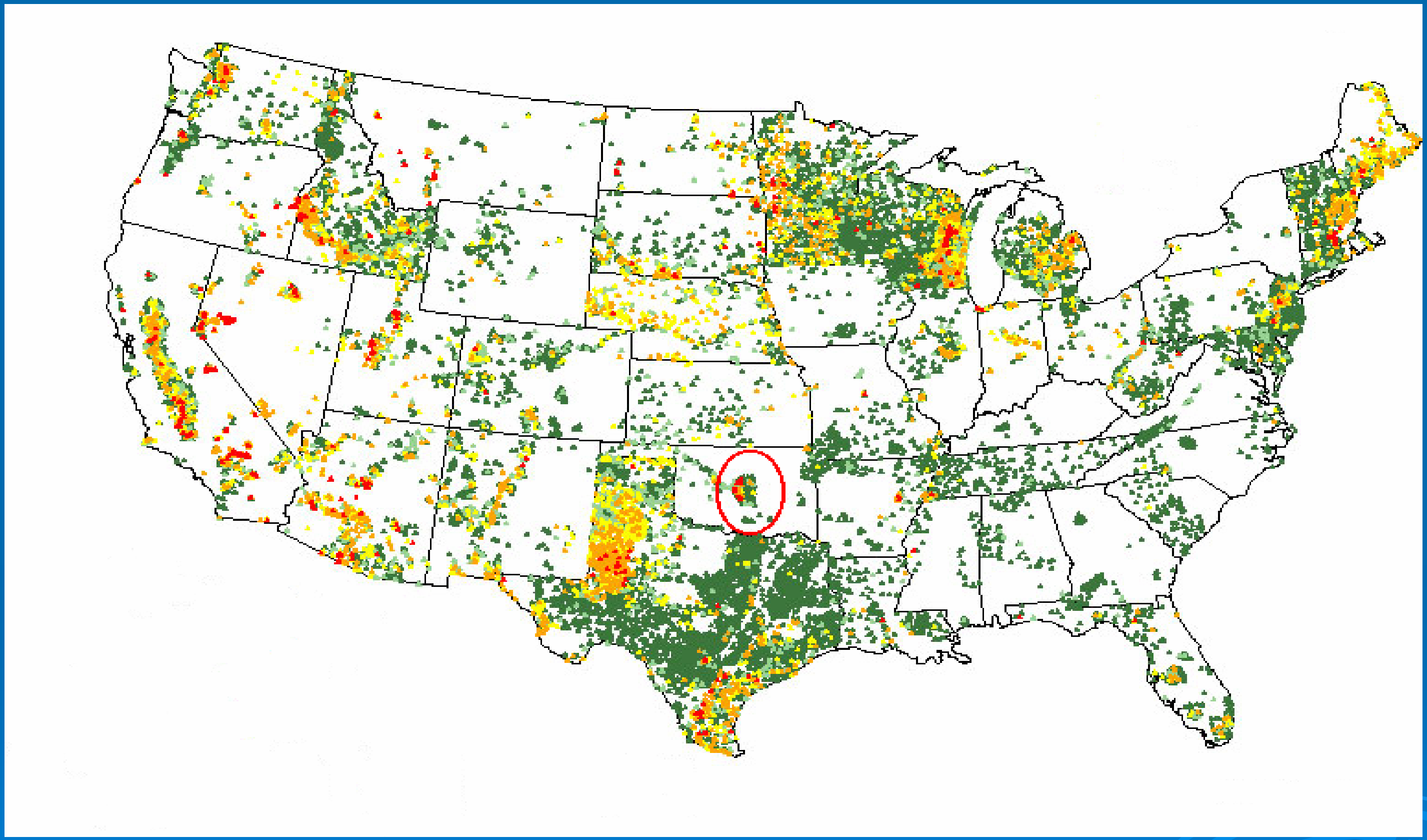
Arsenic Removal from OU Water



Sami Karam Randy Goll Ross Chaffin Roman Voronov

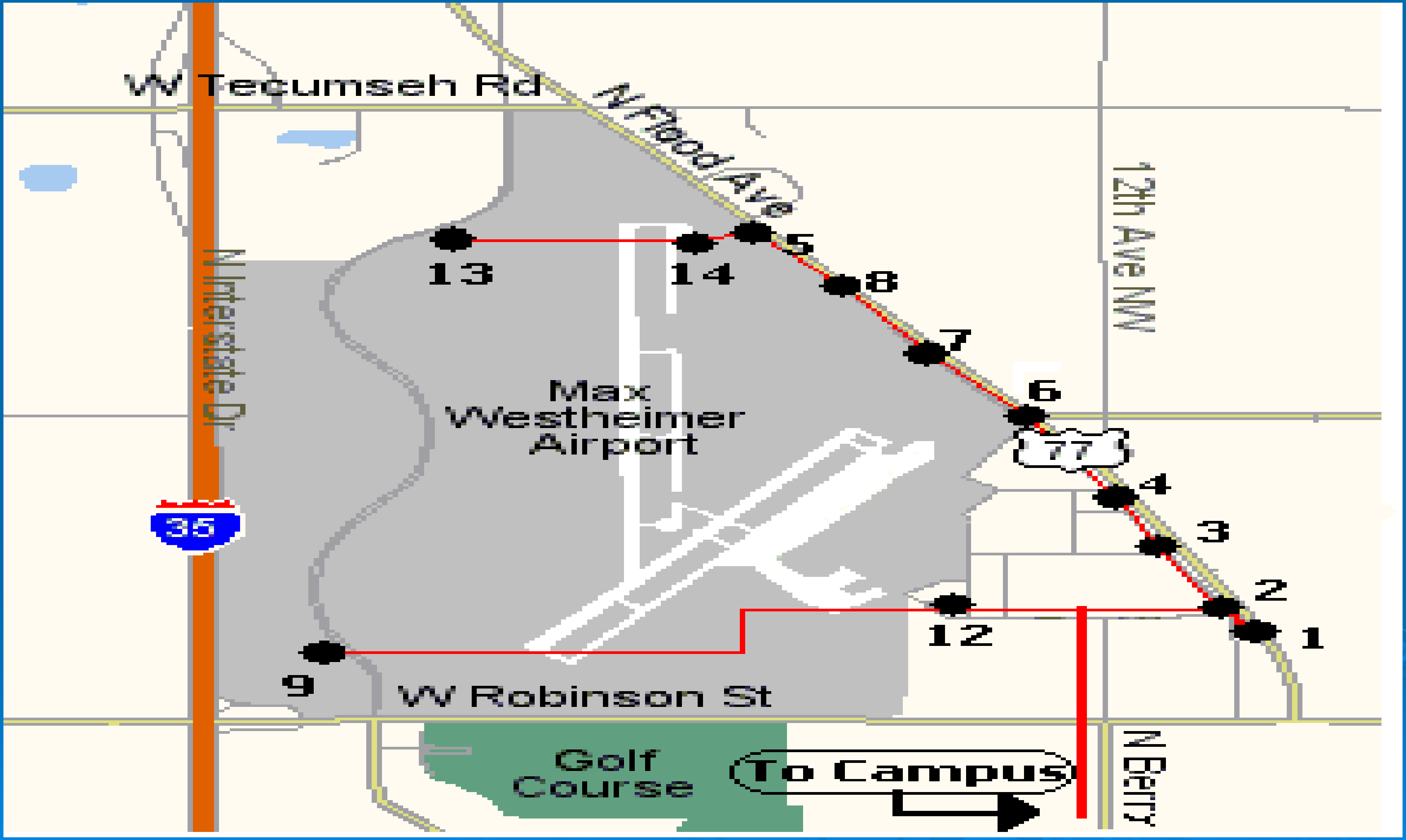
OBJECTIVES

- To find an economical solution to the Arsenic problem on the OU campus
- To make the OU campus self-sufficient and compliant with the new 2006 EPA rule of ***10 ppb*** instead of ***50 ppb*** As. minimum

EFFECTS of ARSENIC

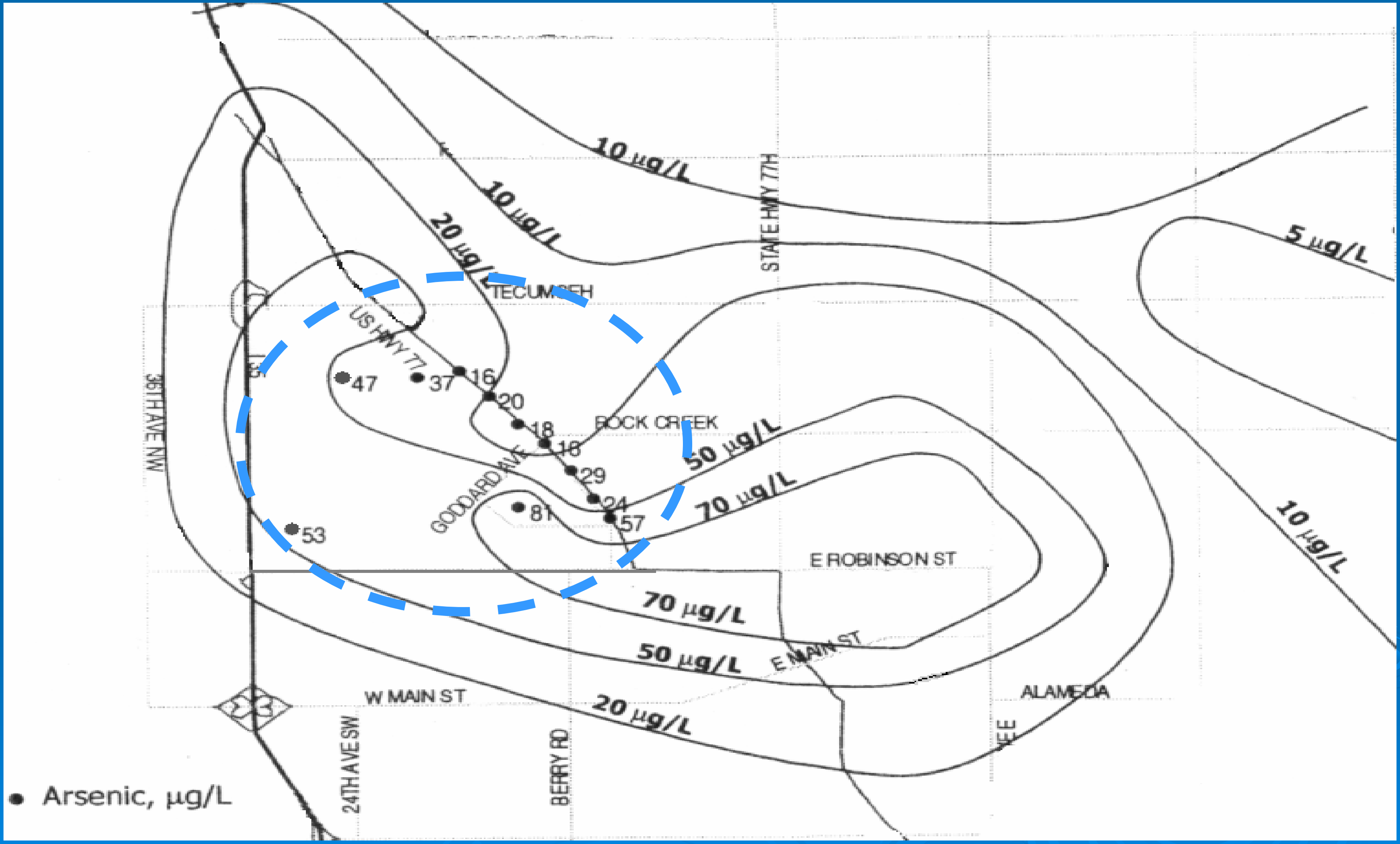
- Skin alterations and lesions
- Repeated exposure may lead to cancerous mutations
- Nervous & Vascular system degenerative diseases

GEOGRAPHY



W Tecumseh Rd
N Flood Ave
12th Ave NW
N Interstate Dr
35
Max Westheimer Airport
77
13
14
5
8
7
6
4
3
2
1
12
9
W Robinson St
Golf Course
To Campus
N Berry

GEOLOGY


10 µg/L
10 µg/L
20 µg/L
5 µg/L
STATE HWY 77H
TECUMSEH
US HWY 77
47
37
16
20
18
18
29
24
57
81
53
ROCK CREEK
50 µg/L
70 µg/L
GODDARD AVE
36TH AVE NW
E ROBINSON ST
70 µg/L
50 µg/L
E MAIN ST
10 µg/L
W MAIN ST
20 µg/L
ALAMEDA
24TH AVE SW
BERRY RD
Arsenic, µg/L

Well Data

➢ Average pH	~8.97
➢ Sulfate content	40 ~ 55 mg/liter
➢ Arsenic	35 ~ 45 ppb

OU Situation

- Max production capacity: $1.8 \times 10^6\ gallons\ /\ day$
- Average daily usage: $1.1 \times 10^6\ gallons\ /\ day$
- Peaks around August @ $2.0 \times 10^6\ gallons / day$
- Projected growth over 20yrs: $25\ \%$

Previous Solutions and Available Options

Previous Studies

- **CH2M-Hill**: Colorado based consulting company (development, environmental solutions, design…)

→ **CH2M Hill Considered OU & the City of Norman as one problem**

- **CE 5244**: Class project to find optimal solution

CH2M-Hill Report

Options

- Drill new wells
- Coagulation/Filtration
- Ion Exchange
- Nanofiltration
- Blending water

CE 5244 Recommendations April 2001

- Recommended reconfiguration, blending and Ion Exchange for Norman

- Recommended C/F for OU

Water Purchase Option

- OU buys water from City of Norman exclusively
- Cost between $0.85/1000 gallons and $1.14/1000 gallons of water
- Least work for OU
- May not be most economical option, lots of parameters

Nanofiltration

- Uses membrane separation
- Differences in pressure cause water to separate into 2 streams
- Very large waste stream (>35%)
- Membranes have high capital cost

Coagulation/Filtration

- $FeCl_3$ is added to water
- Precipitates $Fe(OH)_3$
- Arsenic adsorbs to Fe(OH)
- FeOH is filtered from the water
- Fair amount of waste

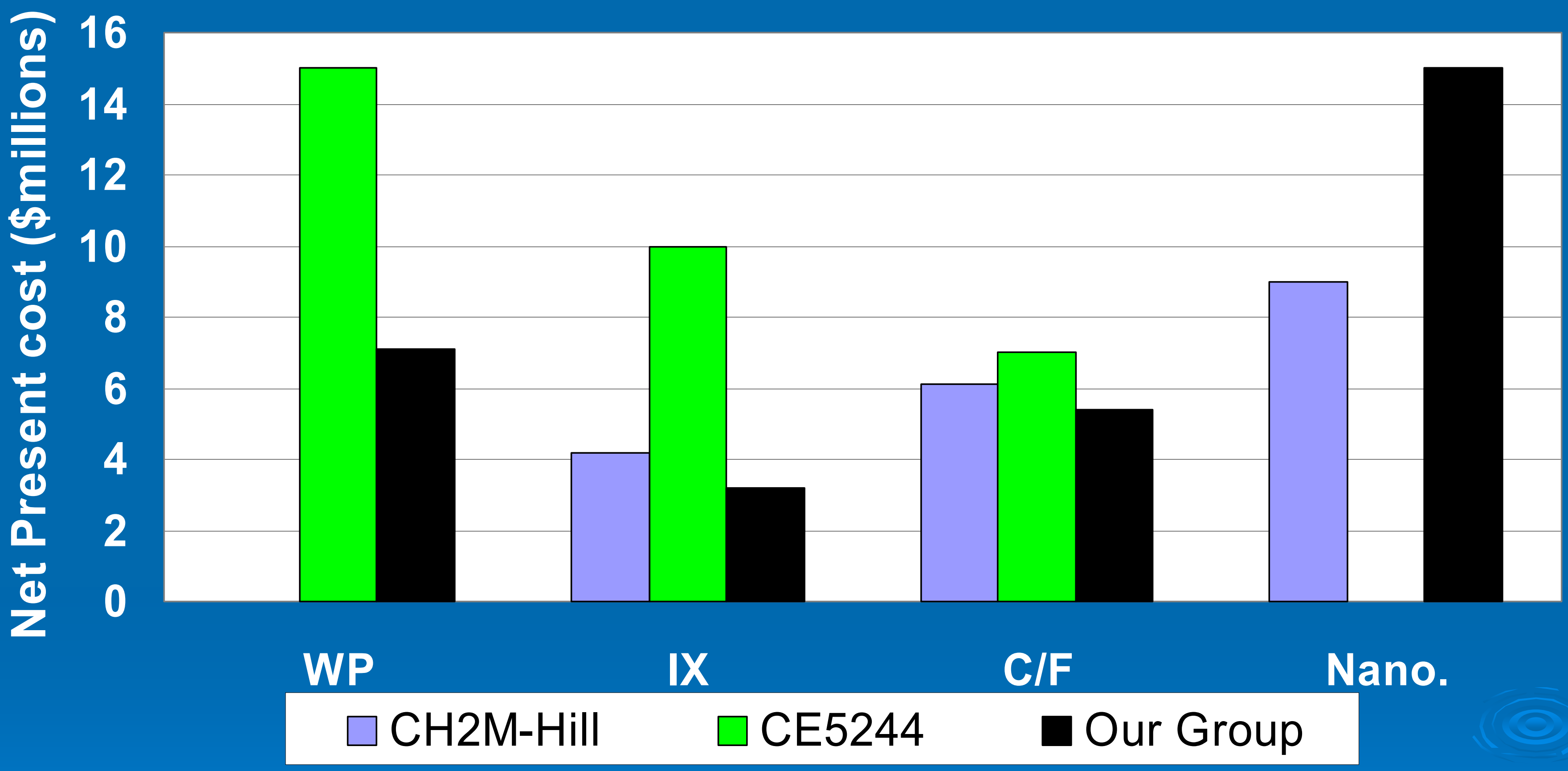
Ion Exchange

- Water run through bed of resin
- Arsenic ions exchange with chloride
- Resin bed is regenerated by brine
- Very low capital cost!!!
- Very low operating cost!!!

Annual and Capital Costs

	Capital Costs	NPC (after 20 years)
Nanofiltration	over $10,000,000	over $10,000,000
Coagulation/Filtration	$3,400,000	$5,700,000
Water Purchase ($1.14/1000 gal)	None	$5,565,000
Water Purchase ($0.85/1000 gal)	None	$4,150,000
Ion Exchange	$1,870,000	$3,600,000

Solutions Comparison



WP: Water Purchase, IX: Ion Exchange, C/F: Coagulation Filtration

Nano: Nanofiltration

Preliminary Conclusion

- <u>**Ion Exchange**</u> most ideal solution!!!

<u>**WHY?**</u>

- ✓ **Economically Attractive**
- ✓ **Self Sufficiency**
- ✓ **Immediate Implementation**

ARSENIC & ION EXCHANGE CHEMISTRY

Arsenic Chemistry

- Arsenic (III)
  - -Non ionic form (H_3AsO_3)
  - -Arsenite
- Arsenic (V)
  - -Ionic form ($HAsO_4^{2-}$)
  - -Arsenate

Arsenic/IX Chemistry

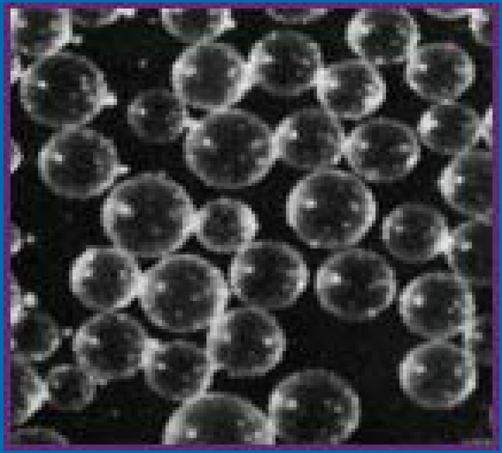
- Arsenite → Arsenate

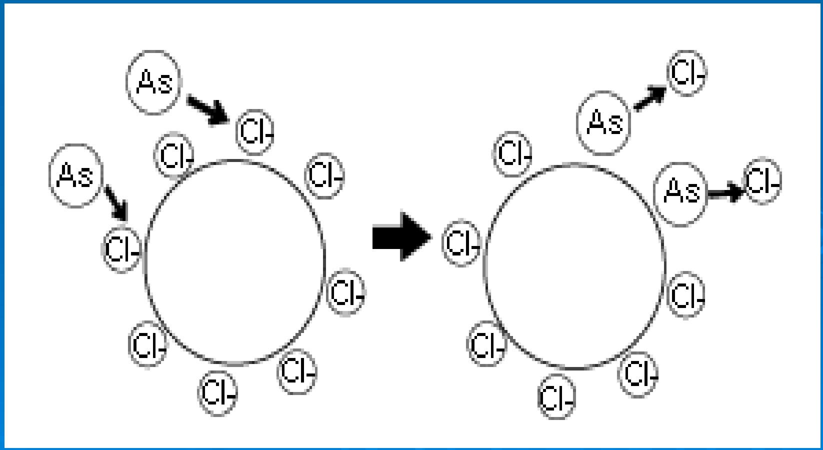
  -Sodium Hypochlorite pre-treatment

- Arsenate ion trades places with Chloride ion.

  - Resin has higher selectivity to sulfate.

- Bed causes pH to go down.





Arsenic/IX Chemistry

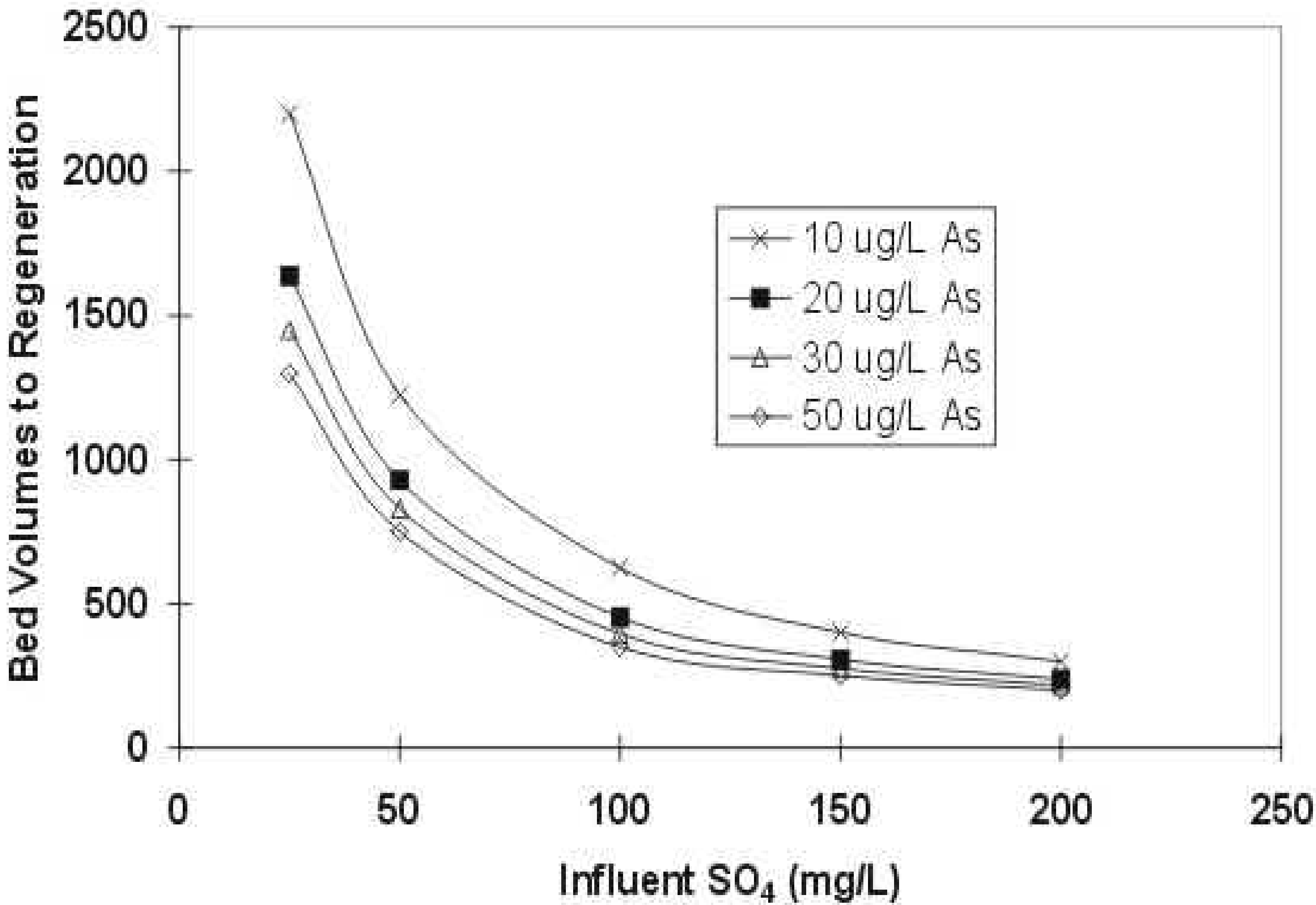
- Regeneration by Concentrated NaCl
  -Le Chatelier's Principle

- Arsenate goes to precipitation tank.

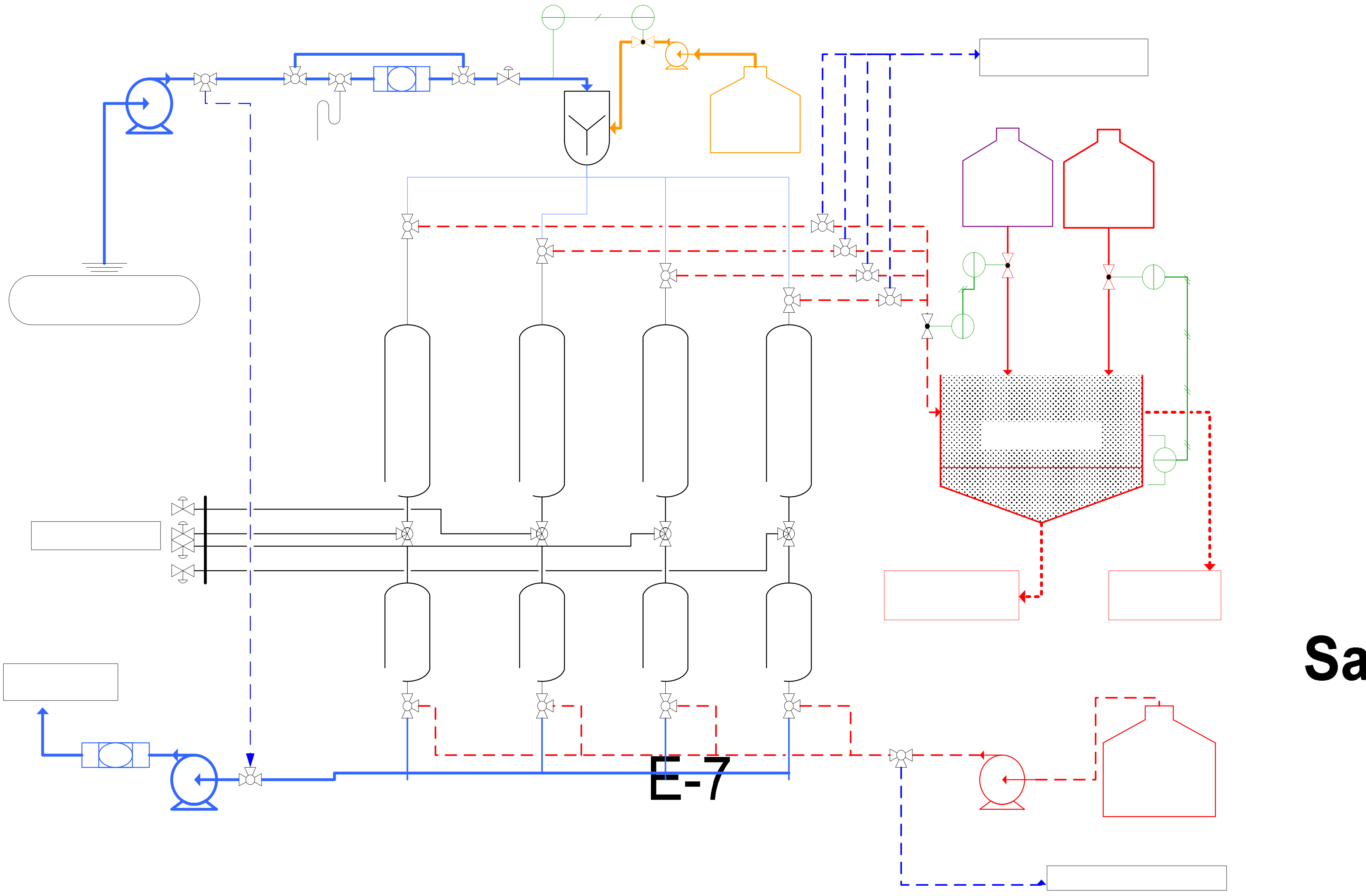
- pH lowered by H_2SO_4

- $FeCl_3$ added to precipitation tank to precipitate $Fe(OH)_3$

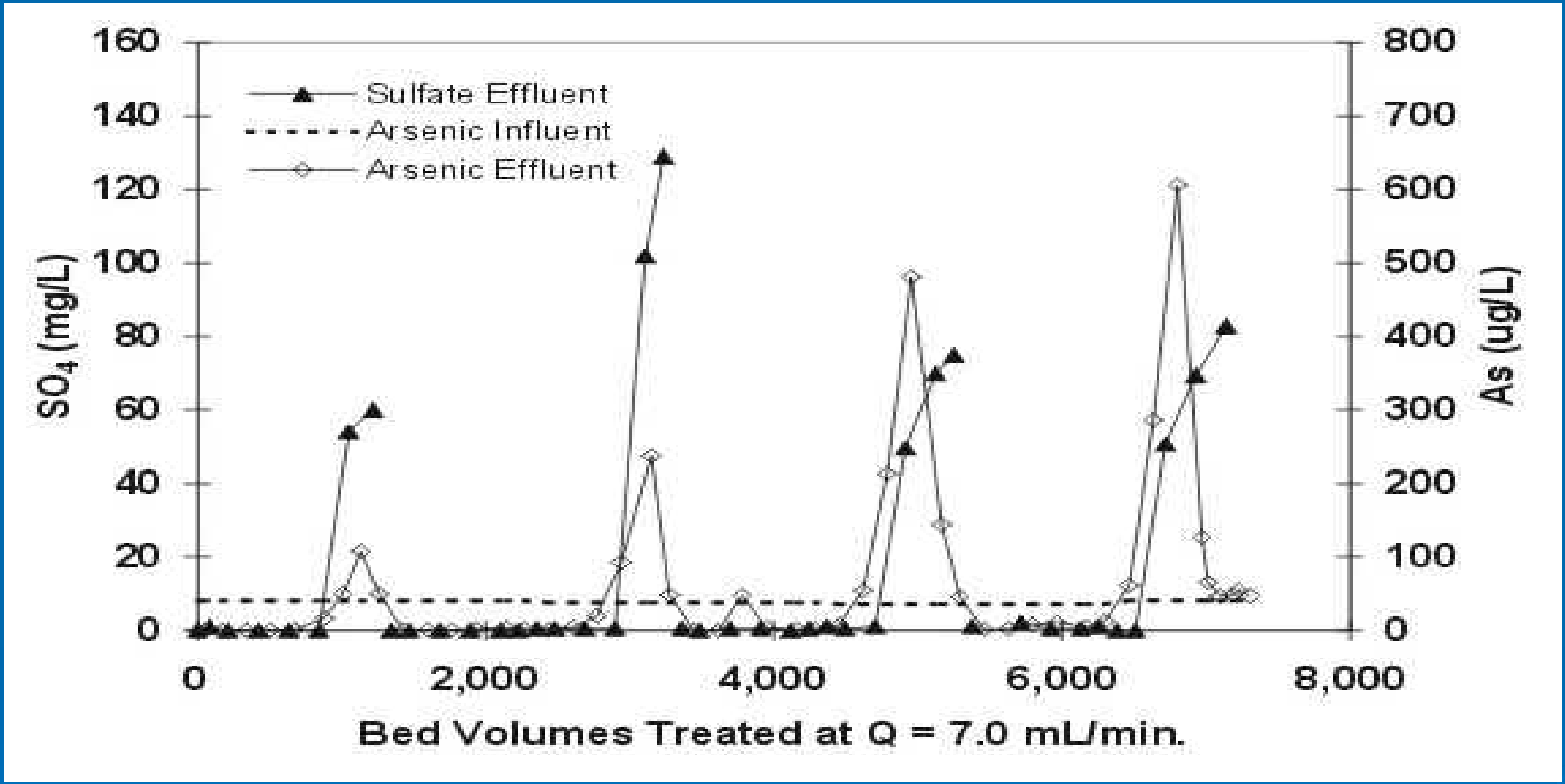
ION EXCHANGE PROCESS



Bed Volumes to Regeneration
2500
2000
1500
1000
500
0
0
50
100
150
200
250
Influent SO4 (mg/L)
10 ug/L As
20 ug/L As
30 ug/L As
50 ug/L As


E-7
Sa

Safety

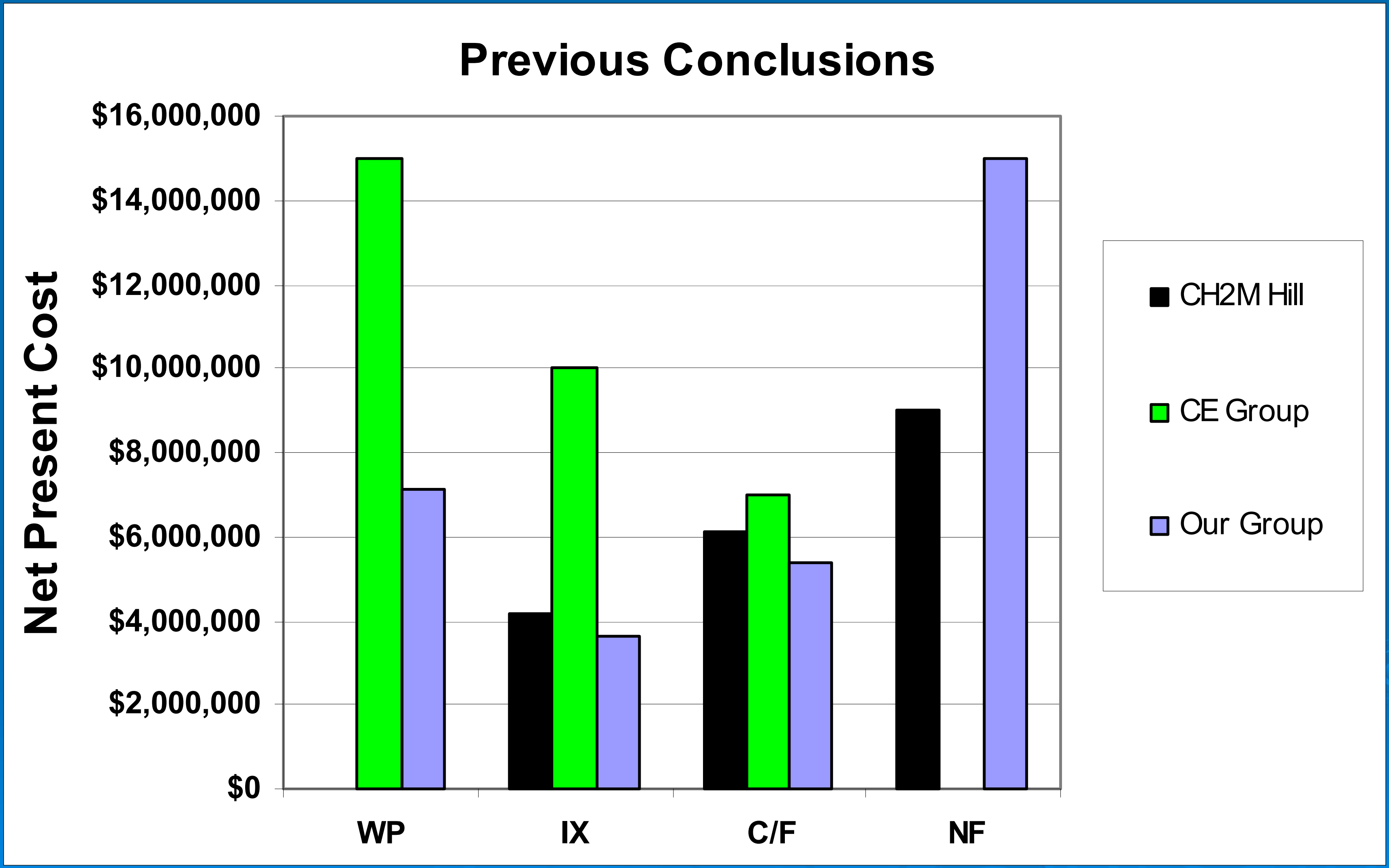


- Process must be designed so that arsenic is not allowed to breakthrough.

Economic Evaluation

(IX vs WP options)

Preliminary Findings



WP: water purchase, IX: Ion Exchange, C/F: Coagulation Filtration, NF: Nanofiltration

Ion Exchange Plant Calculation

- Assume Constant Demand of 1.1 MGD
- CI = $2.1 million (based on capacity)
- OC = $110,000/year (labor, power, and chemical)
- Project Lifetime =20yrs

Calculate NPC!

Water Purchase Calculation

- Assume Constant Demand of 1.1 MGD

- Constant Water Price = $1.14/1000gal

→Low Estimate!

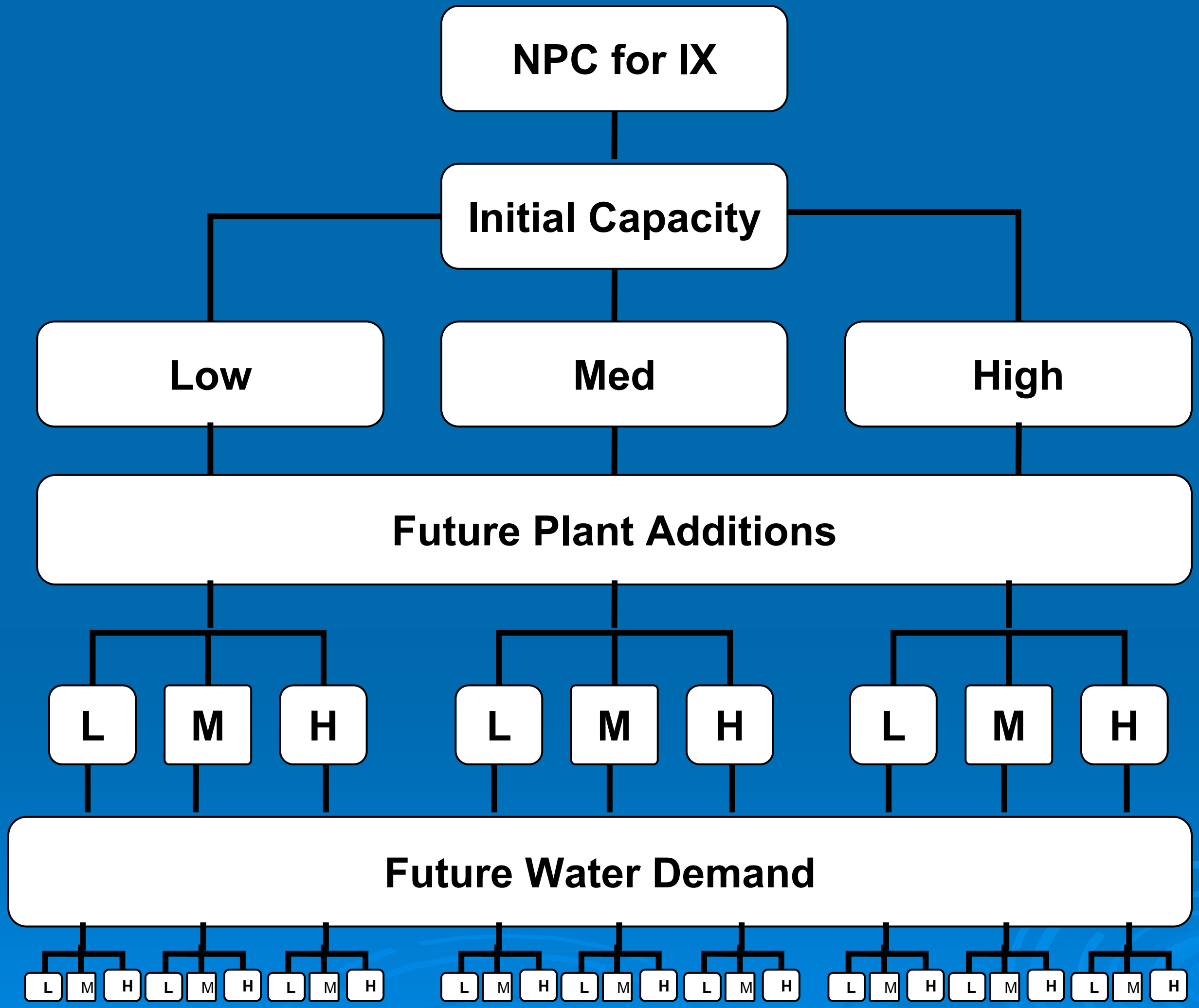
- Project Lifetime = 20yrs

Calculate NPC

Sources of Uncertainty

- Several Unknown Factors in Design:
  - Future Water Price
  - Future Water Demand
  - Initial Plant Capacity
  - Unforeseen Changes In Well-field
  - Later Additions To Existing Plant

Calculation Complexity



Mathematical Model Description

<u>Purpose</u> – Simulate OU As situation

<u>Goal</u> – Cheapest Solution

(by minimizing NPC)

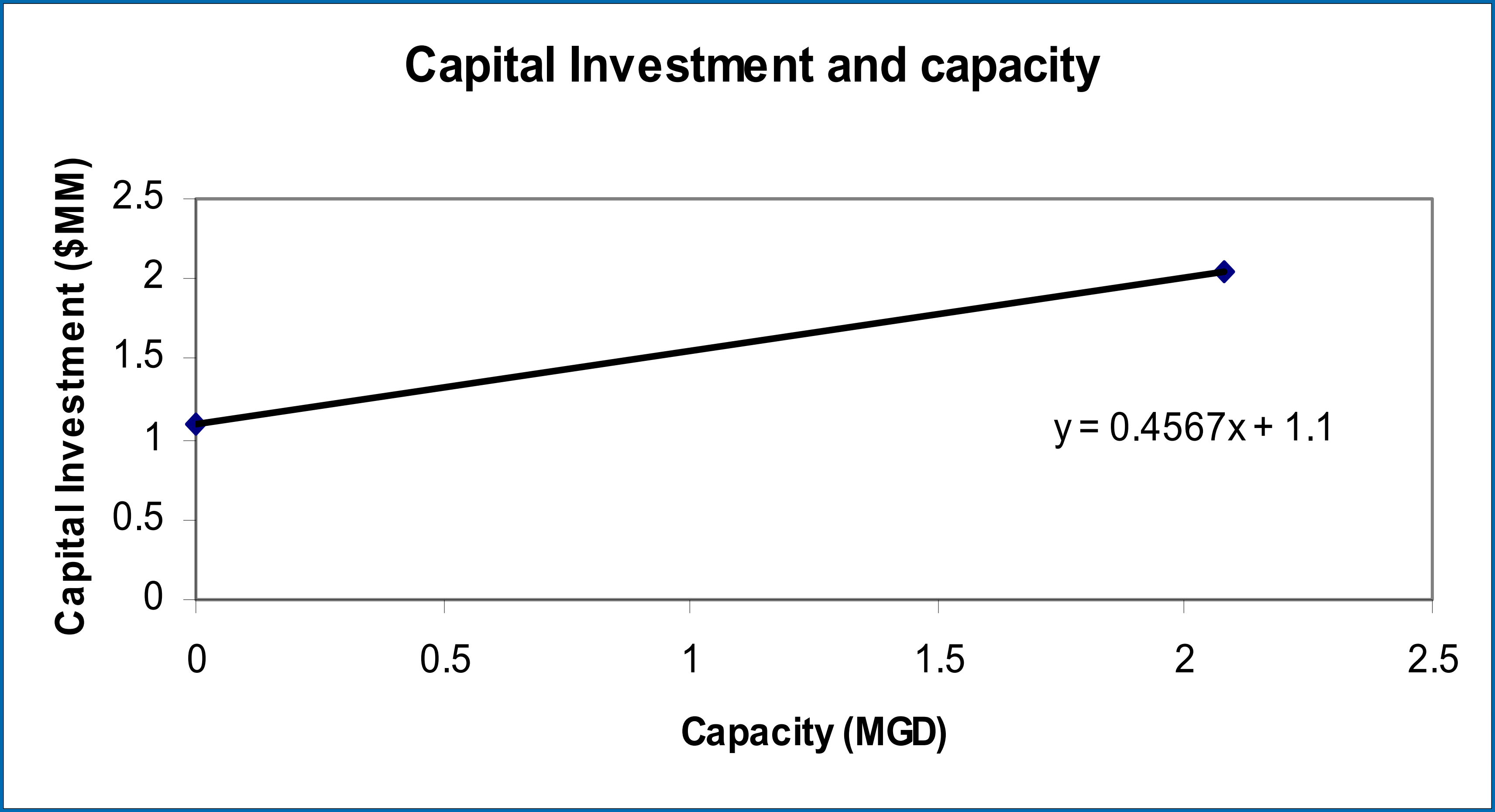
- Chooses between IX or WP
- Meets Water Demand
- Decides When/How Much to Build
- Expands Capacity As Needed
- Buys Wholesale or Emergency
- Borrows/Repays Money

Mathematical Model Parameters

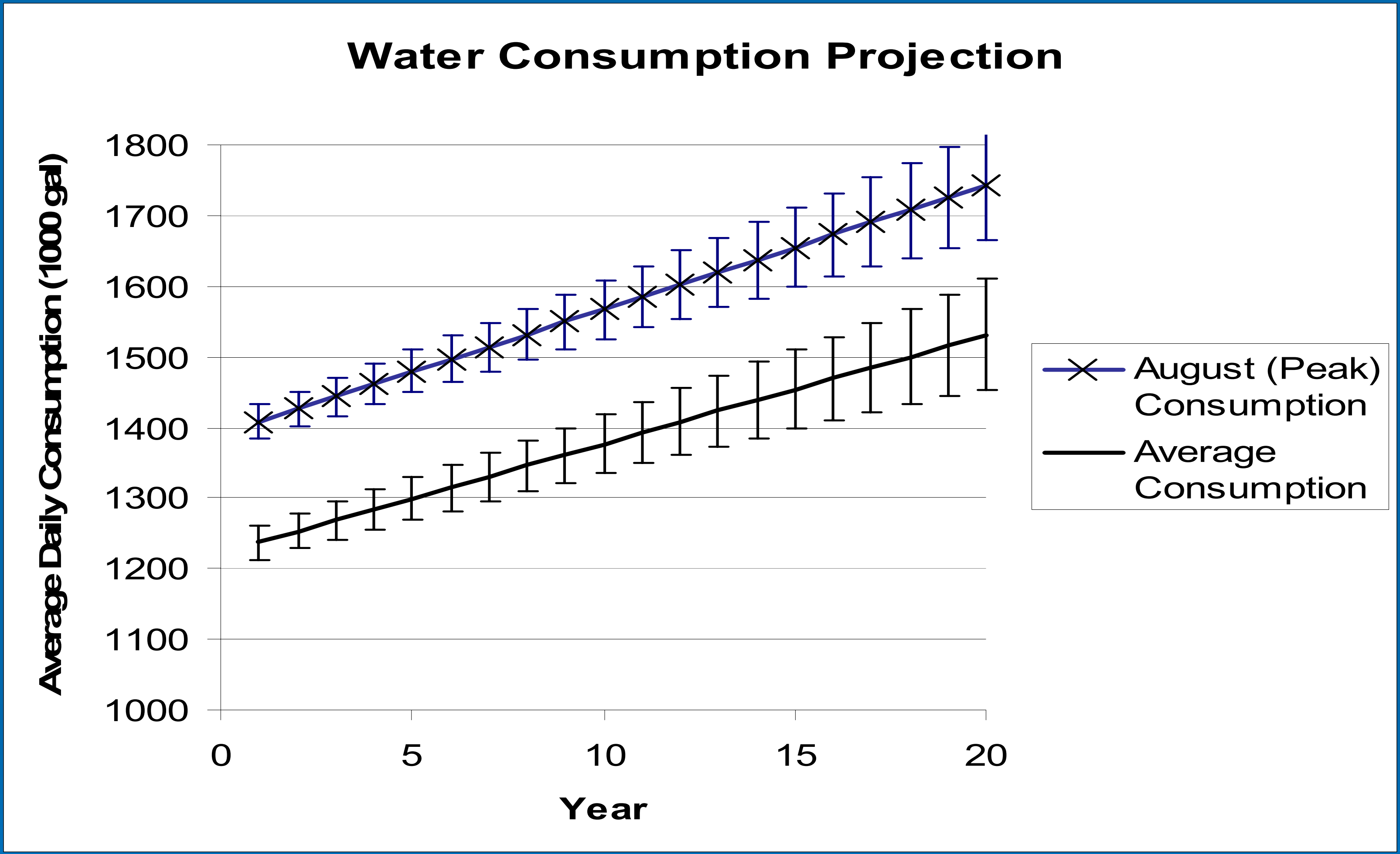
- CI - $1.1 million ($428/1000gal per day of capacity)
- OC - $38,000 ($111/1000gal per day of capacity)
- Demand - 2002 figures; 25% growth (OU Physical Plant)
- Water Price:

  $3.00/1000 gallons Demand Based

  $1.14/1000 gallons Whole Sale



- Fixed: Building, Feed Facility, Brine Unit
- Capacity Based: Number and Sizing of Columns



- Solution must meet the needs of OU by month

Significant Variables

- Capital Investment and Operating Cost per 1000 gallons/day should show significant variation.
- "Wholesale" water price should be shown for $1.14 (current) and $0.85 (possible) per 1000 gal / day.
- Water Demand is randomly generated.

Model in Math Language:

Main Equations:

$$TotalCost = \sum_{s} p_s C_s$$

$$C_s = \sum_{yr} C_{yr} = \sum_{yr} \left(CI_{yr} + OP_{yr} + \Pr ice_{yr} * WP_{yr} * (1+i)^{yr-1} - Borrowed_{yr} + Repaid_{yr} \right) * df_{yr}$$

$$CI_{yr} = a * z_{yr} + b * Cap_{yr}$$

$$Demand_{yr,mo,s} = Q_{yr,mo,s} + WP_{yr,mo,s}$$

$$OP_{yr} = \alpha_F \sum_{\xi=1}^{yr} z_{\xi} + \beta \sum_{mo} Q_{yr,mo,s}$$

$$ztot_{yr} = \sum_{\xi} z_{\xi} \quad if \;\; \xi \le yr$$

$$\Pr ice_{yr,s} = WholeSale\Pr ice * y_{yr,s} + Emergency\Pr ice * (1 - y_{yr,s})$$

Finance Equations: $$Debt_{yr,s} = (1+i) * Debt_{yr-1,s} + Borrowed_{yr,s} - Repaid_{yr,s}$$

Main Constraints:

$$CapTot_{yr} = \sum_{\xi} (Cap_{\xi} + CapAdd_{\xi}) \quad if \;\; \xi \le yr$$

$$Cap_{yr} \le MaxCap * z_{yr}$$

$$CapTot_{yr} \ge Q_{yr,mo,s}$$

$$\sum_{mo} WP_{yr,mo,s} - 1000 * y_{yr,s} \ge 0$$

Finance Constraints:

$$C_{yr,s} \le Budget \qquad Debt_{20,s} = 0$$

$$Repaid_{yr,s} \ge 2 * i * Debt_{yr-1,s}$$

Mathematical Model Code:

```
*=====================EQUATIONS=====================================
*Scenario Probability

*CAPITAL INVESTMENT CALC
captotal(yr).. captot(yr) =e= sum(yrr$(ord (yrr) le ord(yr)),cap(yrr)+capadd(yrr));
qcap(yr,mo,s).. captot(yr) =g= q(yr,mo,s);
capacity(yr).. cap(yr) =l= maxcap*z(yr);
capinv(yr).. ci(yr) =e= (a*z(yr)+b*cap(yr))*(1/(1+df)**(ord(yr)-1));
waterdemand(yr,mo,s).. demands(yr,mo,s) =e= q(yr,mo,s)+wp(yr,mo,s);
totfac(yr).. ztot(yr) =e= sum(yrr$(ord (yrr) le ord(yr)),z(yrr));
opcost(yr,s).. op(yr,s) =e= (alpha * ztot(yr) + beta(s) * sum(mo,q(yr,mo,s)))*(1/(1+df)**(ord(yr)-1));
watcost(yr,s).. wcost(yr,s) =e= yrcost(yr,s)-op(yr,s)-ci(yr)+borrowed(yr,s)-repayed(yr,s);
Capaddd(yr).. capadd(yr) =l= maxcap * x(yr);
constr(yr).. x(yr) =l= ztot(yr-1);
capinvadd(yr).. ciadd(yr) =e= (aa*x(yr)+1.1*b*capadd(yr))*(1/(1+df)**(ord(yr)-1));
*VARIABLE WATER PRICE
chooseprice(yr,s).. sum(mo,wp(yr,mo,s))-1000*y(yr,s) =g= 0;
*waterprice(yr,s).. price(yr,s) =e= (34.2*y(yr,s)+45*(1-y(yr,s)));
*making price linear
pone(yr,s).. m(yr,s)-y(yr,s)*40000 =l=0;
ptwo(yr,s).. m(yr,s) =g= 0;
pthree(yr,s).. (sum(mo,wp(yr,mo,s))- m(yr,s))-(1-y(yr,s))*40000 =l=0;
pfour(yr,s).. sum(mo,wp(yr,mo,s))-m(yr,s) =g=0;

*pricedisplay(yr,s).. price(yr,s)=e=(34.2*m(yr,s)+45*(sum(mo,wp(yr,mo,s))-m(yr,s)));


*FINANCE BUDGET
yearcost(yr,s).. yrcost(yr,s) =e= op(yr,s)+ci(yr)+(1+inflate)**(ord(yr)-1)*(34.2*m(yr,s)+90*(sum(mo,wp(
budgetcost(yr,s).. yrcost(yr,s) =l= budget * (1/(1+df))**(ord(yr)-1);
debteqn(yr,s).. debt(yr,s) =e= (1+i)*debt(yr-1,s)+borrowed(yr,s)-repayed(yr,s);
debtfinal(s).. debt('20',s) =e= 0;
repay(yr,s).. repayed(yr,s) =g= 2*i*debt(yr-1,s);
*repay(yr,s).. repayed(yr,s) =g= Sum(yrr$(ord (yrr) le ord(yr)),i*(1+i)**(20-ord(yrr))*debt(yrr,s)/((1+
*TOTAL COST
```

Model Results

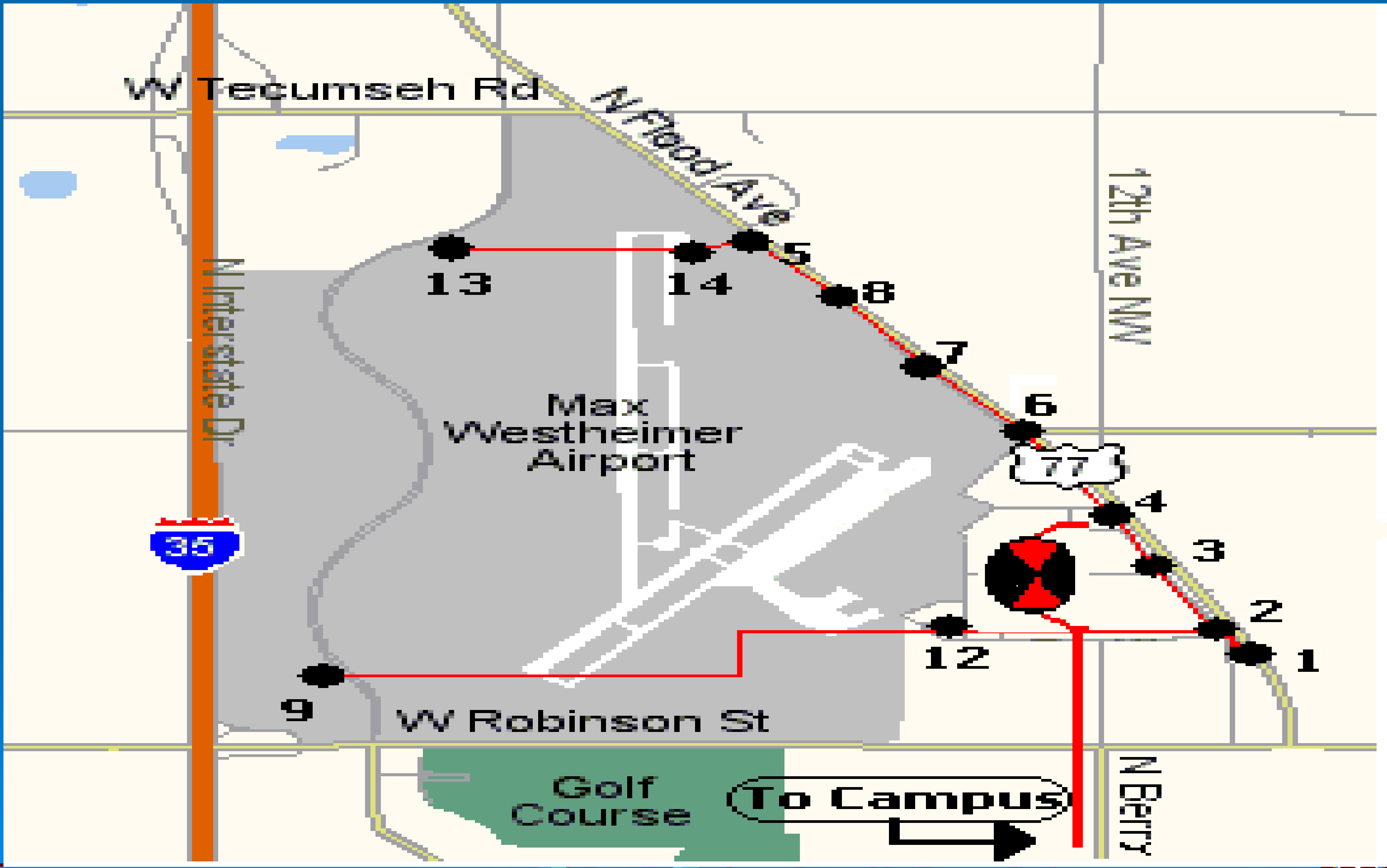
- Facility Built In Year 1 (1.6 MGD Capacity)
- Loan (Repaid Over 10 Yrs)
- Water Purchased In Peak Months
- No Facility Upgrades For 20 Year Period
- Net Present Cost Of $3.1 Million

Implications of Model Results

2600 ft^2 Facility Area

- 2000 Gallon Waste Brine Container
- Four 6ft Dia. IX Columns
- Requires Purchase Of Ferric Chloride, Sodium Hydroxide, Sulfuric Acid And Salt.
- Highly Automated
- Labor requirement of less than $20,000/year (CH2M Hill)

GEOGRAPHY



W Tecumseh Rd
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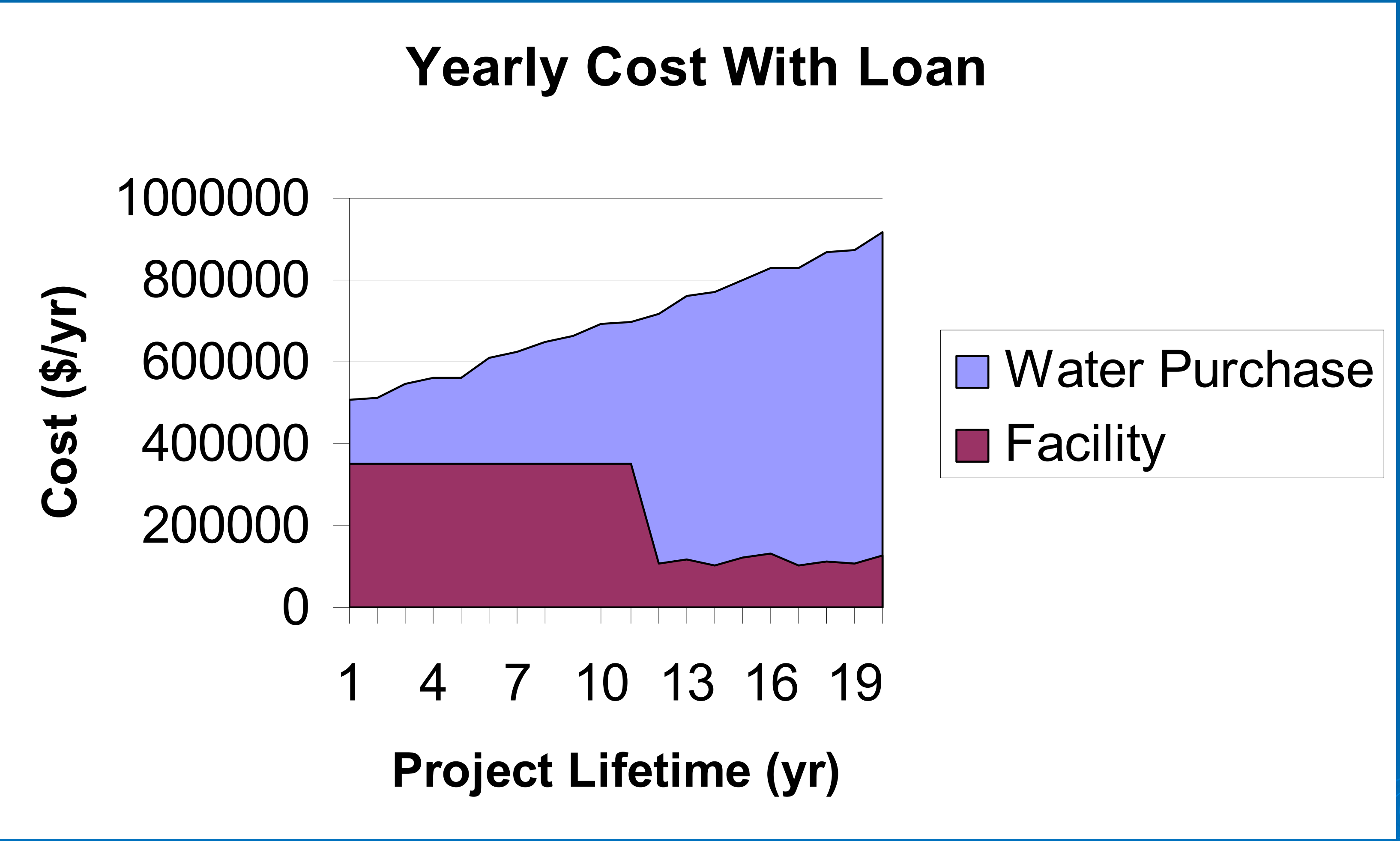
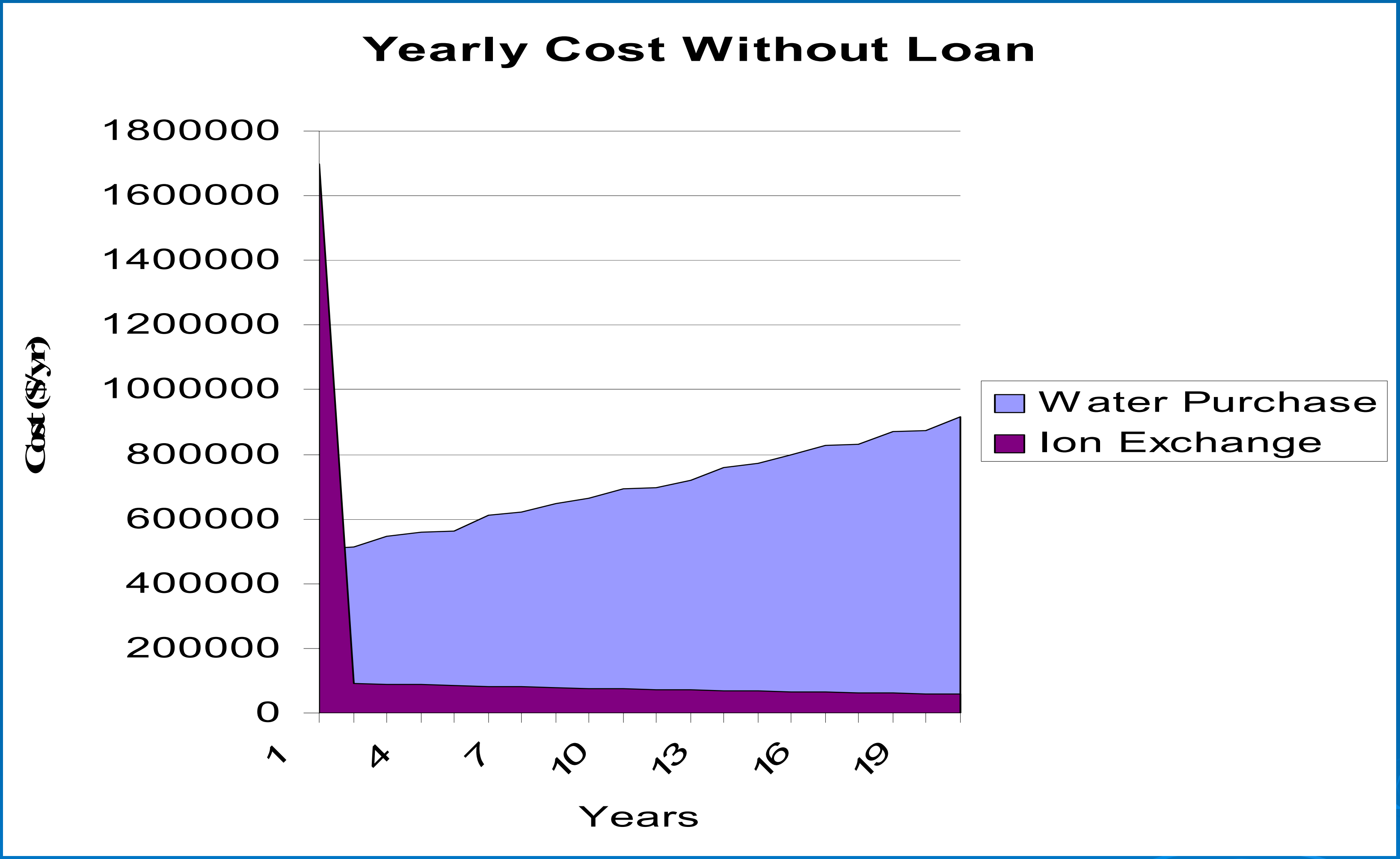


Wholesale Water Price $1.14

Interest Rate = 9%



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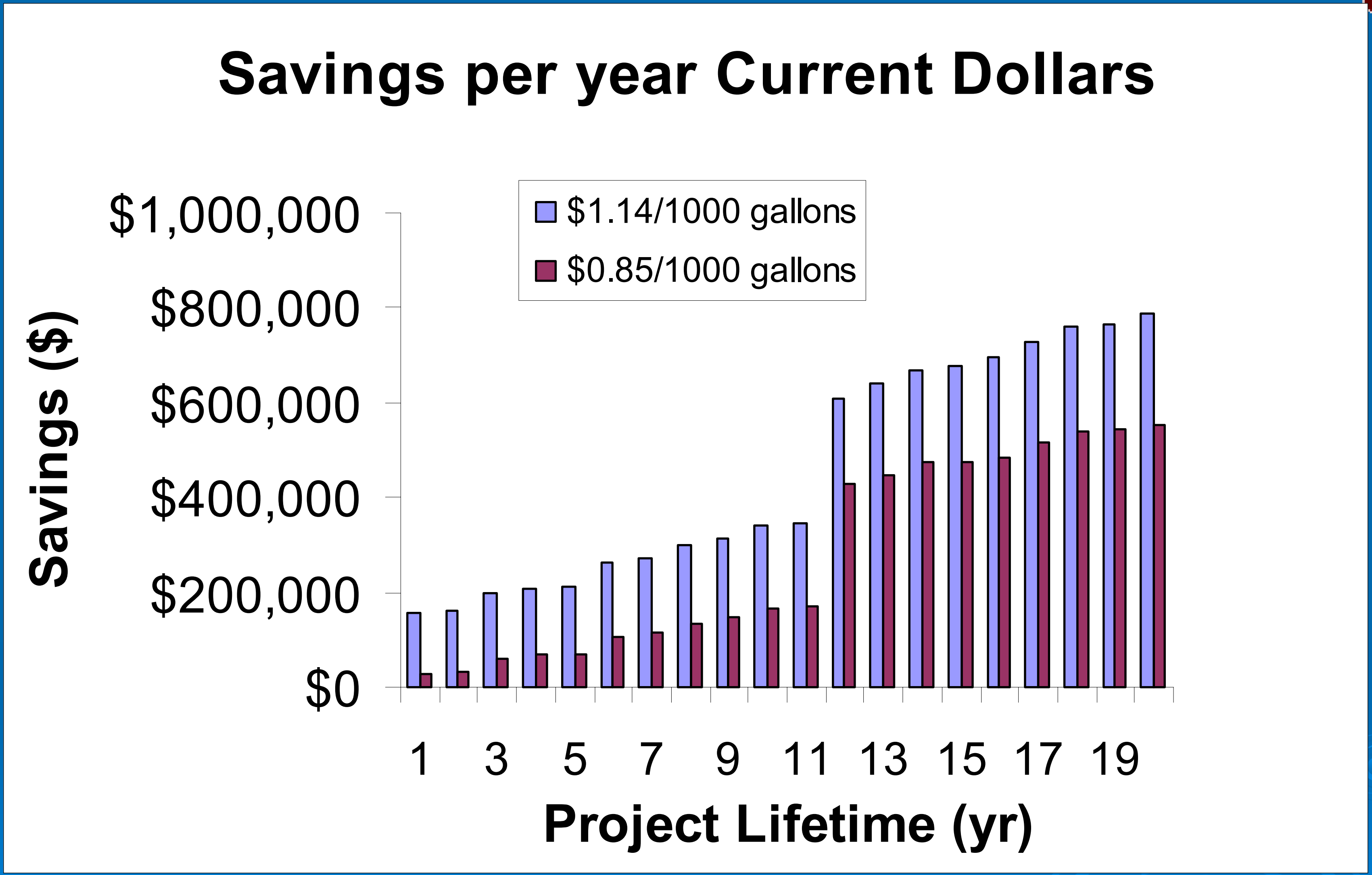
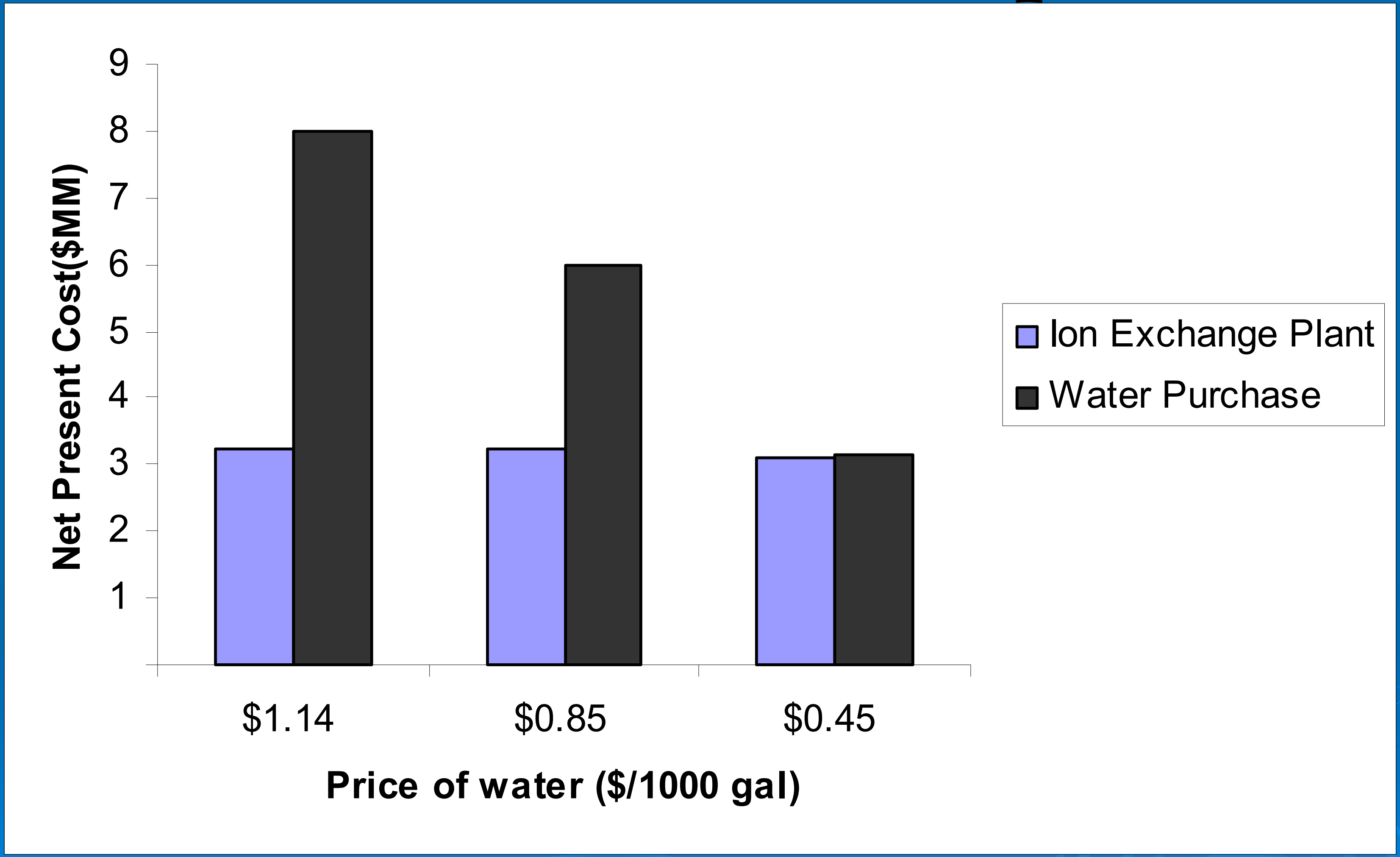


Savings Increase In Year 12!

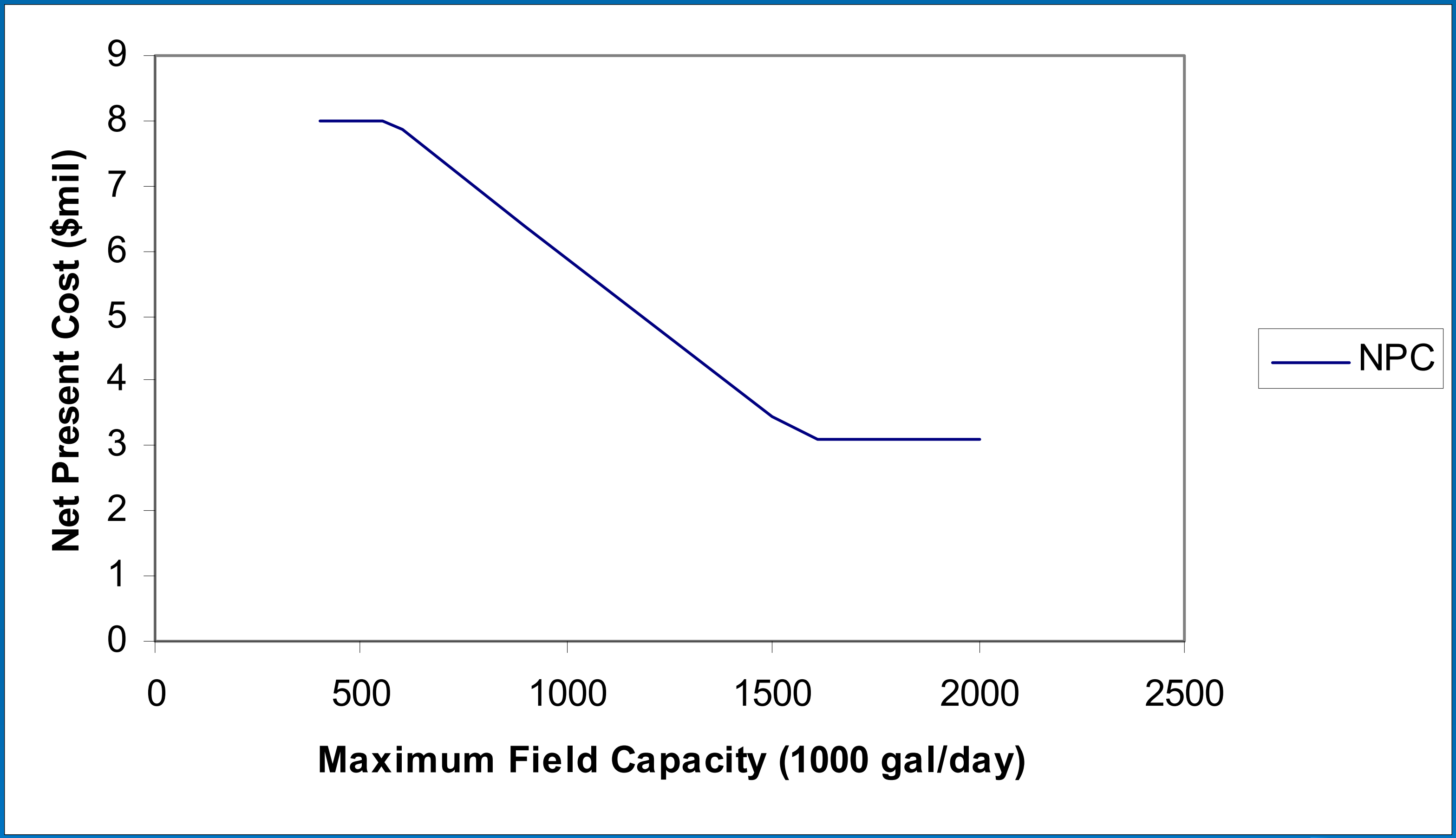
Net Present Cost Comparison



Water Costs $0.60/1000gal to Produce

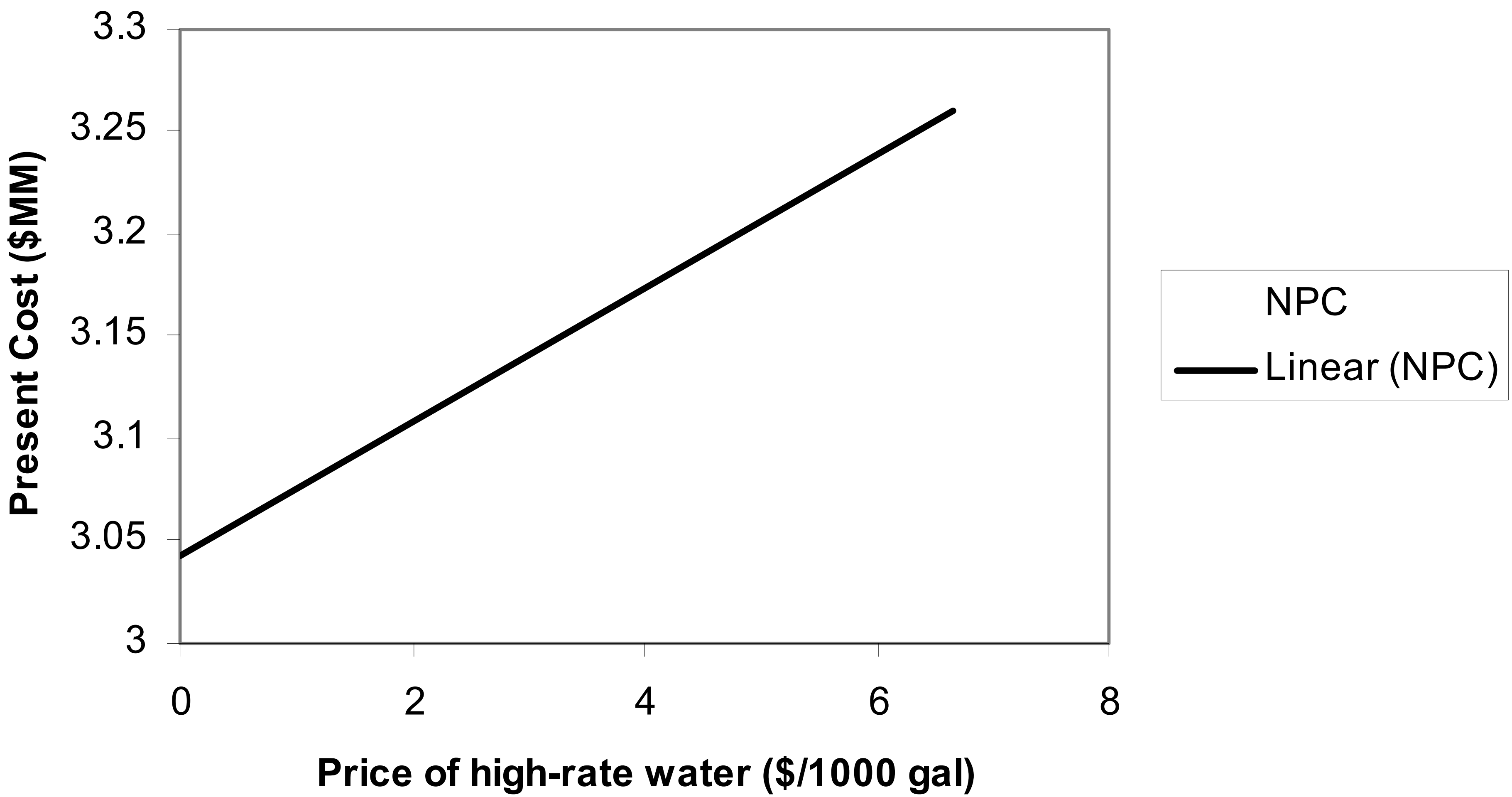
Risk Assessment

Maximum Field Capacity

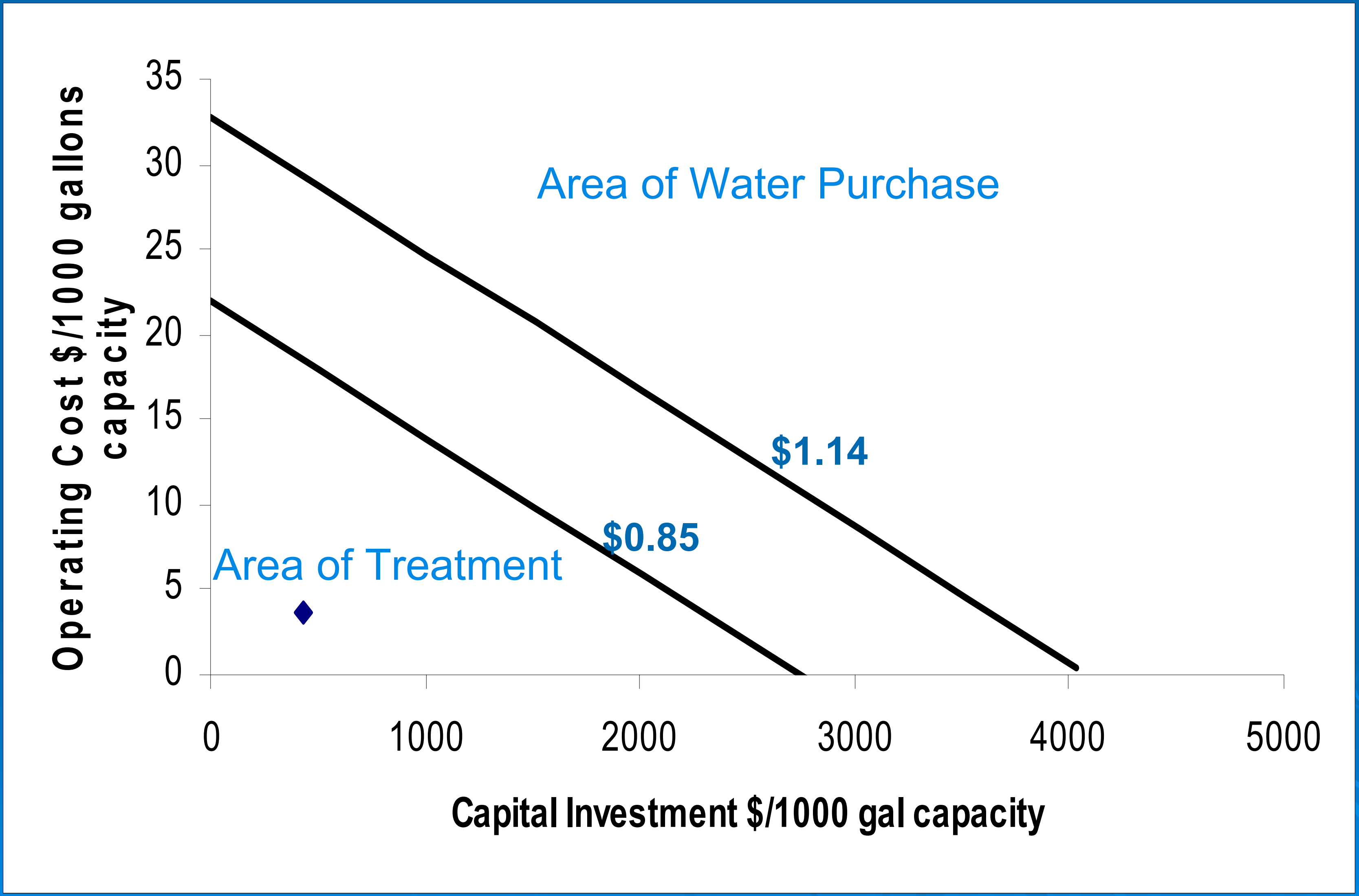


Shows decisions if capacity is lower

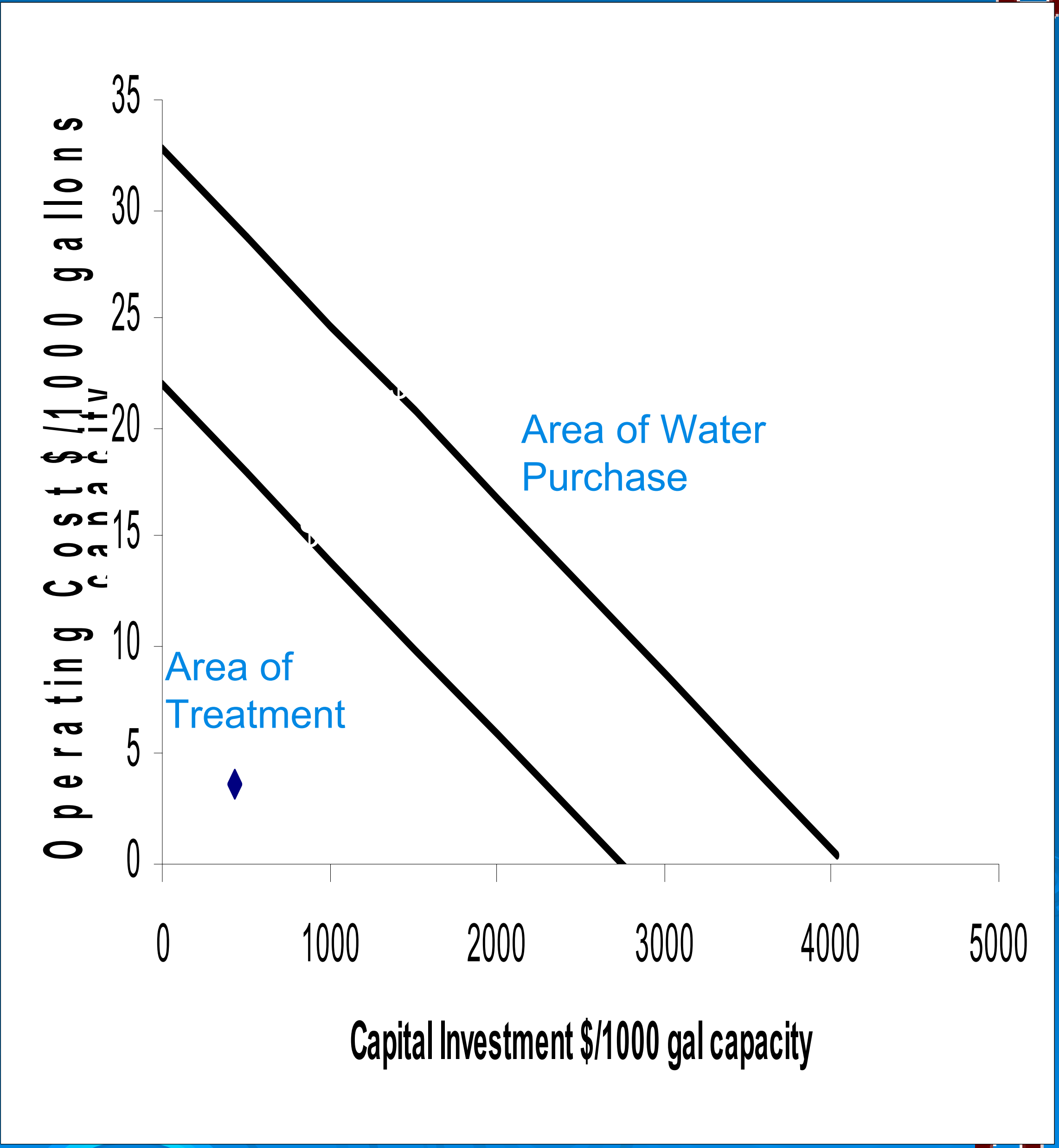
Water Price Sensitivity

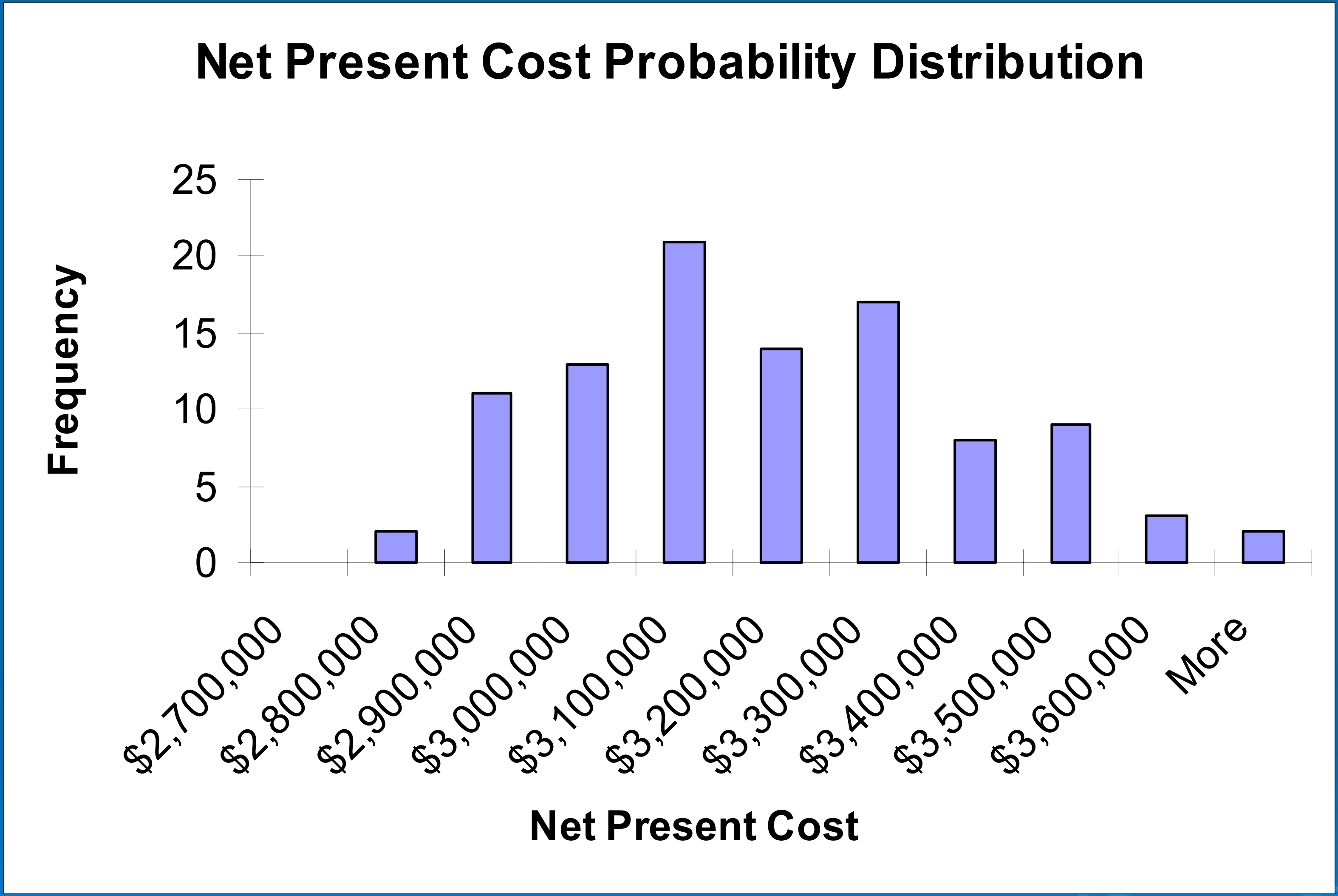


Uncertainty Analysis



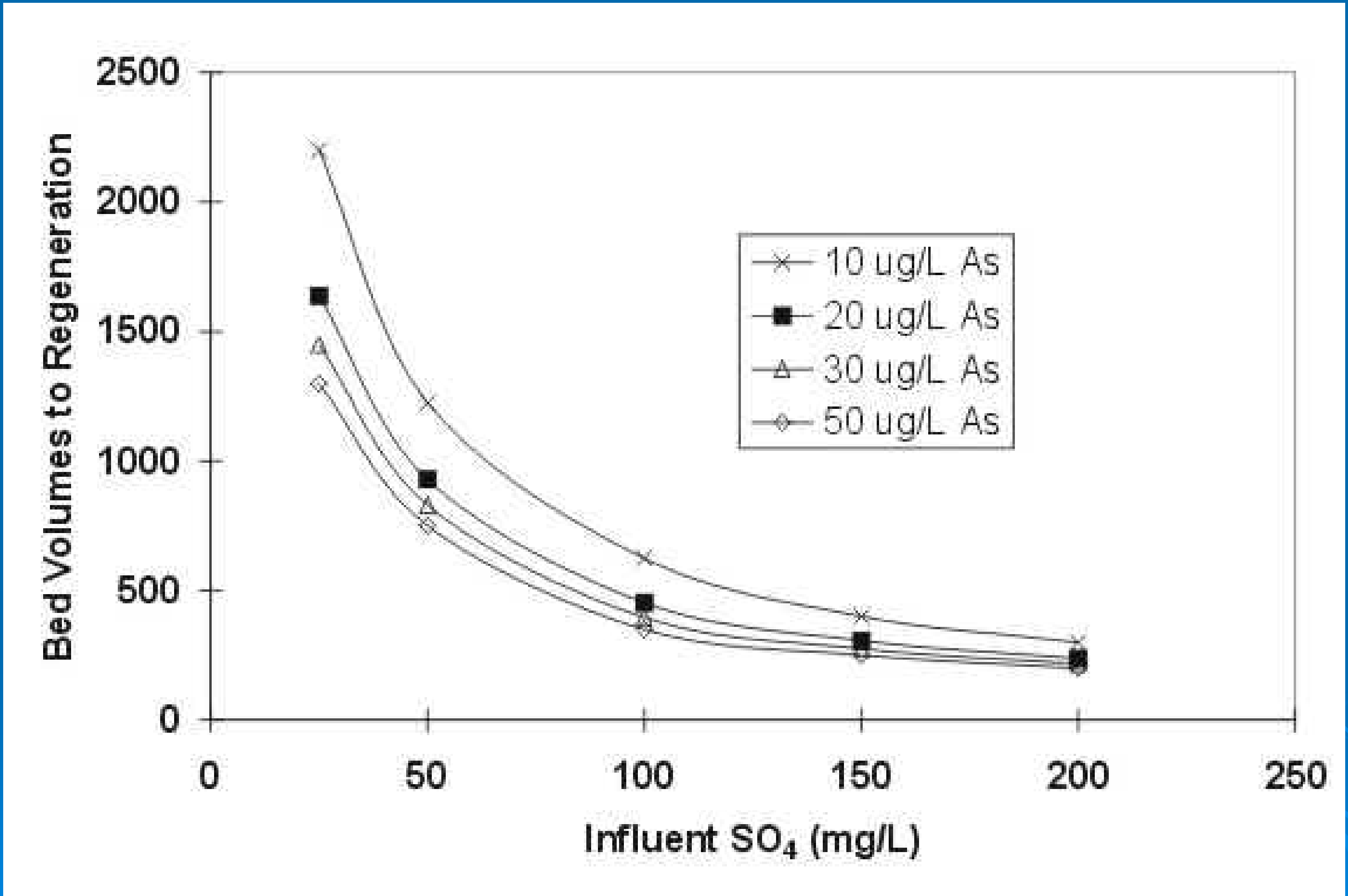
- Doubled values within “Treatment Area”
- 400% (for $0.85) or 600% (for $1.14) cost increase required for WP to become favorable.
- Even with high variability of parameters, treatment is favorable.





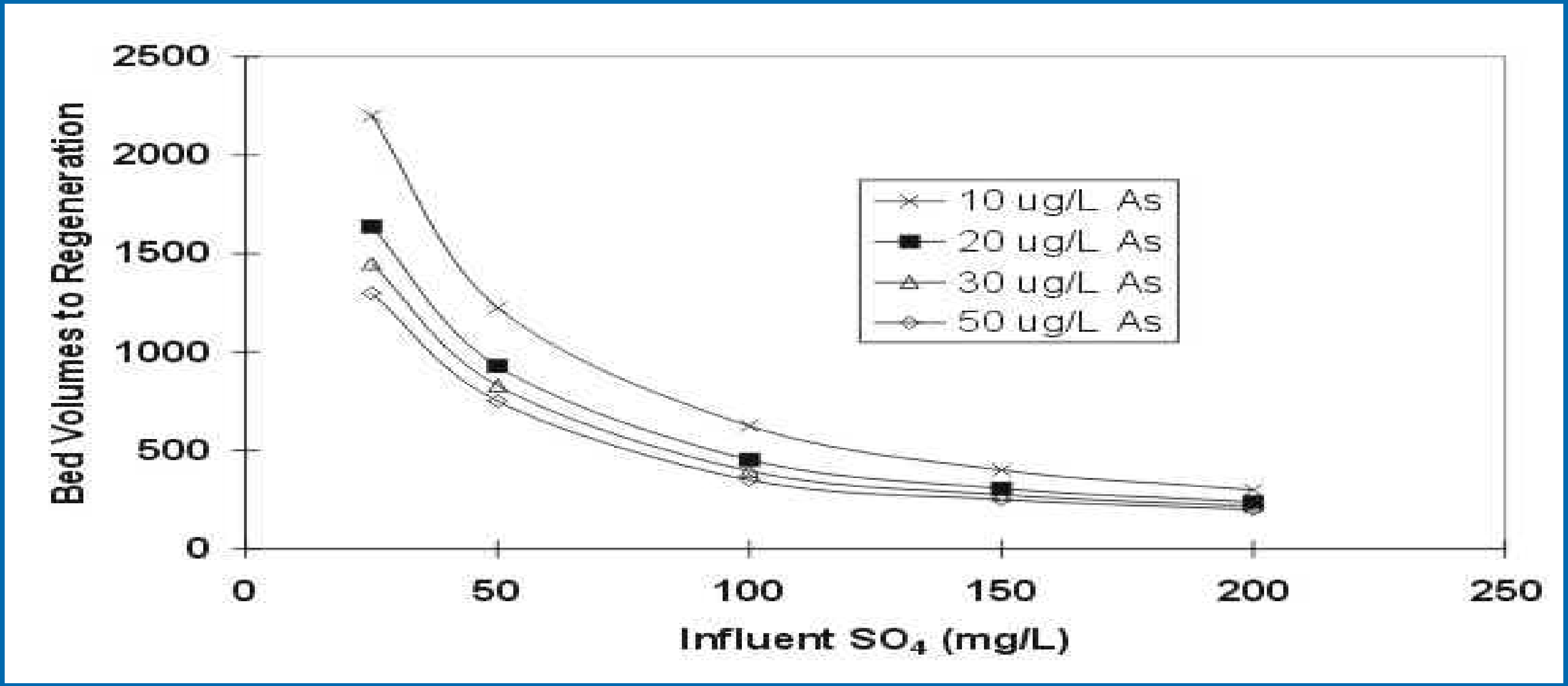
Net Present Cost Probability Distribution
Frequency
25
20
15
10
5
0
$2,700,000
$2,800,000
$2,900,000
$3,000,000
$3,100,000
$3,200,000
$3,300,000
$3,400,000
$3,500,000
$3,600,000
More
Net Present Cost

Safety



2500
2000
1500
1000
500
0
Bed Volumes to Regeneration
0
50
100
150
200
250
Influent SO4 (mg/L)
10 ug/L As
20 ug/L As
30 ug/L As
50 ug/L As

Safety

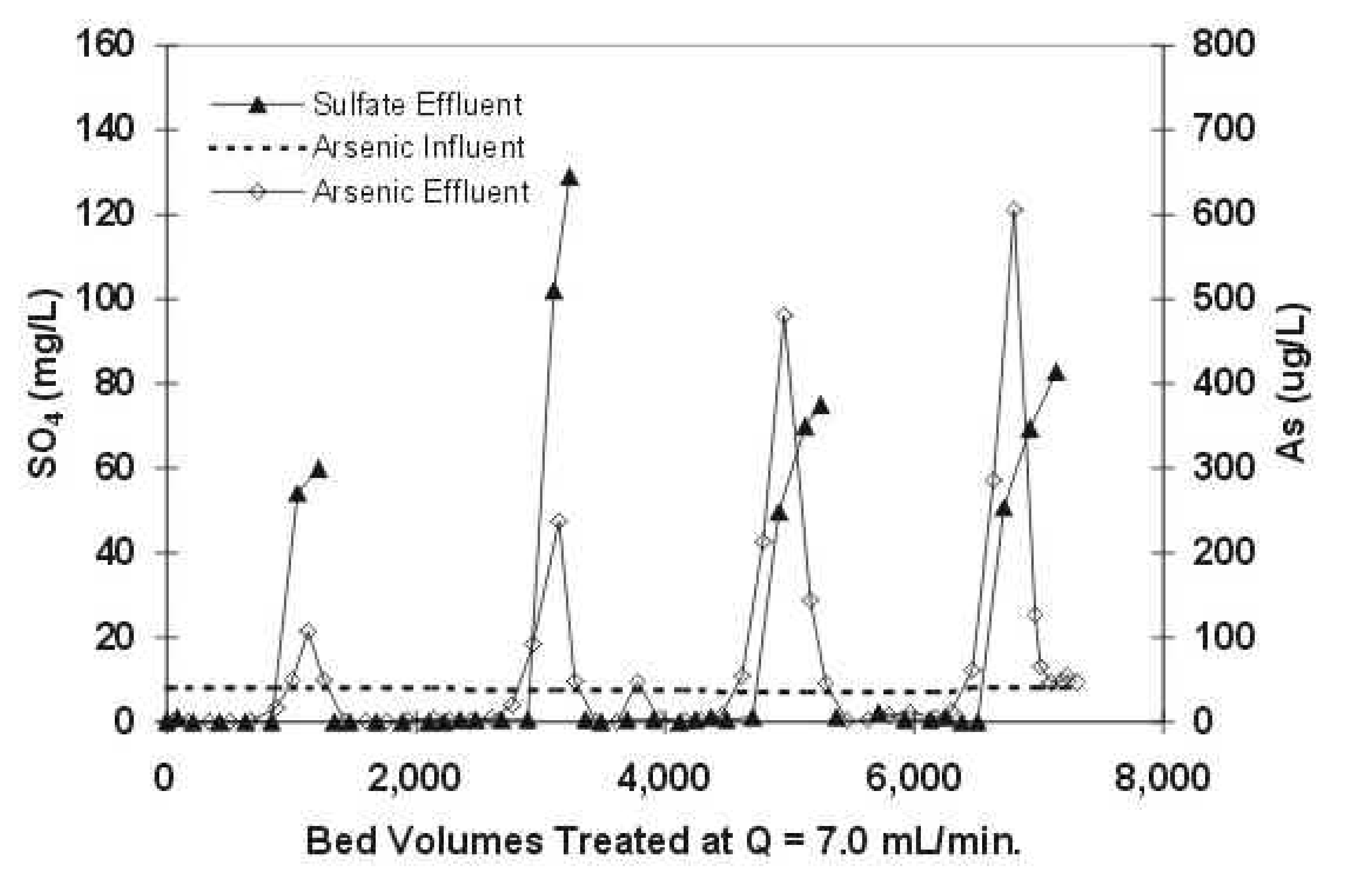


More Bed Volumes =

Higher Number of Chemicals Required =

Higher Operating Cost

Safety



Sulfate Effluent
Arsenic Influent
Arsenic Effluent
SO4 (mg/L)
As (ug/L)
Bed Volumes Treated at Q = 7.0 mL/min.
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700
800
0
2,000
4,000
6,000
8,000

Conclusion

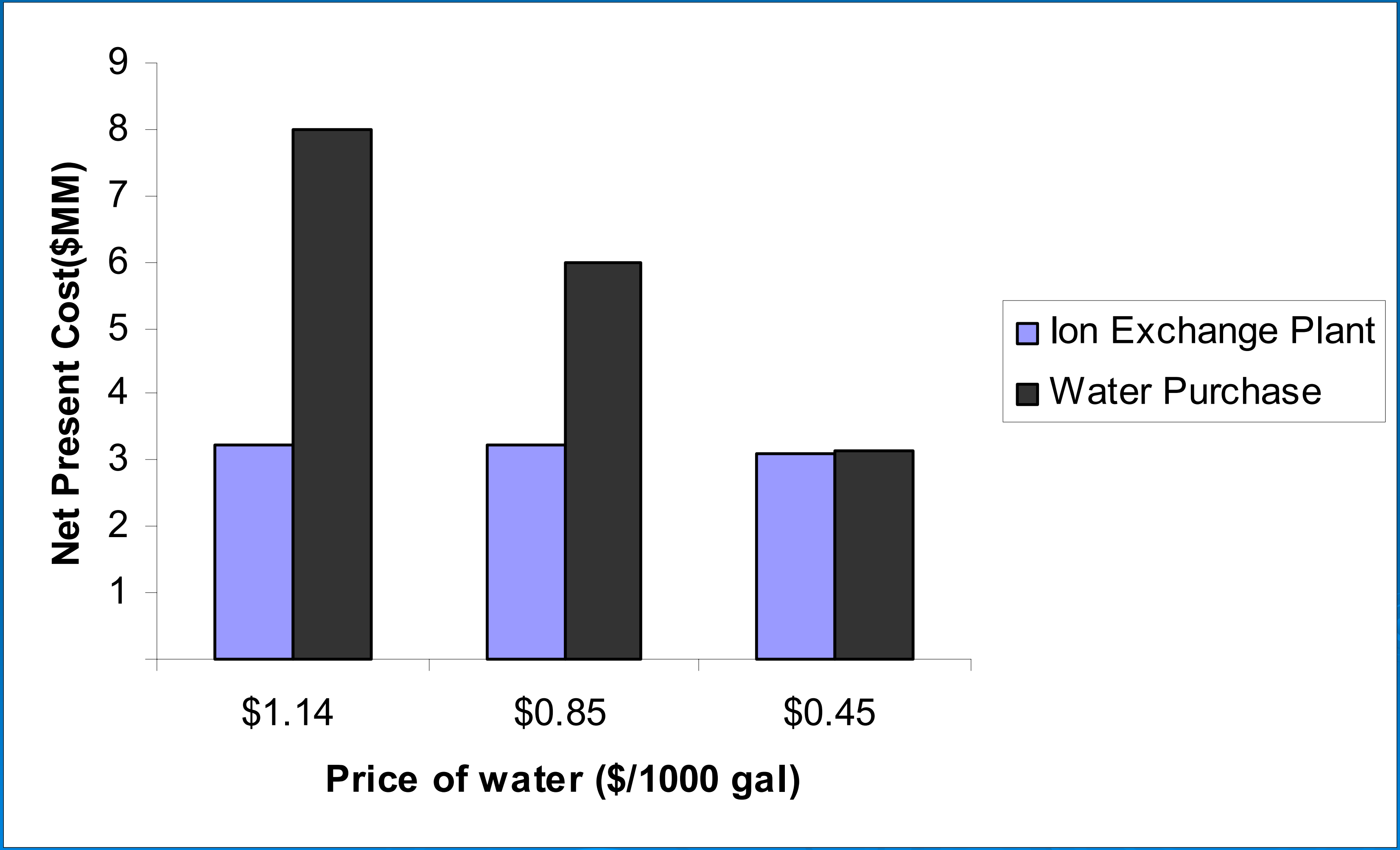
Conclusion:

- At either price level of water, Ion Exchange treatment costs less
- Self-sufficiency and full utilization of natural resources via IX treatment
- By treating water, OU will not contribute as greatly to scarcity of water in the Central Oklahoma Area
- Waste produced roughly equivalent to one Norman-issued trashcan full of non-hazardous waste per day

Recommendations

- Explore waste dilution to reduce As content to < 0.5% solid concentration (TC)
- Water by-pass to reduce regeneration
- Permissible TBLL for Norman
- Dried precipitate concentration to meet TCLP

Conclusion:



9
8
7
6
5
4
3
2
1
Net Present Cost($MM)
$1.14
$0.85
$0.45
Price of water ($/1000 gal)
Ion Exchange Plant
Water Purchase