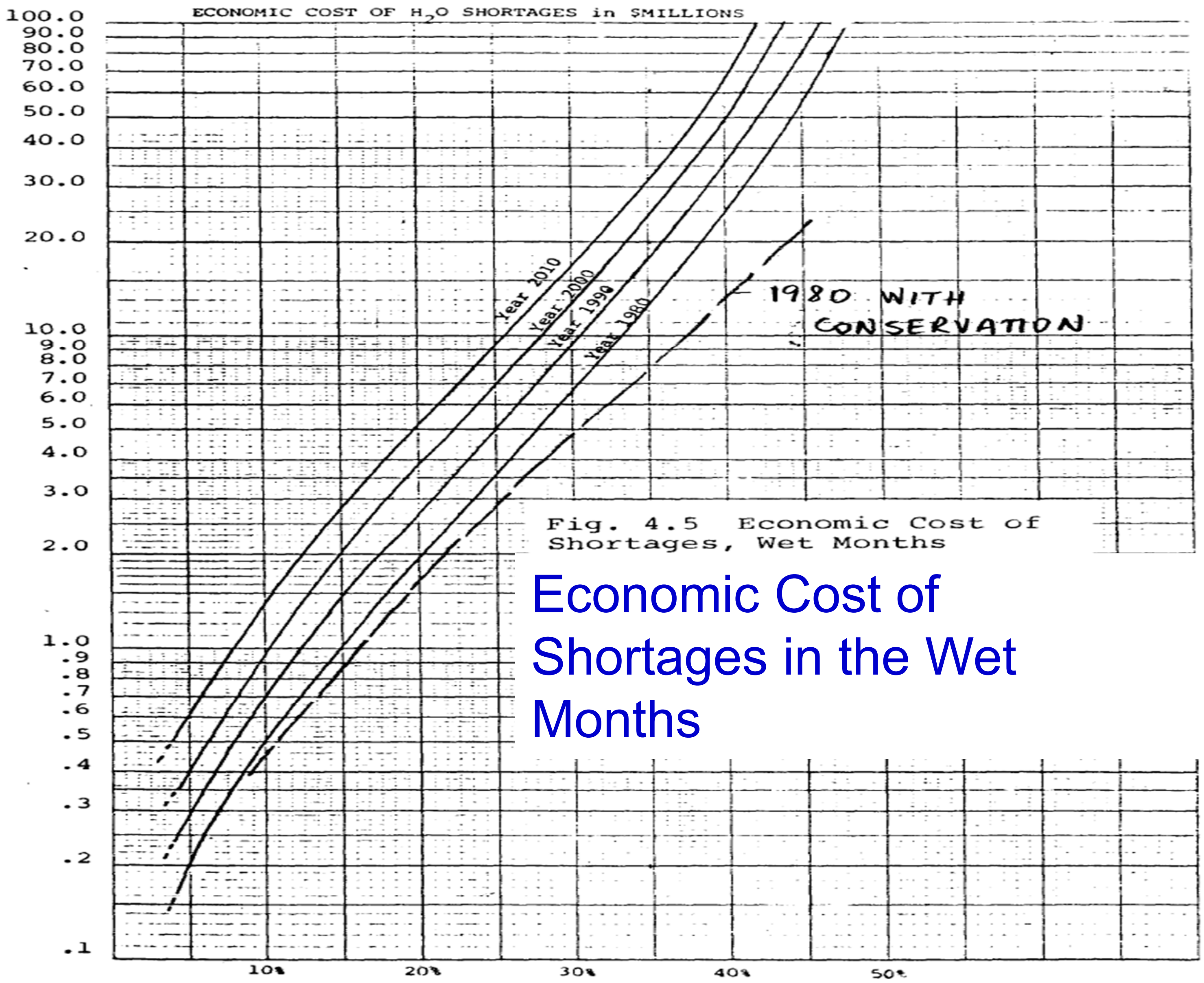


Fig. 4.5 Economic Cost of Shortages, Wet Months

Cost Of Shortage ($M)

Shortage (% of Demand)

Regional Municipality of Ottawa-Carleton

Water Supply Reliability

Final Report
September 28,1995

Water Supply Reliability
Regional Municipality of Ottawa-Carlton – 1995

Charles Howard and Associates Ltd.

Charles Howard & Associates Ltd.
and Resource Futures International

SEP:9312

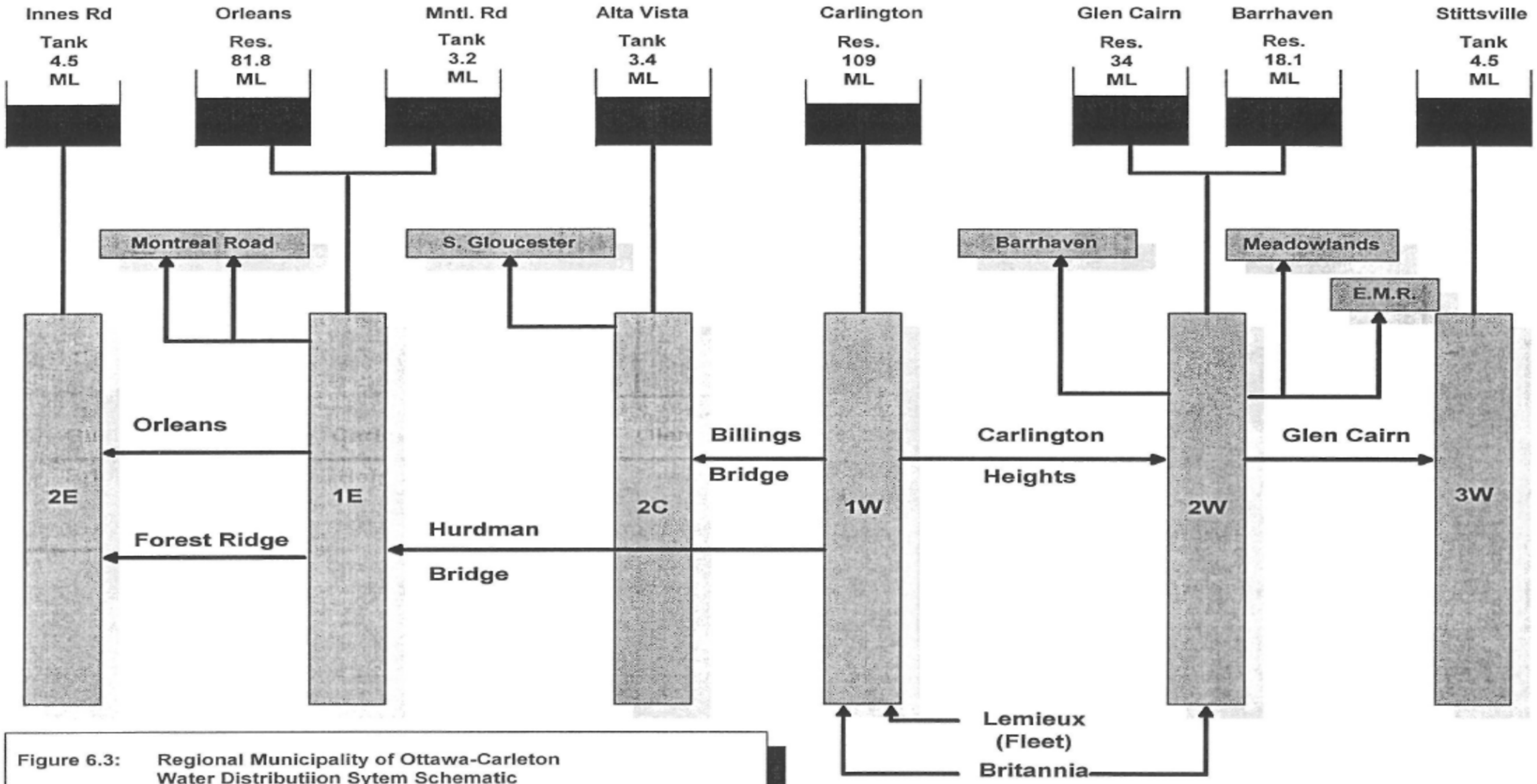


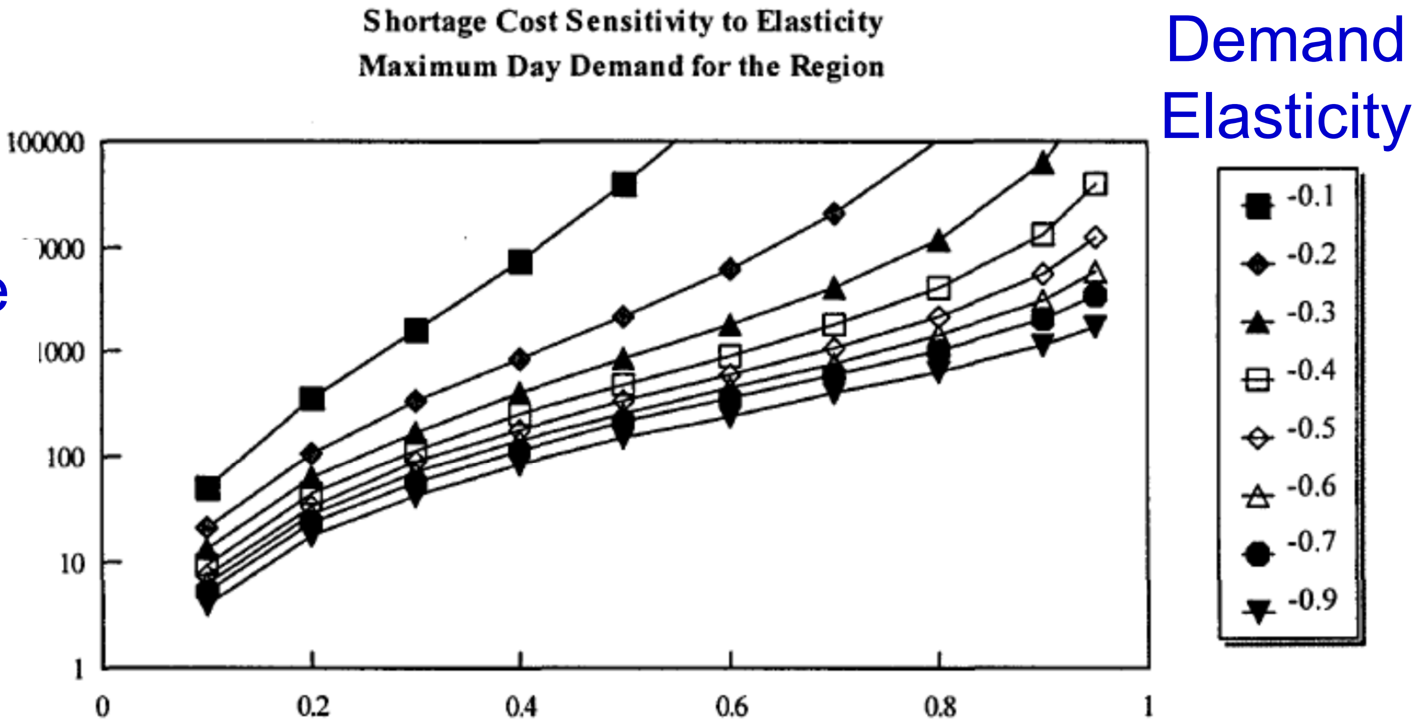
Figure 6.3: Regional Municipality of Ottawa-Carleton
Water Distributiion Sytem Schematic

Legend: Horizontal Rectangle - Closed Pressure Zone (No Storage)
Vertical Rectangle - Major Pressure Zone With Storage

Shortage

Cost

(K$/day)



Demand Elasticity

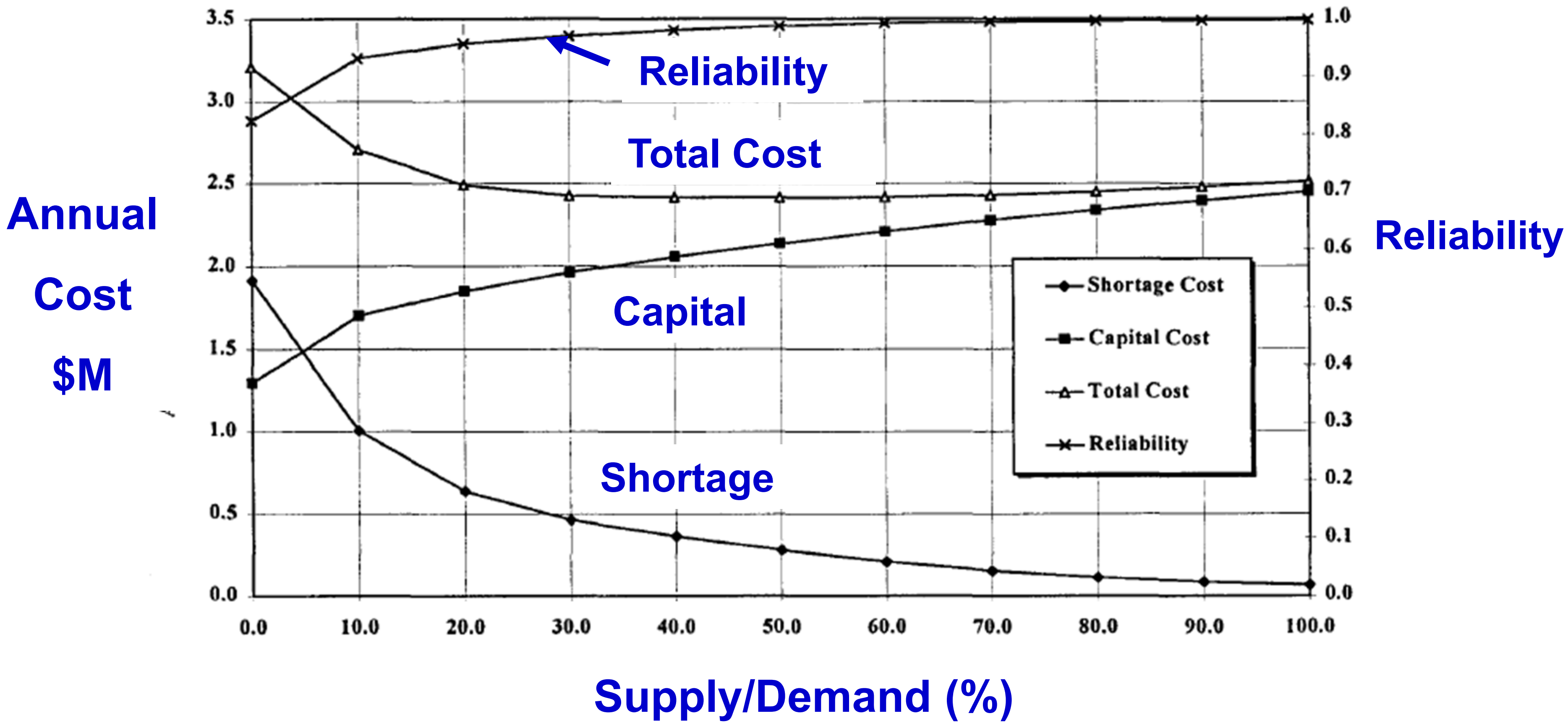
Shortage as fraction of daily demand

Total Max. Day demand for the Region is [illegible] MLD.
The elasticity for RMOC is estimated to be -0.31

Figure 7.3 Sensitivity of the Shortage Cost Function to Changes in Elasticity

Larger (negative) Elasticity → Lower Loss

Figure 8.4b: Storage to Augment Supply Rate of 640 MLD, Zone = Region, DSF = 1.5



Methodology: create two complementary backup sub-systems, such that one survives when a failure occurs, each subject to the same or different (lower) constraints, optimize jointly the full + two backup sub-systems

$$(\text{P1})\ \underset{\mathbf{q}\in\mathbf{Q}}{\text{minimize}}\left\{\phi(\mathbf{q}) = wc(\mathbf{q}) + \underset{\mathbf{X}_p\geq 0;\,\mathbf{RR}\geq 0}{\text{minimize}}\left[\mathbf{a}_p^T(\mathbf{q})\mathbf{X}_p + \frac{1}{2}\mathbf{RR}^T\mathbf{H}(\mathbf{q})\mathbf{RR}\right]\right\} \quad (1)$$

$$\text{subject to: } [\mathbf{L}_p^k \quad \bar{\mathbf{I}}_p \quad \mathbf{J}_p^k(\mathbf{q}^k)]\mathbf{X}_p = \mathbf{b}^k \quad \forall\, k \quad (2)$$

$$[\mathbf{P}_p^k \quad \bar{\mathbf{I}}_p \quad \mathbf{J}_p^k(\mathbf{q}^k)]\mathbf{X}_p \leq \Delta\mathbf{H}_{\max}^k \quad \forall\, k \quad (3)$$

$$\bar{\mathbf{I}}_a\mathbf{X}_p = \mathbf{a}; \quad \mathbf{A}(\mathbf{q})\mathbf{X}_p \leq \mathbf{0}; \quad \mathbf{B}(\mathbf{q})\mathbf{RR} \leq \bar{\mathbf{c}}(\mathbf{q}) \quad (4-6)$$

Is decomposed into

$$(\text{P1-QH})\ \underset{\mathbf{X}_p\geq 0}{\text{minimize}}\ \mathbf{a}_p^T(\mathbf{q})\mathbf{X}_p \quad (7)$$

$$\text{subject to: } [\mathbf{L}_p^k \quad \bar{\mathbf{I}}_p \quad \mathbf{J}_p^k(\mathbf{q}^k)]\mathbf{X}_p = \mathbf{b}^k \quad \forall\, k \quad (8)$$

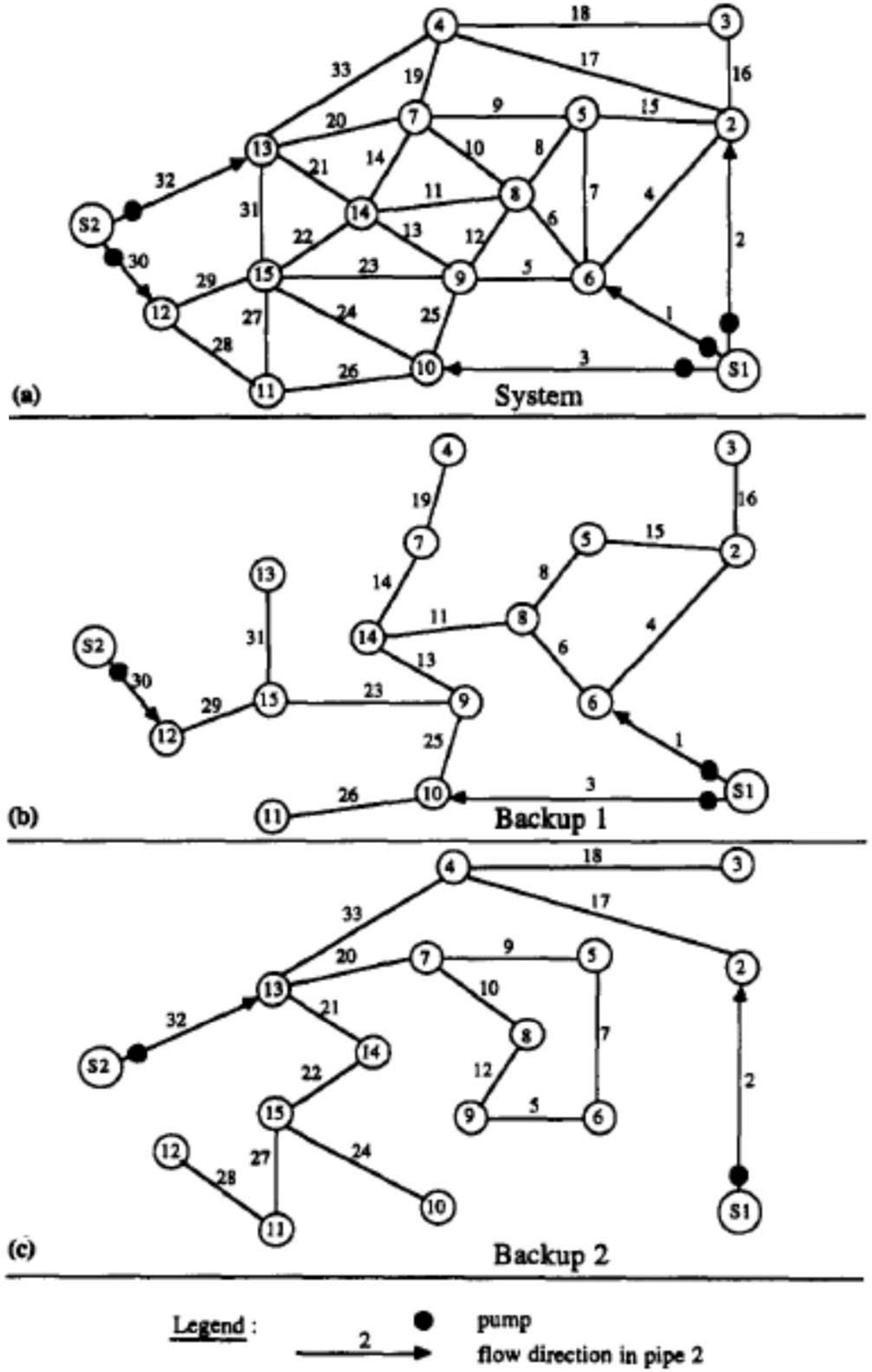
$$[\mathbf{P}_p^k \quad \bar{\mathbf{I}}_p \quad \mathbf{J}_p^k(\mathbf{q}^k)]\mathbf{X}_p \leq \Delta\mathbf{H}_{\max}^k \quad \forall\, k \quad (9)$$

$$\bar{\mathbf{I}}_a\mathbf{X}_p = \mathbf{a}; \quad \mathbf{A}(\mathbf{q})\mathbf{X}_p \leq \mathbf{0} \quad (10, 11)$$

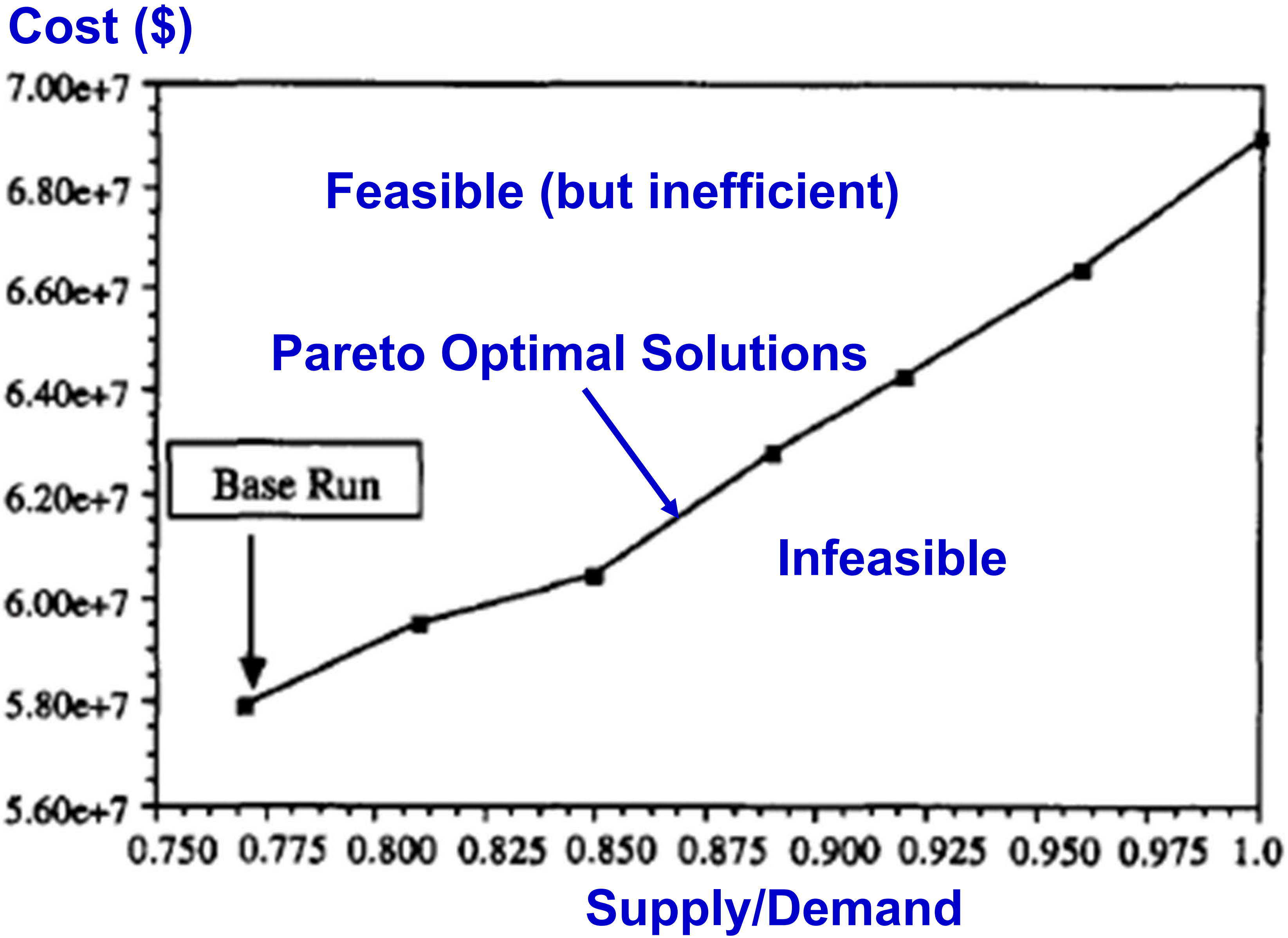
and

$$(\text{P1-QC})\ wc(\mathbf{q}) + \underset{\mathbf{RR}\geq 0}{\text{minimize}}\ \frac{1}{2}\mathbf{RR}^T\mathbf{H}(\mathbf{q})\mathbf{RR} \quad (12)$$

$$\text{subject to: } \mathbf{B}(\mathbf{q})\mathbf{RR} \leq \bar{\mathbf{c}}(\mathbf{q}) \quad (13)$$

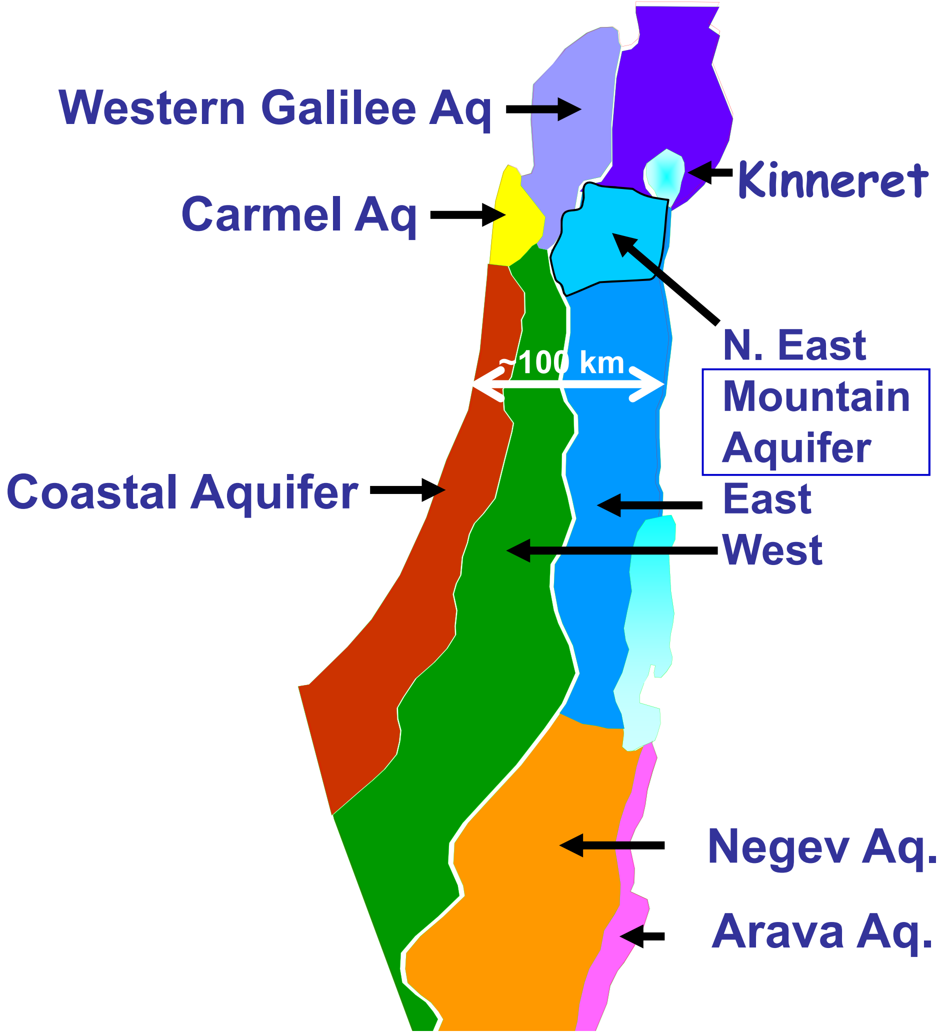


Tradeoff between Cost and Reliability



WATER SOURCES

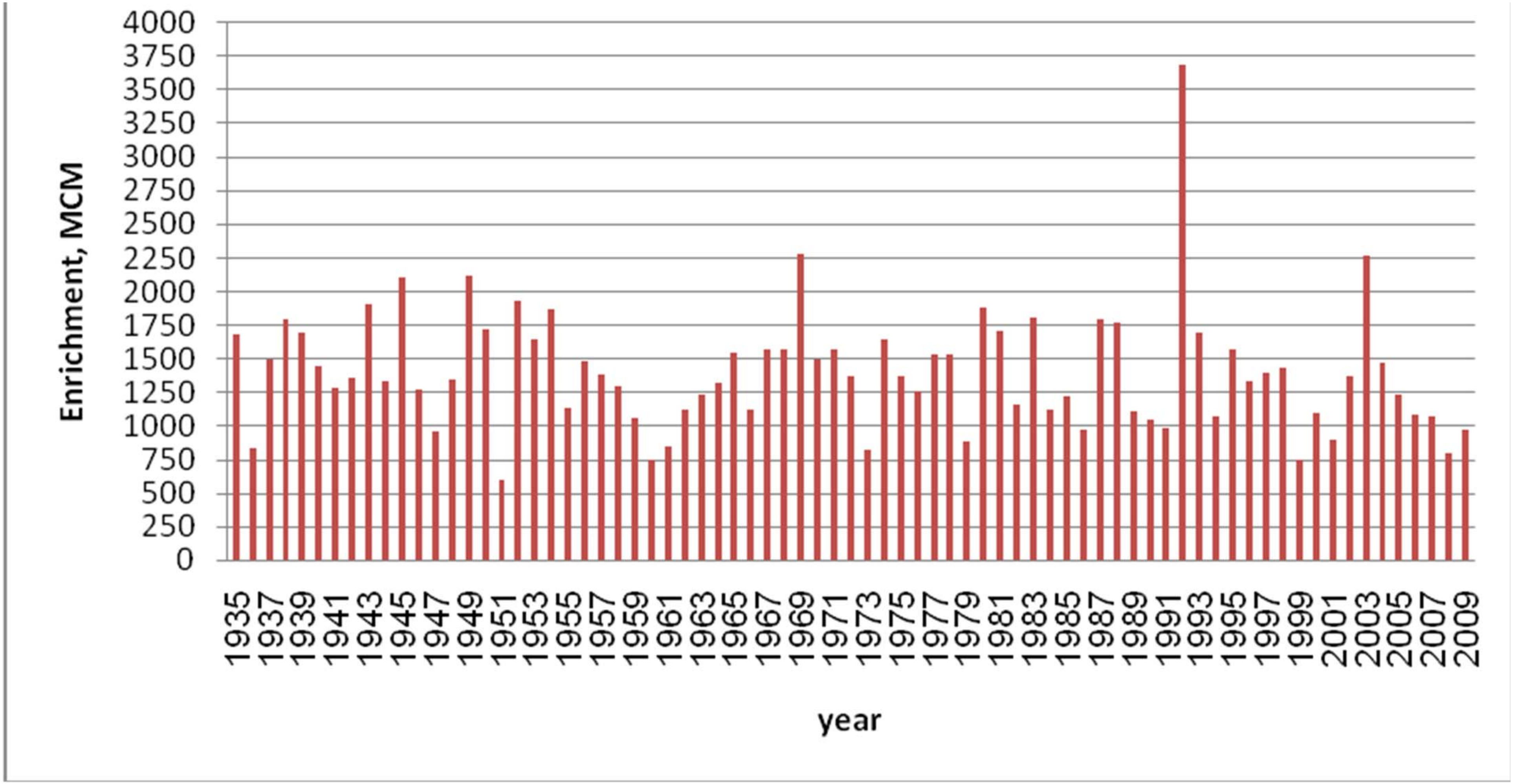
Highly integrated national and regional water systems



Average Annual Potential
~1,200 mcm/yr Israeli control
~1,700 mcm/yr whole area

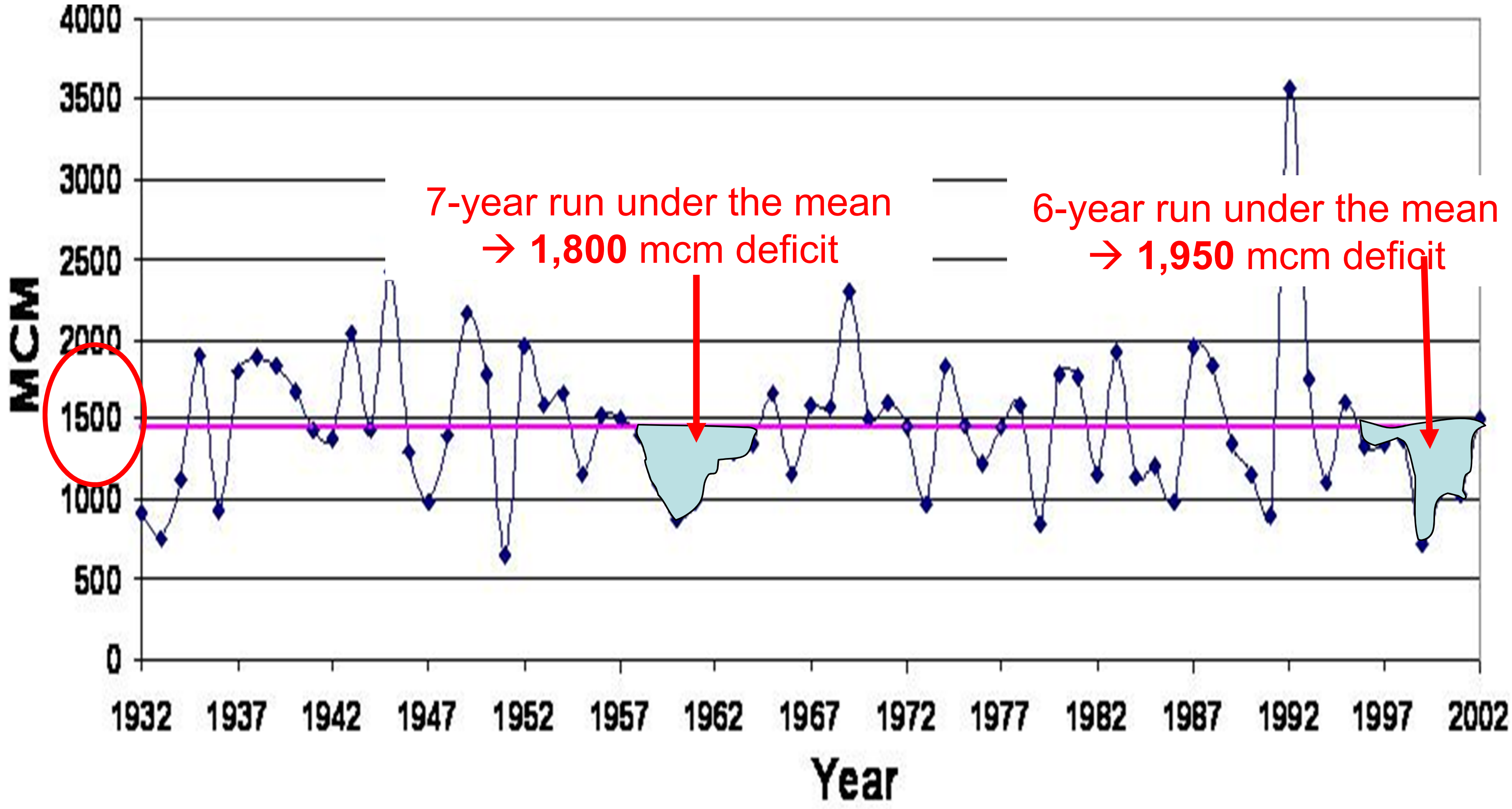
Natural Replenishment (MCM) to the water sources between the Mediterranean Sea and the Jordan River

Kinneret Lake and Watershed, Yarkon-Taninim, Coastal, Carmel and Western Galilee Aquifers



Annual Replenishment of the Natural Sources (mcm/yr) 1932-2002: Average=1,457, SD=458, Range 657-3,563

The variability is forecasted to grow with climate change



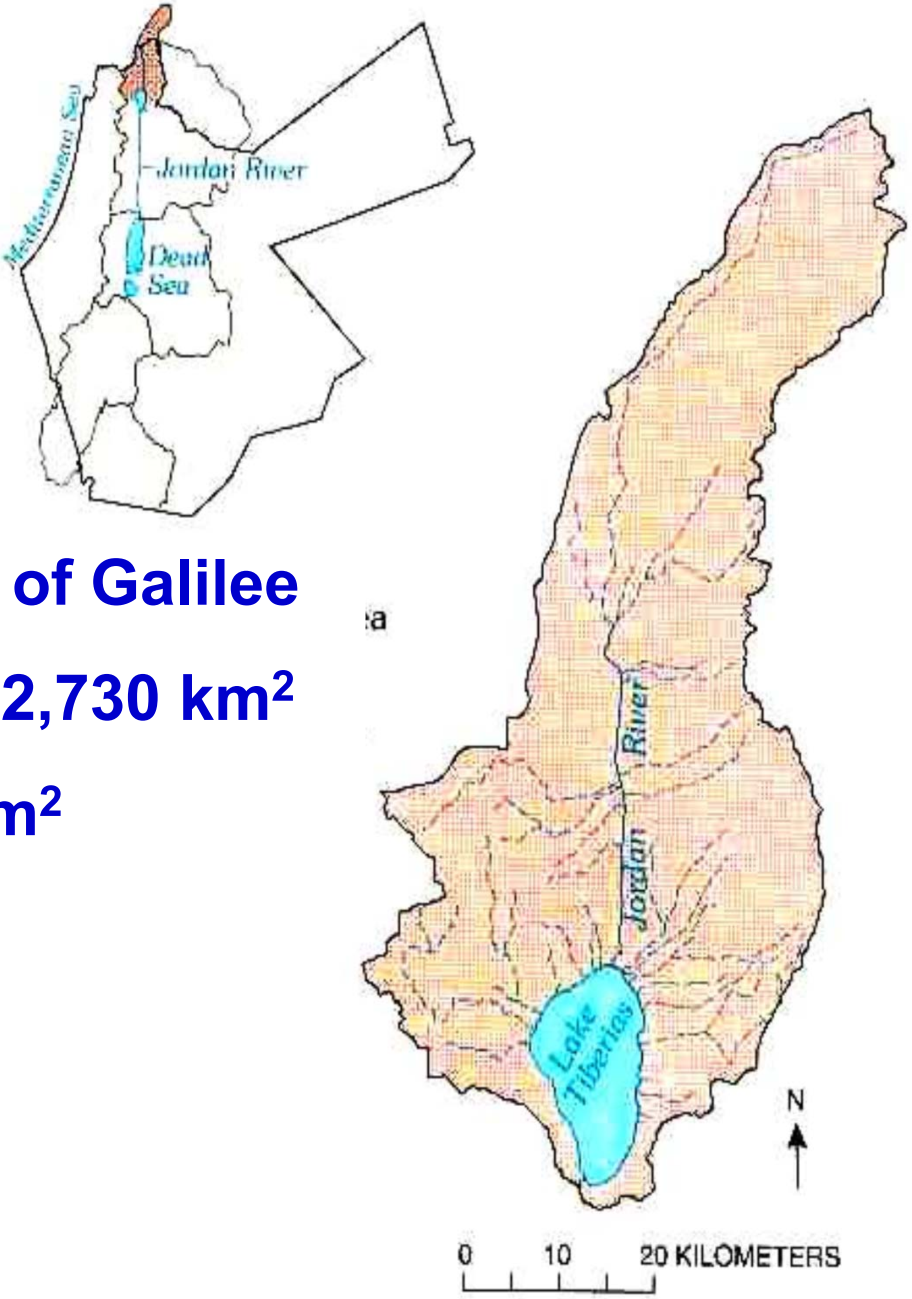
7-year run under the mean
→ **1,800** mcm deficit

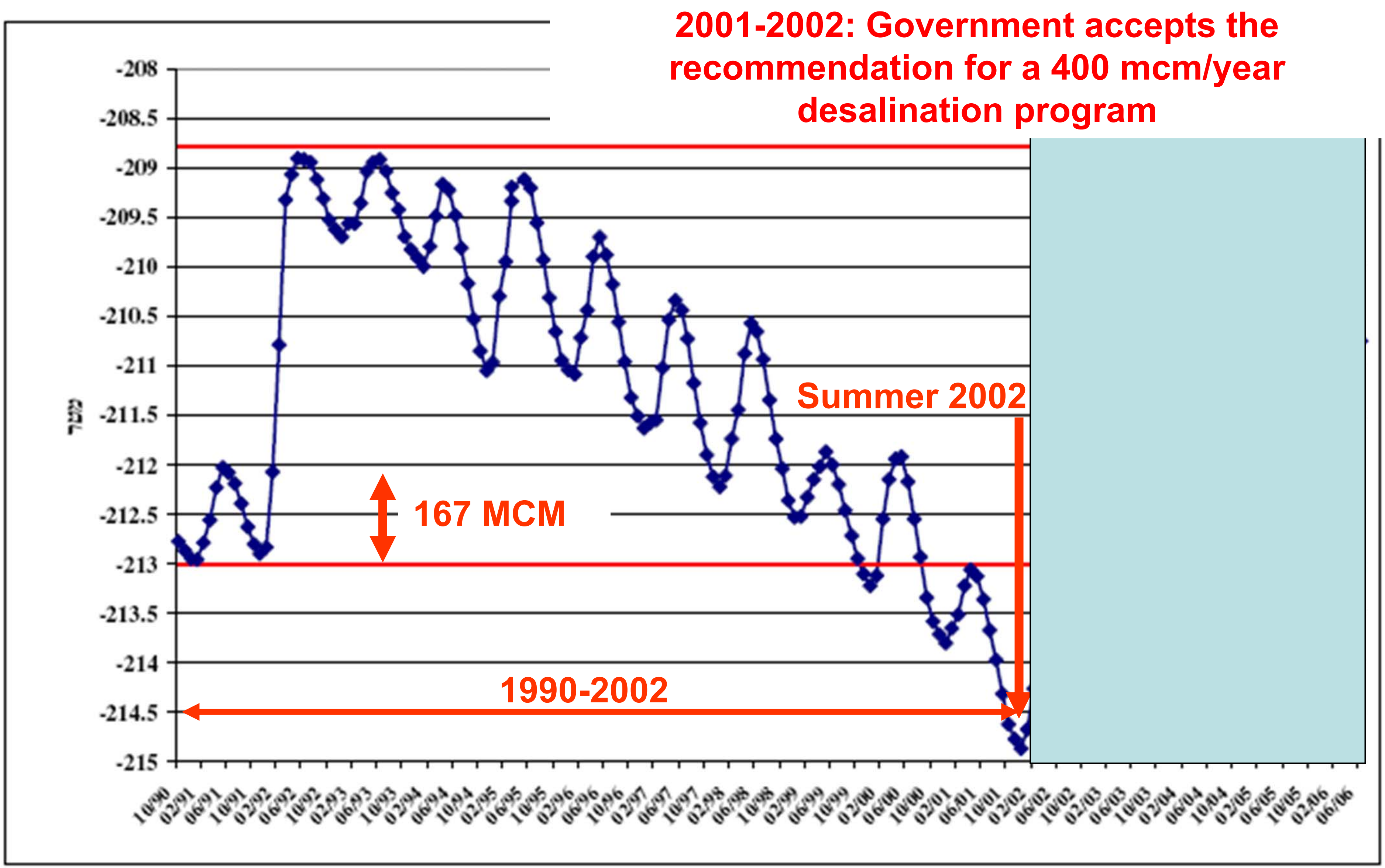
6-year run under the mean
→ **1,950** mcm deficit

Kinneret/Sea of Galilee

Watershed = 2,730 km²

Lake = 167 km²





2001-2002: Government accepts the recommendation for a 400 mcm/year desalination program

Summer 2002

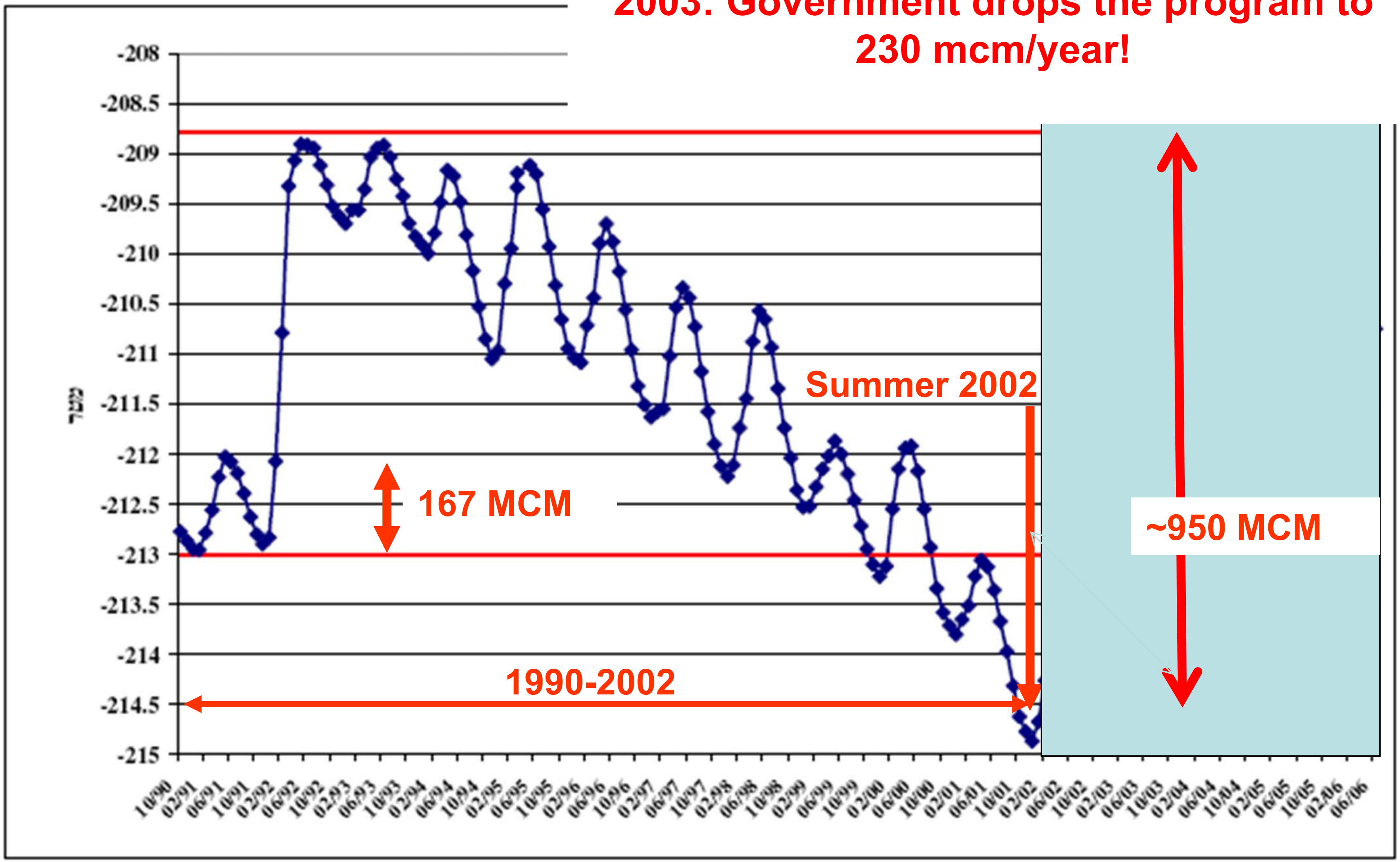
167 MCM

1990-2002

Kinneret Water Levels: Due to Inflow and Withdrawals

Kinneret 2002

2003: Government drops the program to 230 mcm/year!



Summer 2002

167 MCM

~950 MCM

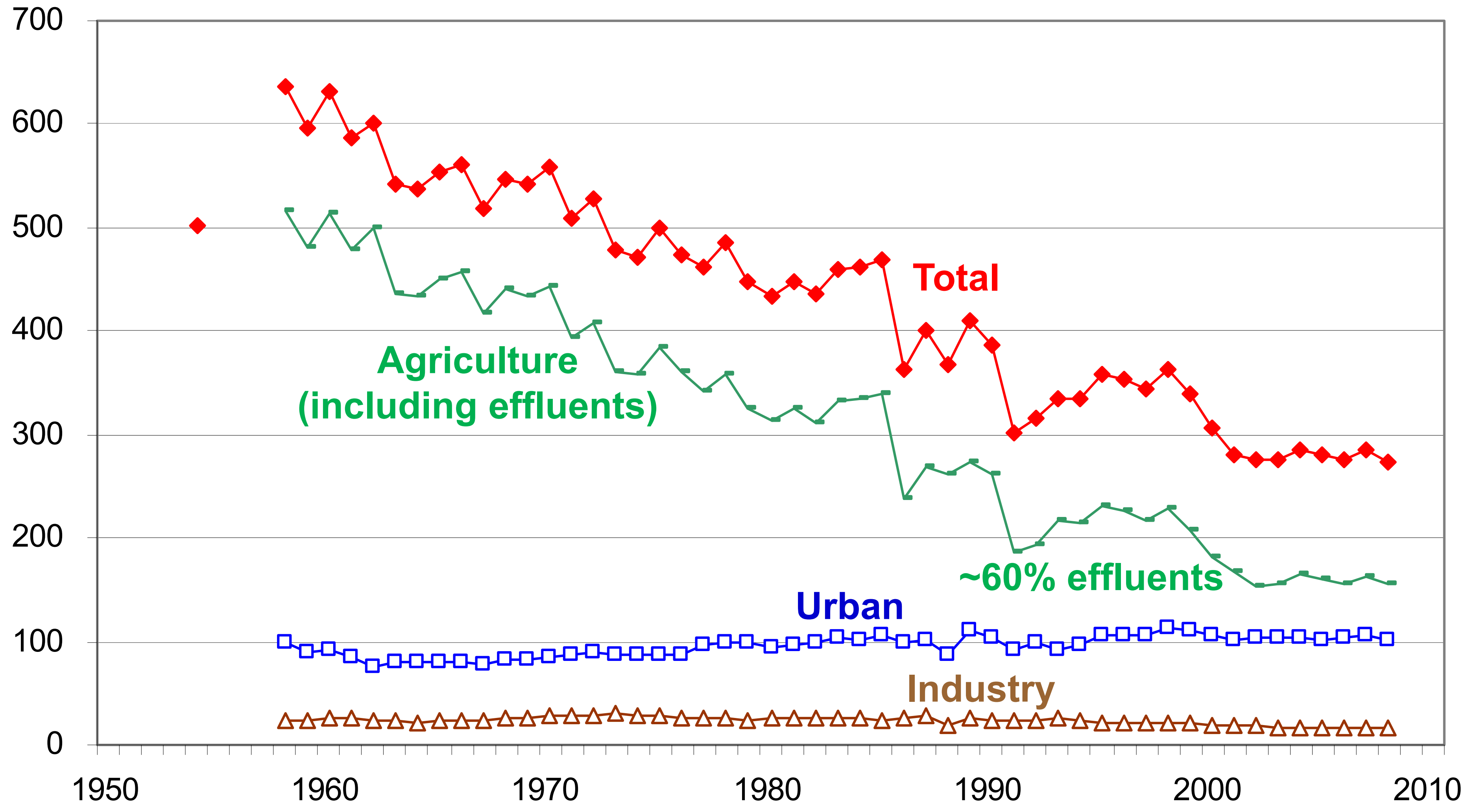
1990-2002

Kinneret Water Levels: Due to Inflow and Withdrawals

Responses / Decisions: policies, planning, operation

- Demand management
- Reuse of sewage effluents (72%) in agriculture
- Desalination of sea-water 400→230 mcm/year
- Renewed in 2006, raised to 600-750 mcm/year
- 2008-2012: New Master Plan

Water (incl. effluents) consumption, m^3/cap/year



Source: Prof. Yoav Kislev

Private homes

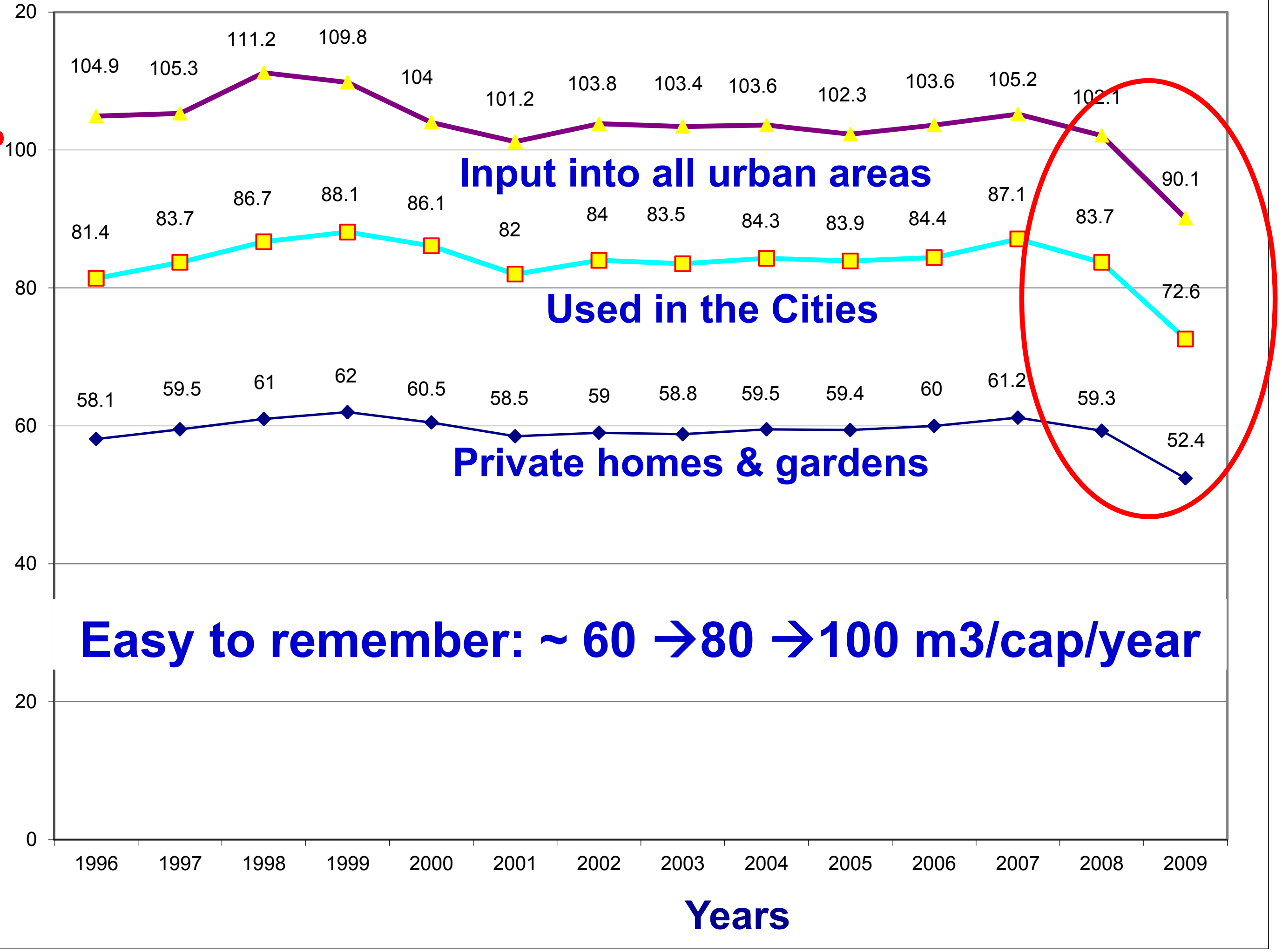
Annual Per Capita Consumption, 1996-2009 (m^3/capita/year)

Reduction 2008→2009

(102.1-90.1)/102.1=12% = 90 mcm

(83.7-72.6)/83.7=13%

(59.3-52.4)/59.3=12%

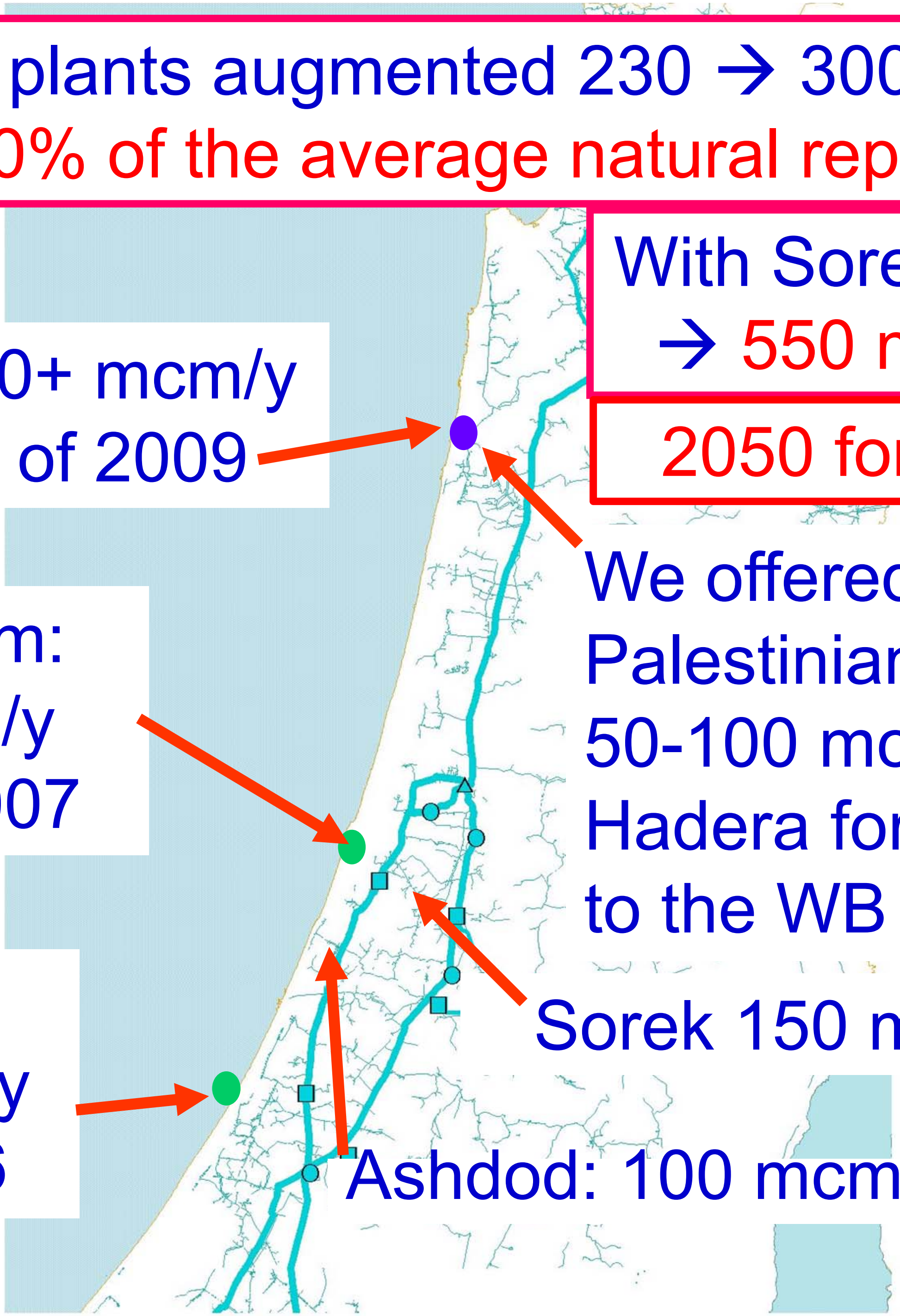


Easy to remember: ~ 60 →80 →100 m3/cap/year

Existing plants augmented 230 → 300 mcm/year
About 30% of the average natural replenishment

With Sorek and Ashdod
→ 550 mcm/y = 50%

2050 forecast: 1,700



Hadera: 100+ mcm/y
since end of 2009

We offered the Palestinians to locate a 50-100 mcm plant at Hadera for direct supply to the WB

Palmachim:
30+ mcm/y
since 6/2007

Sorek 150 mcm/y in 2013

Ashkelon:
100+ mcm/y
since 2006

Ashdod: 100 mcm/y in 2013

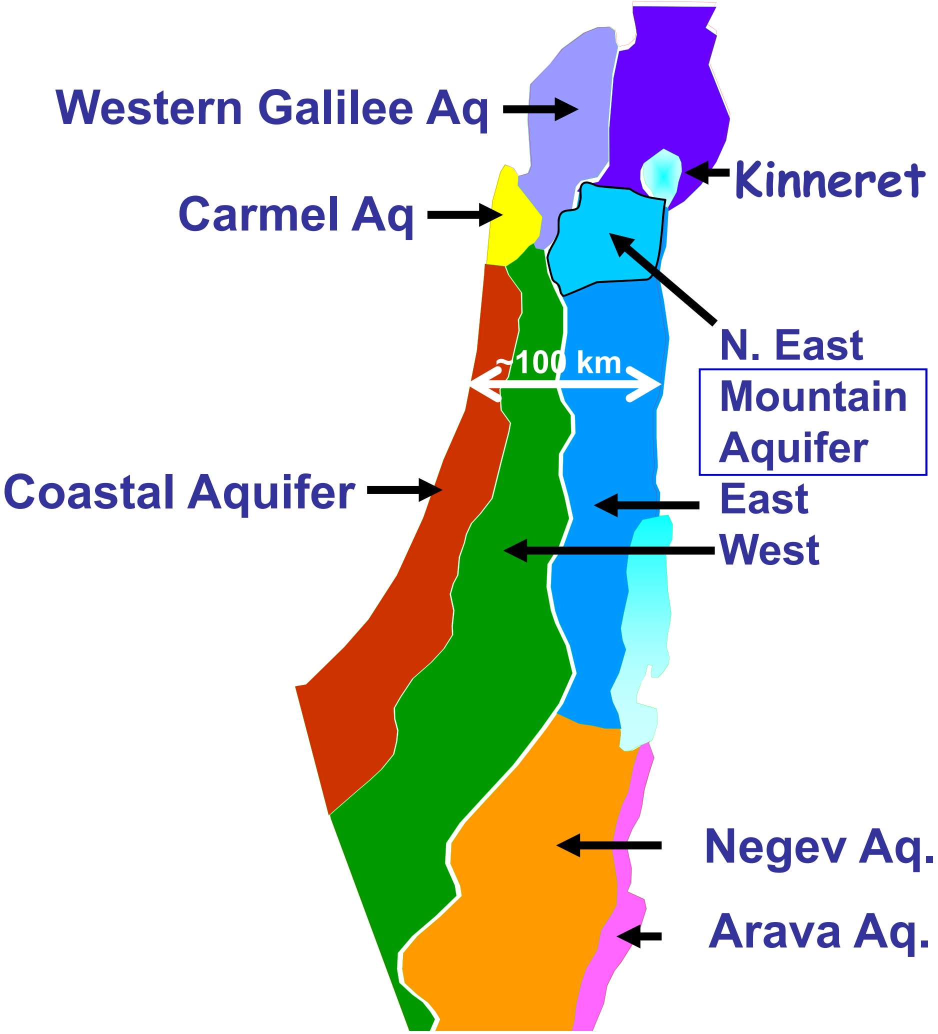
Some new developments in Optimization under Uncertainty

Based on the 2011 PhD of Mashor Housh

- Highly efficient solution of the deterministic model for solving (many) scenarios
- Efficient Stochastic programming, “wait and see” “here and now”, two-stage and Multi-stage (MSP)
- Limited Multi-stage Stochastic Programming (LMSP)
- Info-Gap model
- Robust Optimization: Robust Counterpart (RC), Affine Robust Counterpart (ARC), Affine Adjustable Robust Counterpart (AARC)

WATER SOURCES

Highly integrated national and regional water systems

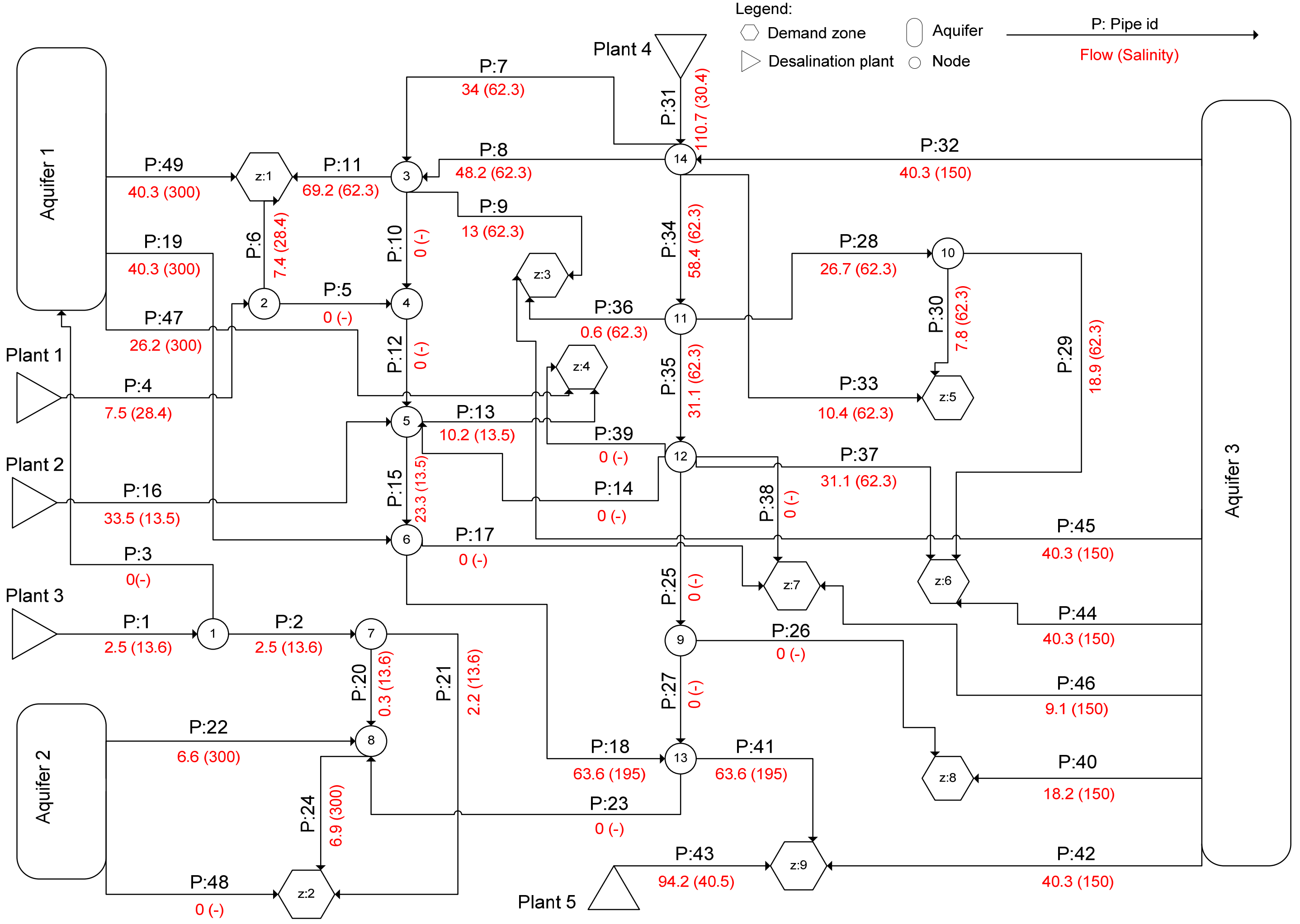


Average Annual Potential

~1,200 mcm/yr Israeli control

~1,700 mcm/yr whole area

WSS2: Central part of the INWSS



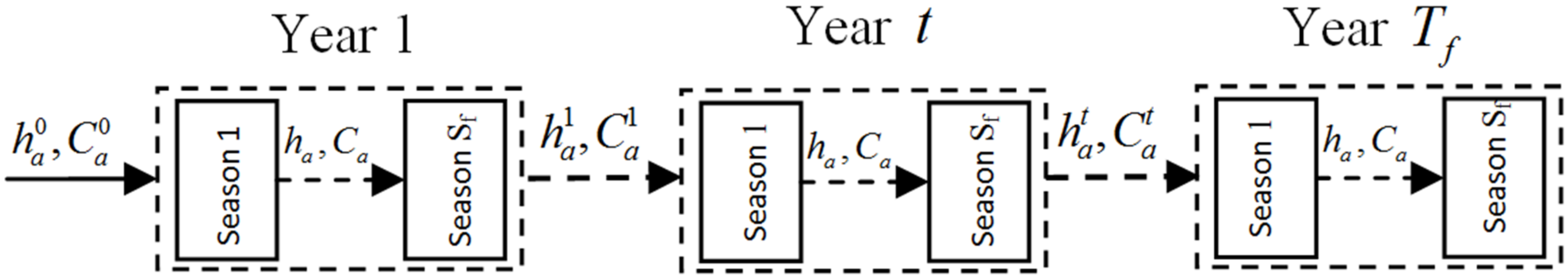
3 aquifers, 5 desalination plants, 9 consumer zones, 14 network nodes

Model Structure

- Minimum total cost
  - Desalination cost
  - Conveyance cost
  - Aquifers depletion penalty (sustainability)
- Constraints
  - Water and salt mass balance
  - Aquifer state equations for water and salt
  - Conveyance capacity in the network
  - Source capacities

Mathematical Model

- Building block: seasonal/annual model
- State variables linking the seasons and years (horizon ~10 years)
  - – Water level
  - – Water quality



Mathematical Model (cont’d)

Annual/seasonal model objective function:

Flow decision variables, quality decision variables and state variables

$$\sum_{S}\left(\underbrace{\sum_{p} coff_{1p}\cdot Q_{p}^{2.852}}_{Conveyance}+\underbrace{\sum_{a}(coff_{2a}\cdot h_{a}+coff_{3a})\cdot Q_{a}}_{Extraction}+\underbrace{\sum_{d}\left(coff_{4d}+\frac{1}{\left(C_{d}\right)^{Coff_{5d}}}\right)\cdot Q_{d}}_{Desalination}\right)$$

State equations:

$$h_{a}^{S}=\frac{R_{a}^{S}-Q_{a}^{S}}{SA_{a}}+h_{a}^{S-1}$$

$$C_{a}^{S}=\frac{1}{h_{a}^{S}}\left(\frac{\left(C_{R}\right)_{a}^{S}\cdot R_{a}^{S}-C_{a}^{S-1}\cdot Q_{a}^{S}}{SA_{a}}+C_{a}^{S-1}\cdot h_{a}^{S-1}\right)$$

h_{a}^{S} – Water Level State Variable

C_{a}^{S} – Water Quality State Variable

Mathematical Model (cont'd)

Annual/seasonal model constraints:

- Water and salinity balance:

$$A \cdot [Q_a, Q_d, Q_p, Q_z]^T = 0$$

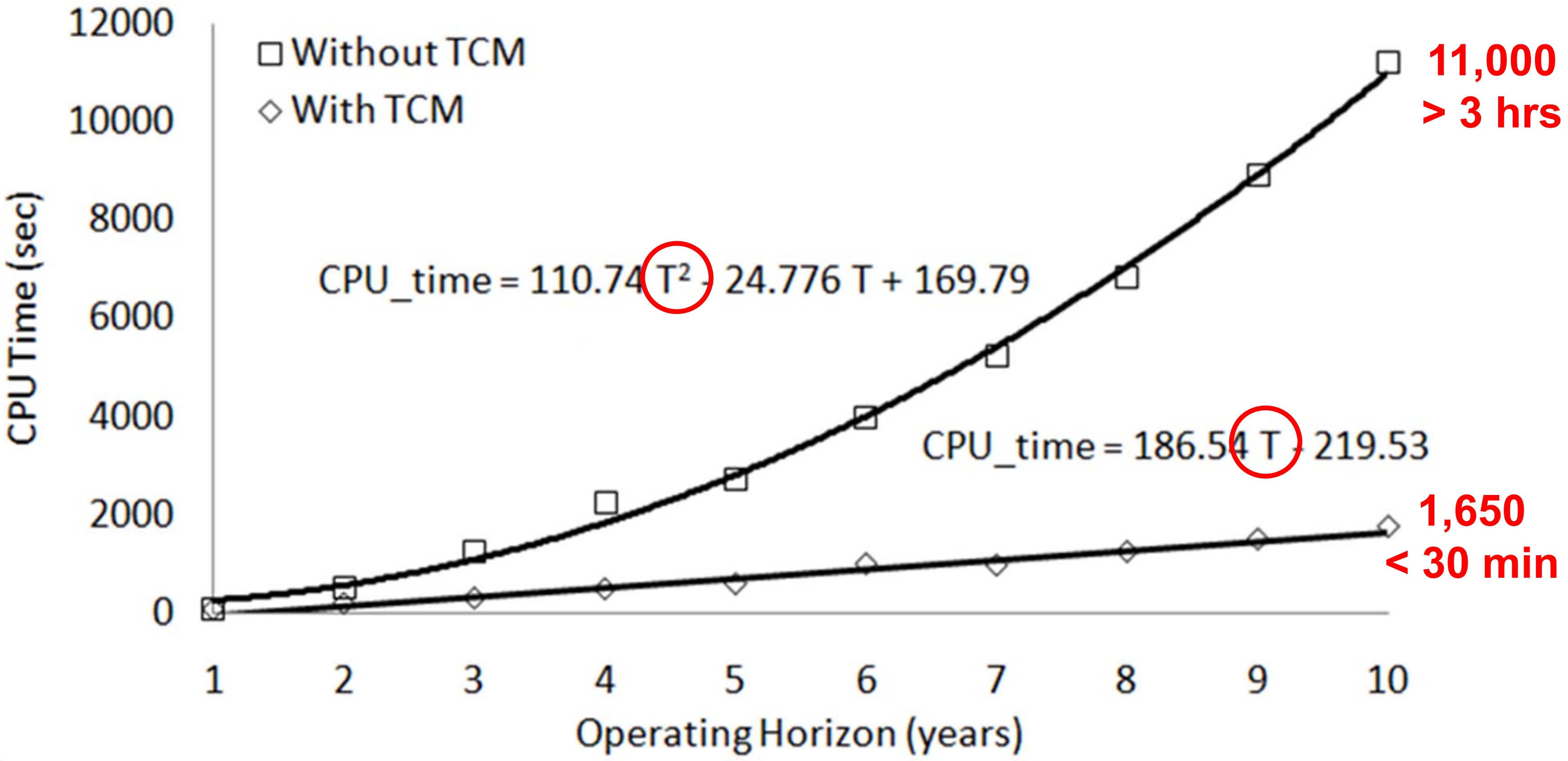
$$B \cdot [C_a, C_d, C_p, C_z]^T = 0$$

$$A \cdot [Q_a \cdot C_a, Q_d \cdot C_d, Q_p \cdot C_p, Q_z \cdot C_z]^T = 0$$

- Bounds on all the variables:

Flow variables, quality variables and state variables

The TCM Efficiency: WSS-2, 10-years



Mathematical formulation (LP)

$$\sum_{t=1}^{T_f}\left[\sum_{d} des_{d,t}\cdot Q_{d,t}+\sum_{l} C_{l,t}\cdot Q_{l,t}\right]+\sum_{a}\left[(\hat{h}_a-h_{a,T_f})\cdot E_a\right]\to \min$$

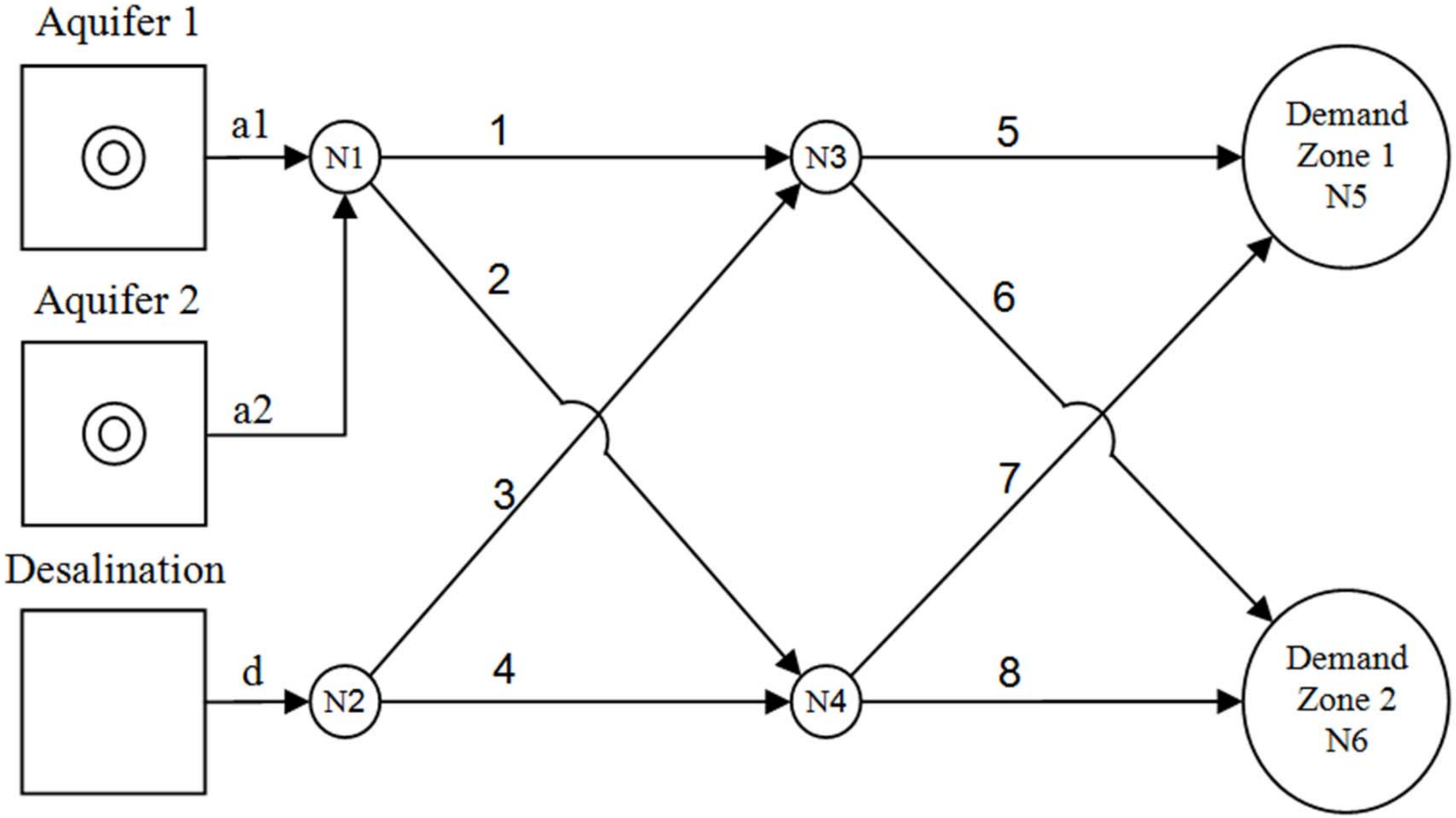
Subject to

$$\left.\begin{aligned}
&G\cdot Q_t=S_t\\
&h_{a,t}=h_{a,0}+\frac{1}{SA_a}\left(\sum_{i=1}^{t}\overset{\substack{\text{Uncertain}\\ \downarrow}}{R_{a,i}}-\sum_{i=1}^{t}Q_{a,i}\right)\\
&h_{a,t}^{\min}\le h_{a,t}\le h_{a,t}^{\max}\\
&Q_t^{\min}\le Q_t\le Q_t^{\max}
\end{aligned}\right\}\forall t\forall a$$

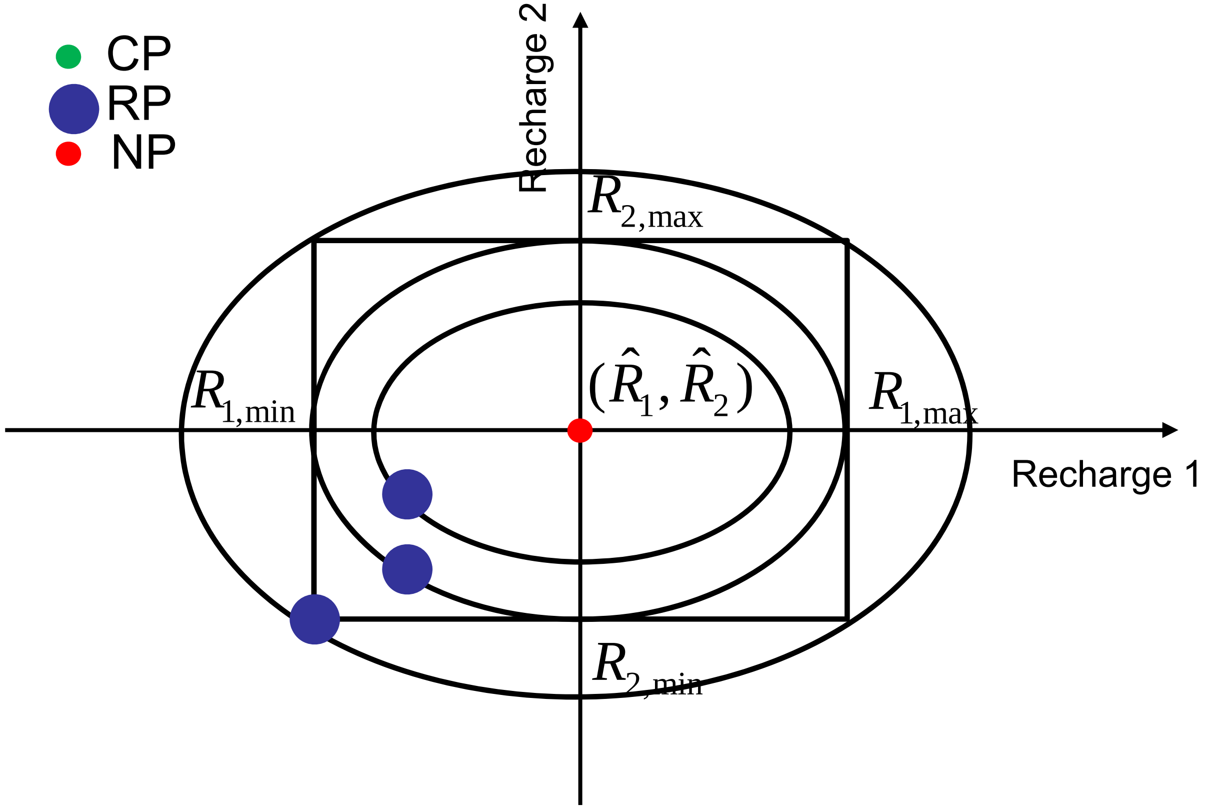
Robust Optimization

- NP: one point selected in the uncertain domain
- CP: “worst case“ in the uncertainty domain
- Robust Policy (RP): ellipsoidal uncertainty set → the solution remains feasible for any realization of the uncertain variables within the uncertainty set
- Ellipsoidal = it is assumed that the “worst case” (all variables at their worst value) has very low (even zero) probability and is excluded from the uncertainty set

WSS1: For development & demo

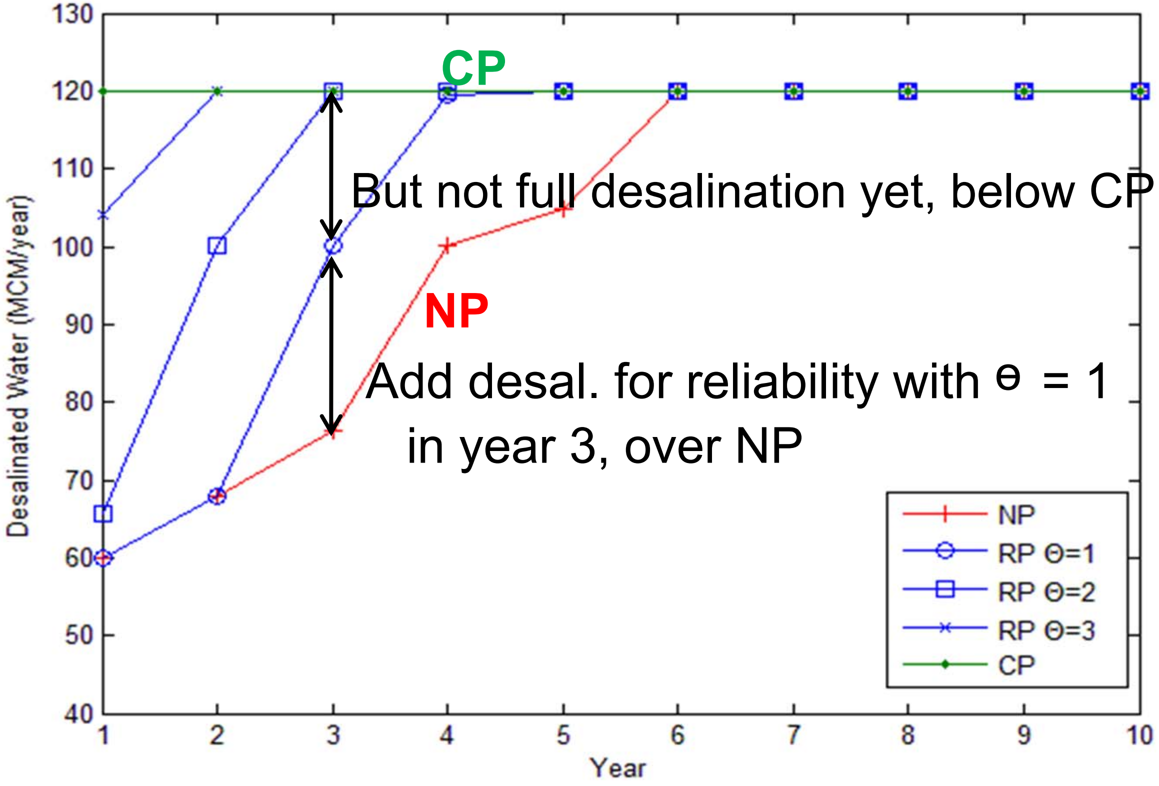


Controlling Conservativeness



- Simultaneous worst case (CP) is outside the ellipsoidal uncertainty set
- The size of the ellipse is set by a user defined parameter

Results: Development of Desalination



CP

But not full desalination yet, below CP

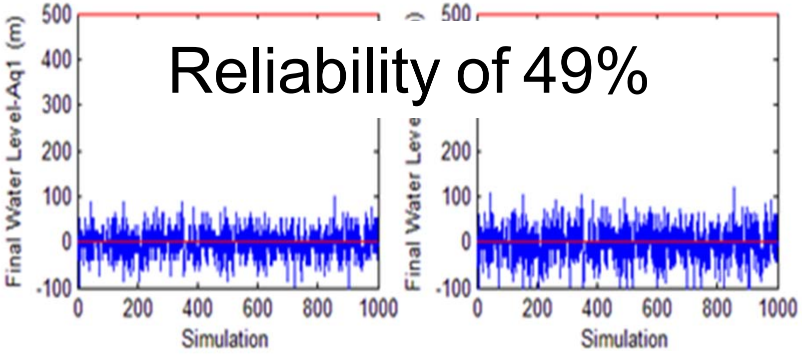
NP

Add desal. for reliability with θ = 1
in year 3, over NP

RP vs. NP by 1,000 simulations

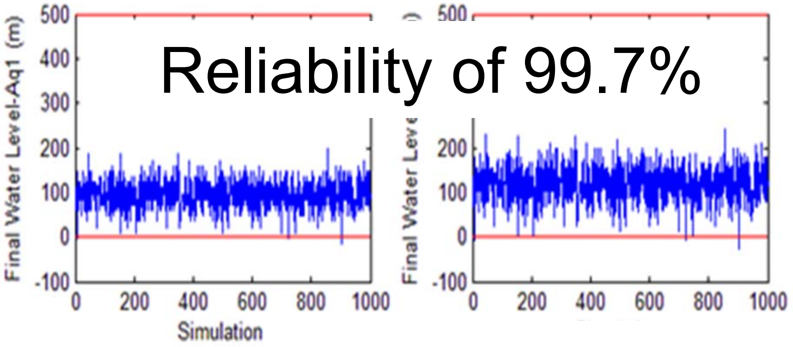
Final levels in the aquifers

Nominal solution



Reliability of 49%

Robust solution $\theta = 3$

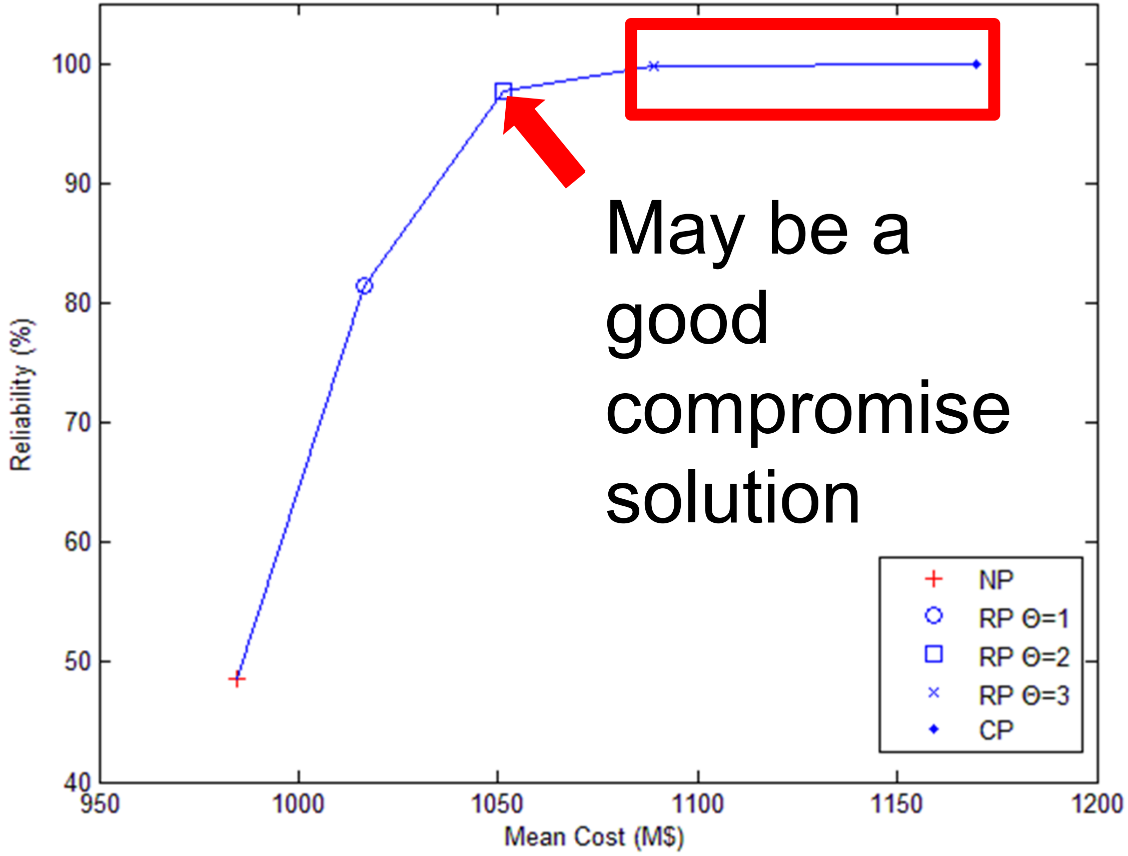


Reliability of 99.7%

Cost including penalty

$$\text{Price of Robustness} = 2.05 \frac{\text{M\$}}{1\% \text{ reliability}}$$

Reliability vs. Mean Cost



May be a good compromise solution

Is it justified to add 80.5 M$ for 0.3 % reliability?

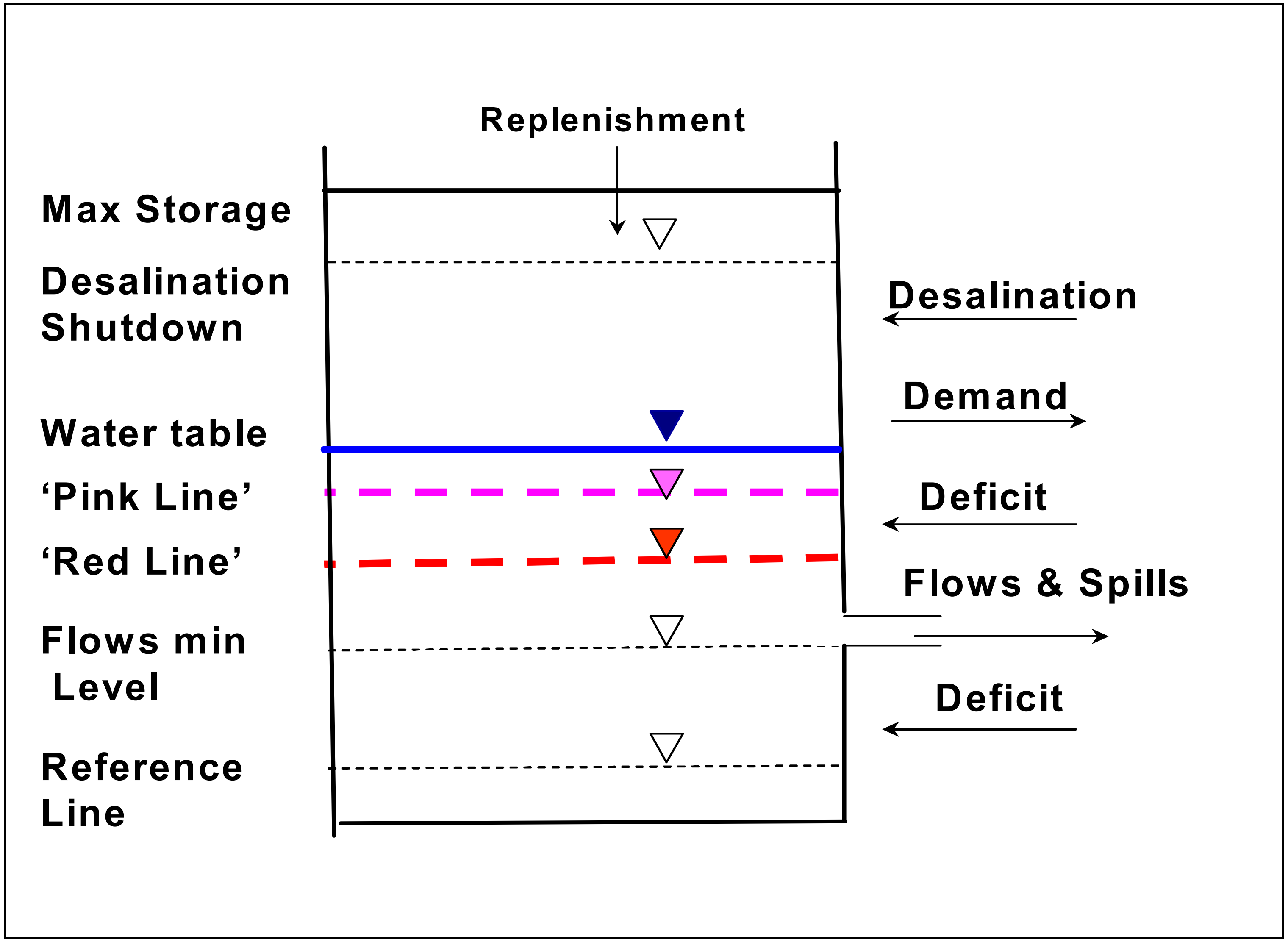
Robust Optimization

- No PDF assumptions
- No scenarios assumptions
- Subjective reliability parameter
- Only convex mathematical models

- Rolling Horizon: first year’s decisions are implemented, and the model is run again when there are new data (hydrology, demands, costs, benefits, additional system components ...), e.g., next year
- This “rolling horizon” can also be simulated

2012 Master Plan for the Israeli National Water Sector:

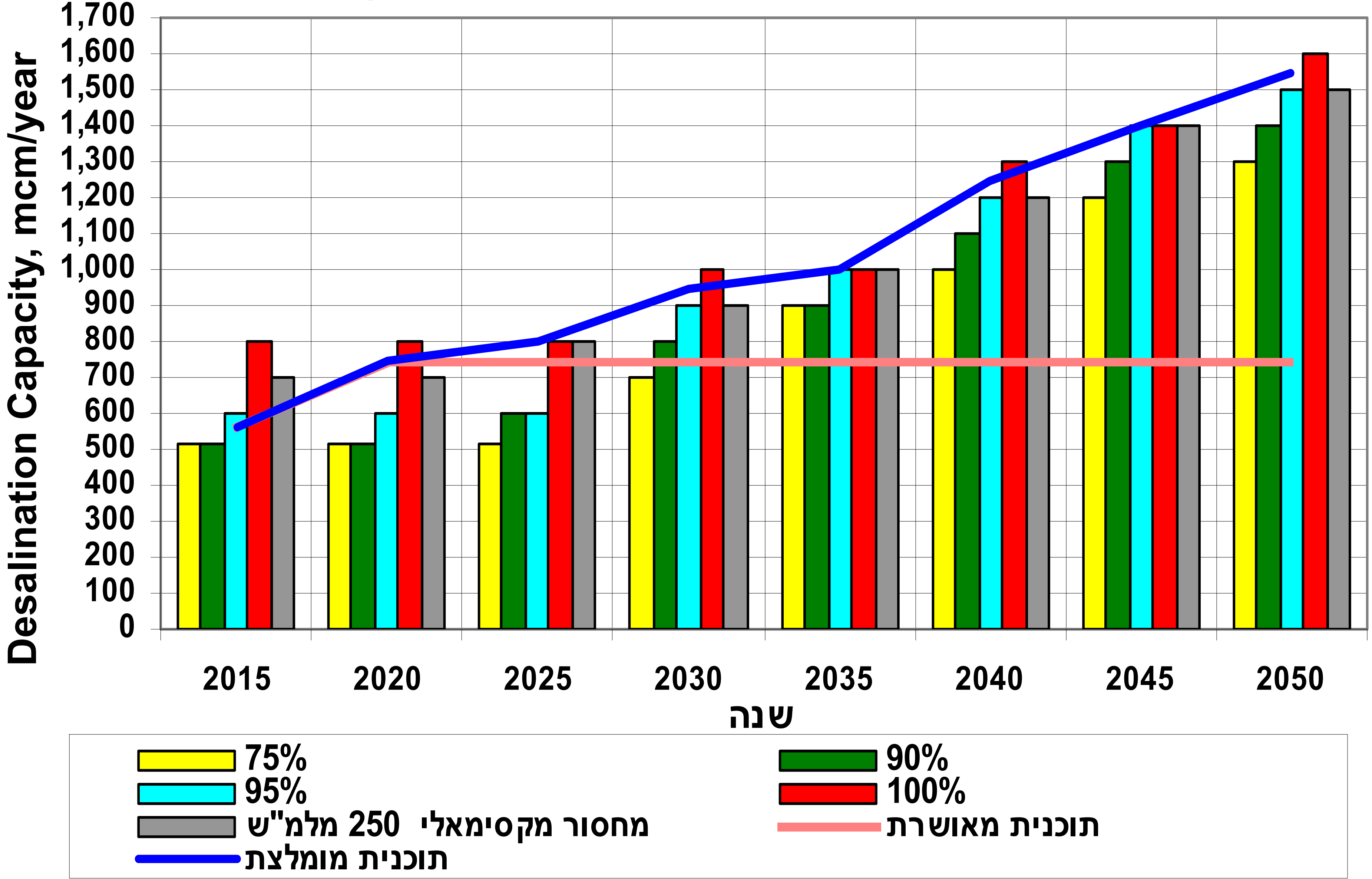
Use of an Aggregate Model of the System



Simulation with this Model

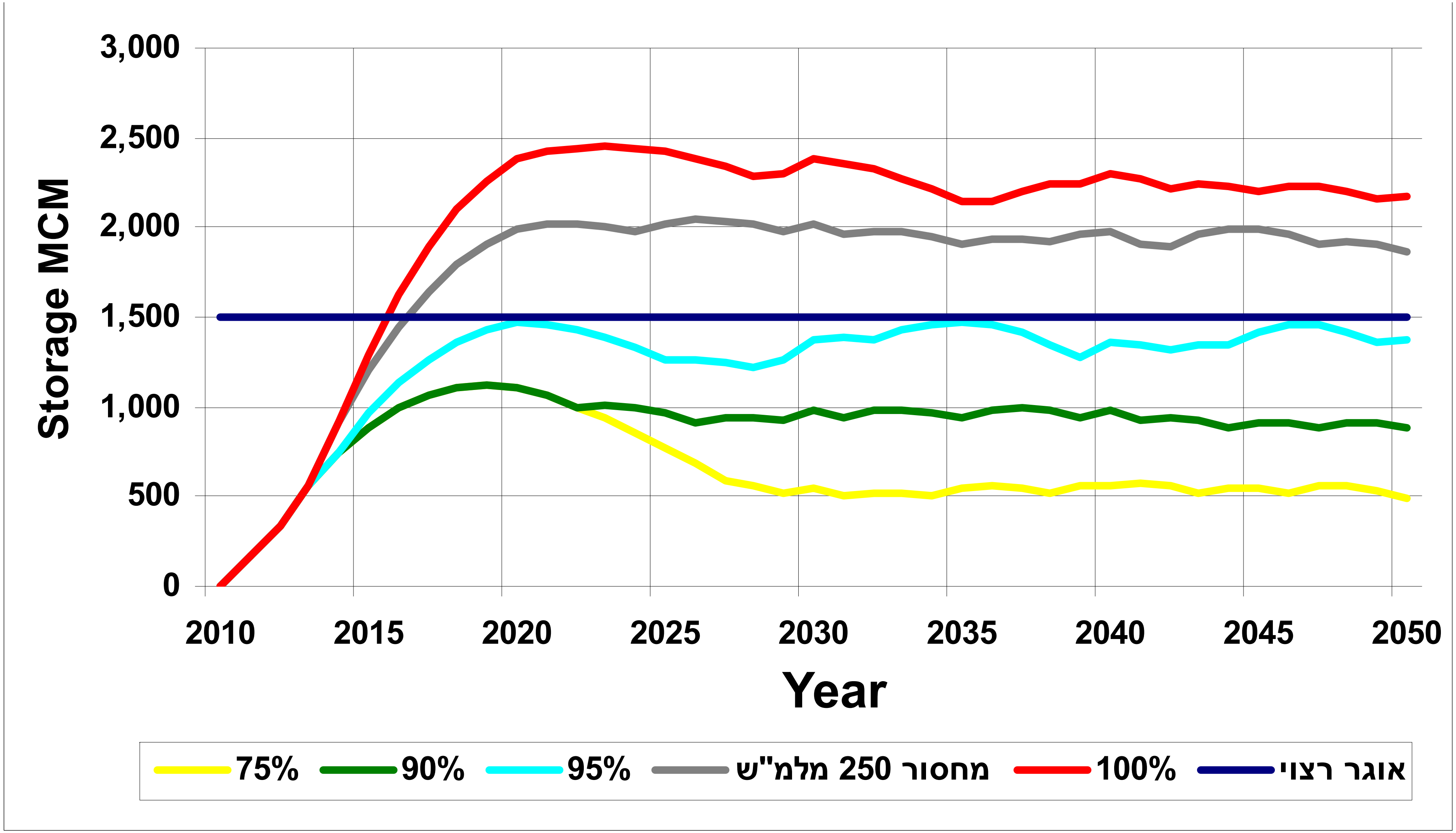
- Historical recharge data, “recycled” around itself: each run begins with a different year (with wrap-around) and serial structure is maintained
- Demand and other supply side variables (but not desalination) are sampled from continuous or discrete distribution
- Storage and spills are tracked by the model
- Calculated = gap between demand and natural recharge, which is to be closed by desalination
- Adjust the desalination capacity at decadal intervals to achieve different prescribed reliabilities

Desalination Capacity Development, as function of Required Reliability



* נבחנה על בסיס תרחישים שהוגדרו

Expected value of storage above “Red Lines”, as a function of Reliability With the Recommended Desalination Capacity Development Plan



Conclusions

- It takes a long time to go from theory to practice
- It is very difficult to convey to DMs and to the public the true meaning of uncertainty and how the information can and should be used in making actual decisions
- While the problems of WRMuU may no have changed over time (probably exacerbated!) methodologies have evolved and have a better chance of finding application in the real world
- WRM analysts must continue to develop skills for communicating with DMs and the public

Thanks

To the many students, colleagues and DMs with whom I have had the privilege and pleasure of working in research, development and implementation of WRM theory and practice, in the past 45 years

To Peter and Karel for organizing this important and useful meeting

And to you for your attention