EFFECTS OF WITHDRAWALS FROM A SIMULATED ISLAND FRESHWATER LENS AQUIFER SYSTEM: AN ANALYTIC ELEMENT MODELING APPROACH

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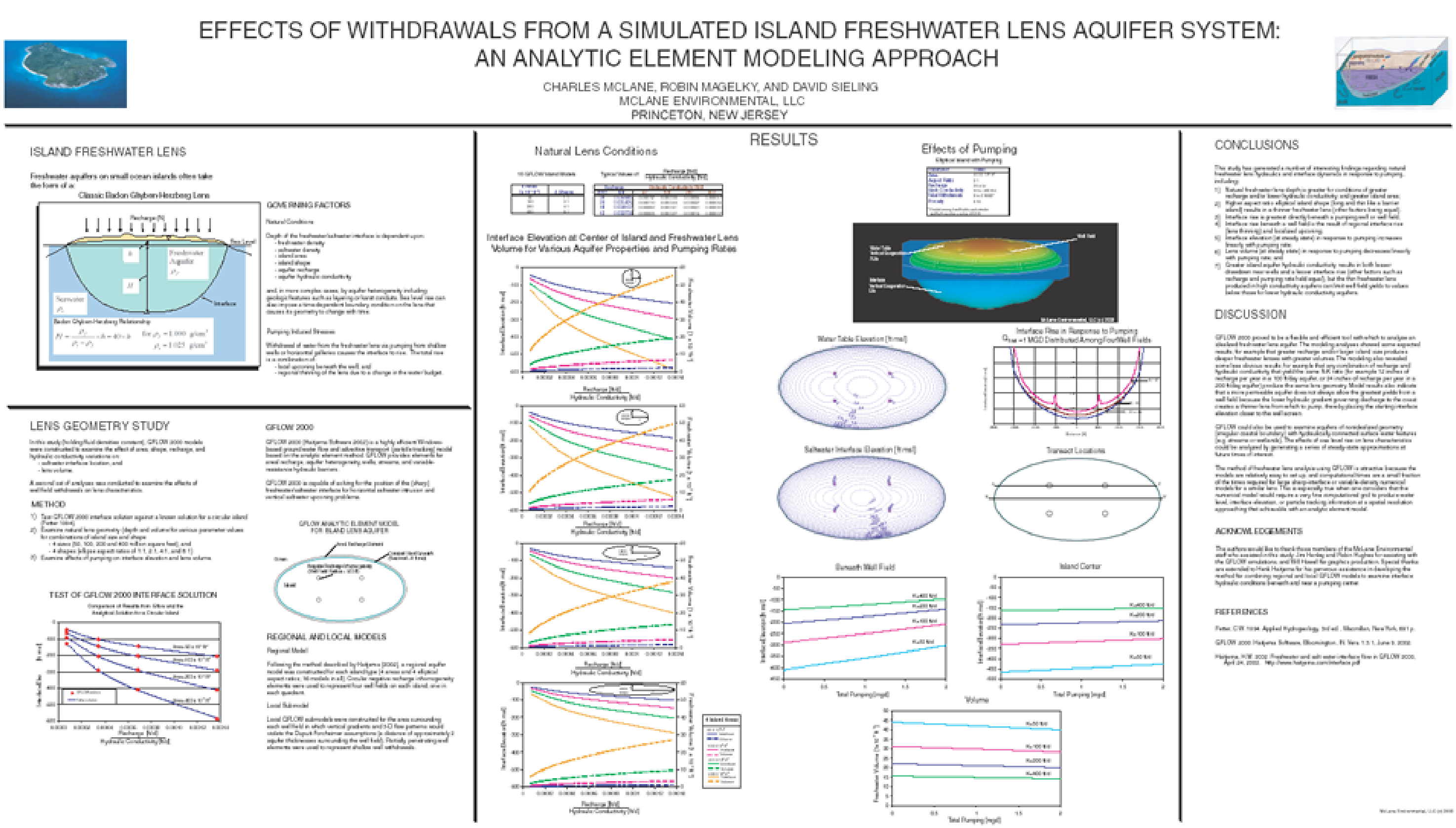
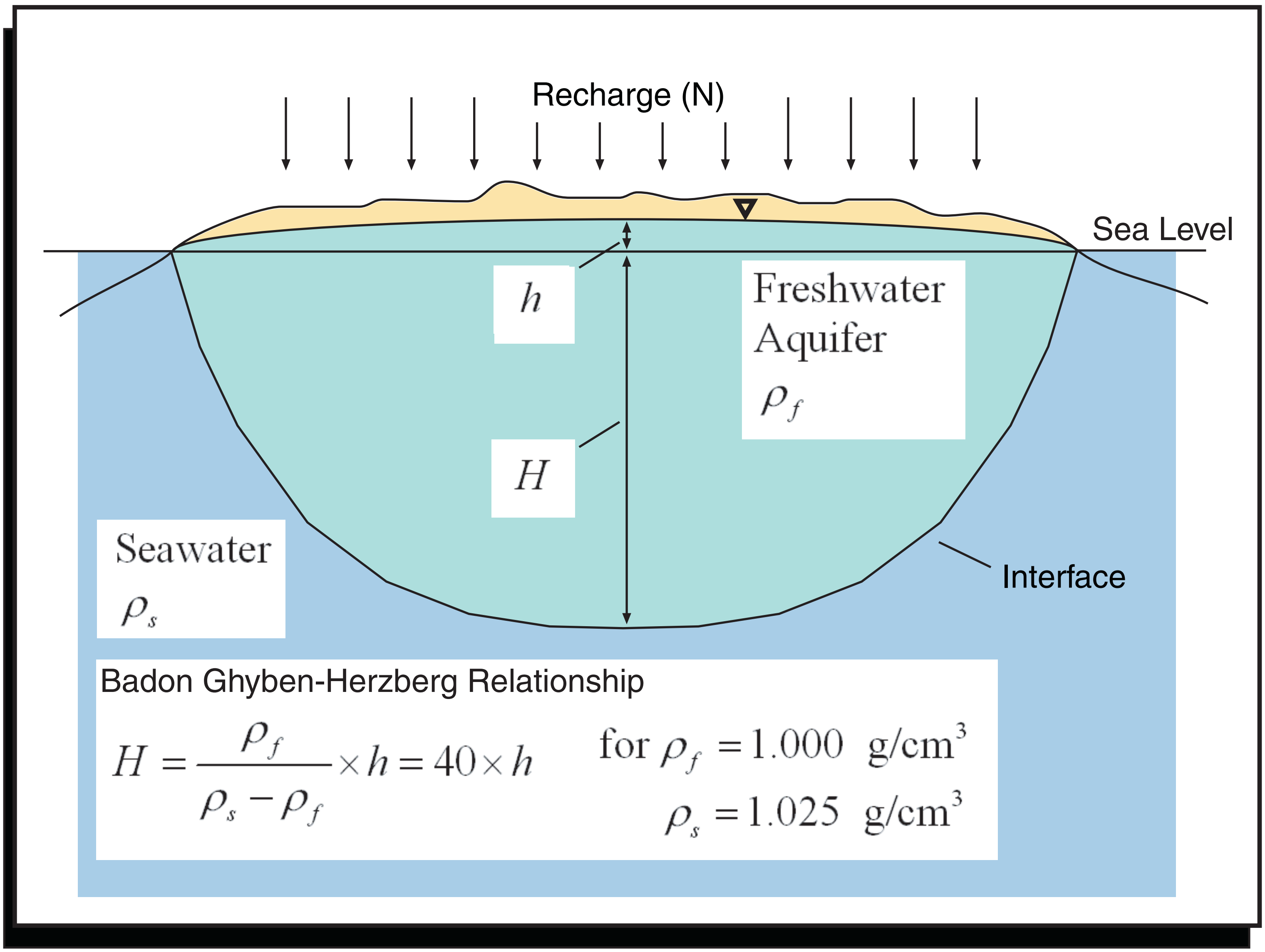


ISLAND FRESHWATER LENS

Freshwater aquifers on small ocean islands often take the form of a:

Classic Badon Ghyben-Herzberg Lens



GOVERNING FACTORS

Natural Conditions

Depth of the freshwater/saltwater interface is dependent upon:

- freshwater density
- saltwater density
- island area
- island shape
- aquifer recharge
- aquifer hydraulic conductivity

and, in more complex cases, by aquifer heterogeneity including geologic features such as layering or karst conduits. Sea level rise can also impose a time-dependent boundary condition on the lens that causes its geometry to change with time.

Pumping Induced Stresses

Withdrawal of water from the freshwater lens via pumping from shallow wells or horizontal galleries causes the interface to rise. The total rise is a combination of:

- local upconing beneath the well, and
- regional thinning of the lens due to a change in the water budget.

LENS GEOMETRY STUDY

In this study (holding fluid densities constant), GFLOW 2000 models were constructed to examine the effect of area, shape, recharge, and hydraulic conductivity variations on:

- saltwater interface location, and
- lens volume.

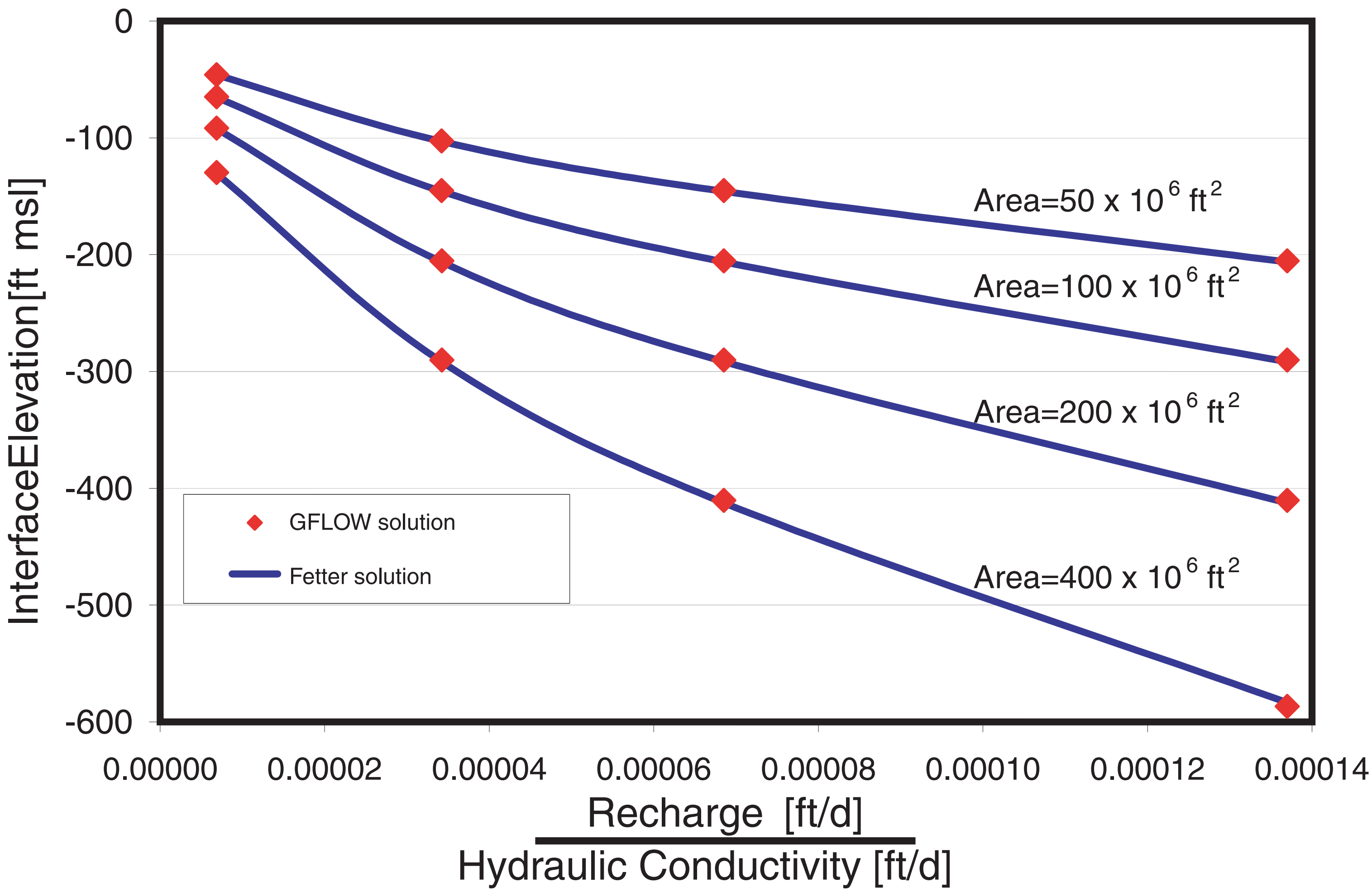
A second set of analyses was conducted to examine the effects of well field withdrawals on lens characteristics.

METHOD

1) Test GFLOW 2000 interface solution against a known solution for a circular island (Fetter 1994).
2) Examine natural lens geometry (depth and volume for various parameter values for combinations of island size and shape
    - 4 sizes (50, 100, 200 and 400 million square feet), and
    - 4 shapes (ellipse aspect ratios of 1:1, 2:1, 4:1, and 8:1)
3) Examine effects of pumping on interface elevation and lens volume.

TEST OF GFLOW 2000 INTERFACE SOLUTION

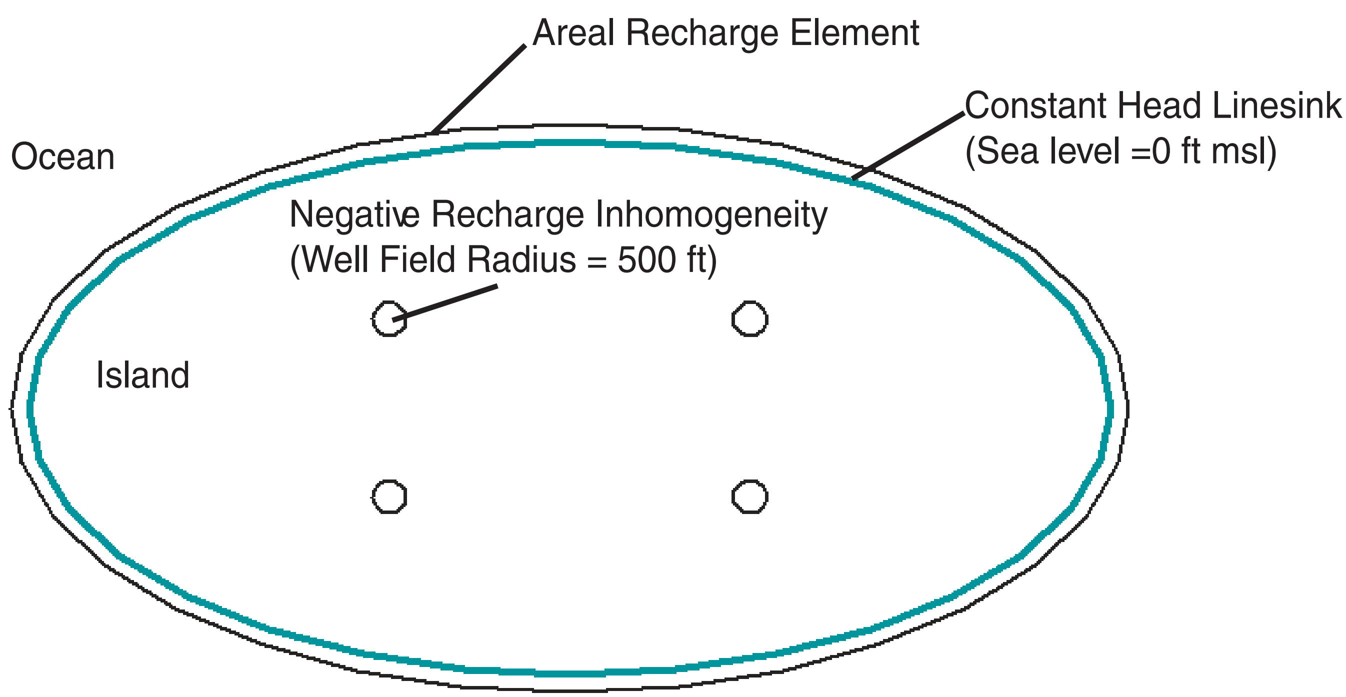
Comparison of Results from Gflow and the
Analytical Solution for a Circular Island



GFLOW 2000

GFLOW 2000 (Haitjema Software 2002) is a highly efficient Windows based ground water flow and advective transport (particle tracking) model based on the analytic element method. GFLOW provides elements for areal recharge, aquifer heterogeneity, wells, streams, and variable resistance hydraulic barriers. GFLOW 2000 is capable of solving for the position of the (sharp) freshwater/saltwater interface for horizontal saltwater intrusion and vertical saltwater upconing problems.

GFLOW ANALYTIC ELEMENT MODEL
FOR ISLAND LENS AQUIFER



REGIONAL AND LOCAL MODELS

Regional Model

Following the method described by Haitjema (2002), a regional aquifer model was constructed for each island type (4 areas and 4 elliptical aspect ratios; 16 models in all). Circular negative recharge inhomogeneity elements were used to represent four well fields on each island; one in each quadrant.

Local Submodel

Local GFLOW submodels were constructed for the area surrounding each well field in which vertical gradients and 3-D flow patterns would violate the Dupuit-Forcheimer assumptions (a distance of approximately 2 aquifer thicknesses surrounding the well field). Partially penetrating well elements were used to represent shallow well withdrawals.

Natural Lens Conditions

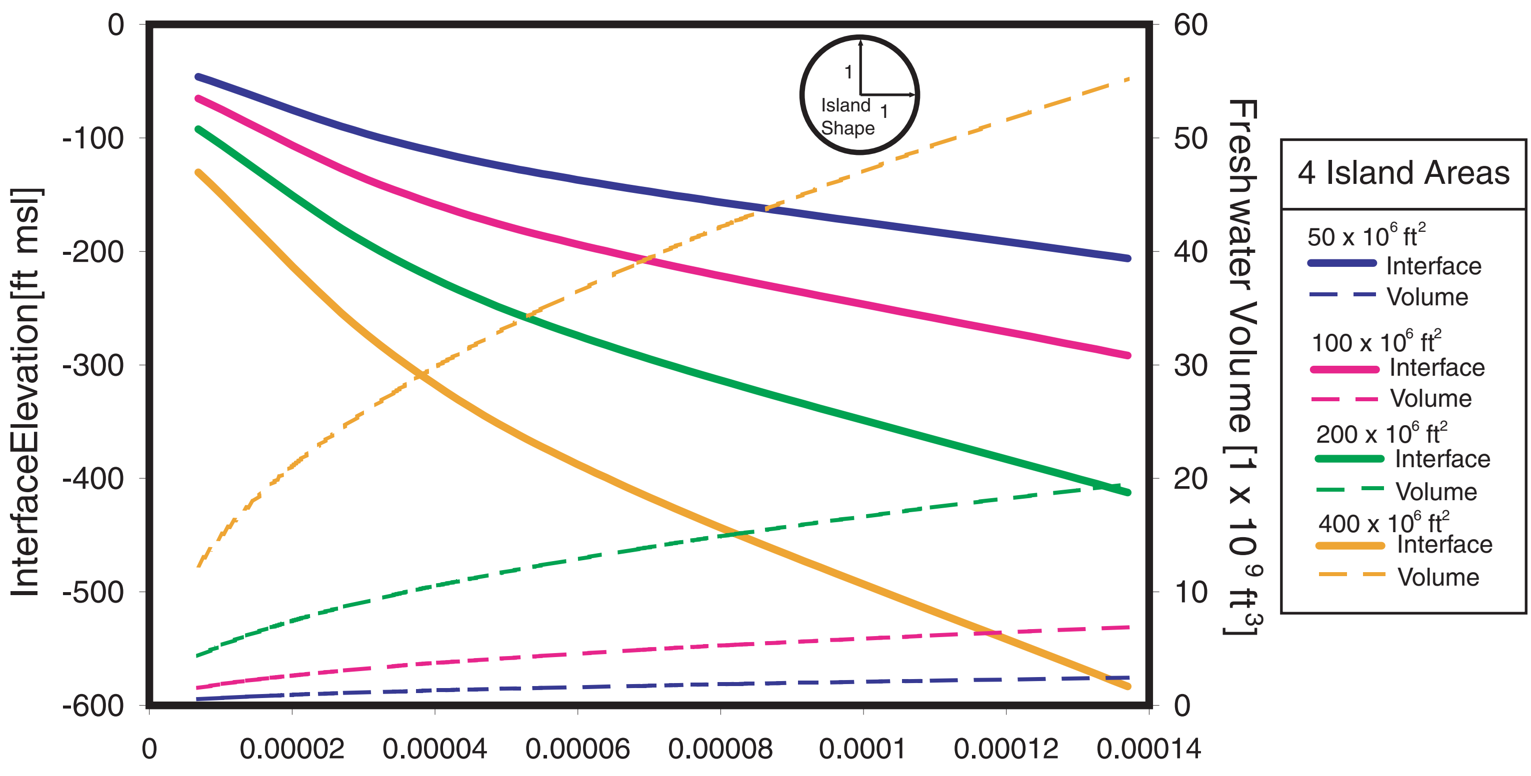
16 GFLOW Island Models

4 Areas [x 10^6 ft^2]	4 Shapes
50	1:1
100	2:1
200	4:1
400	8:1

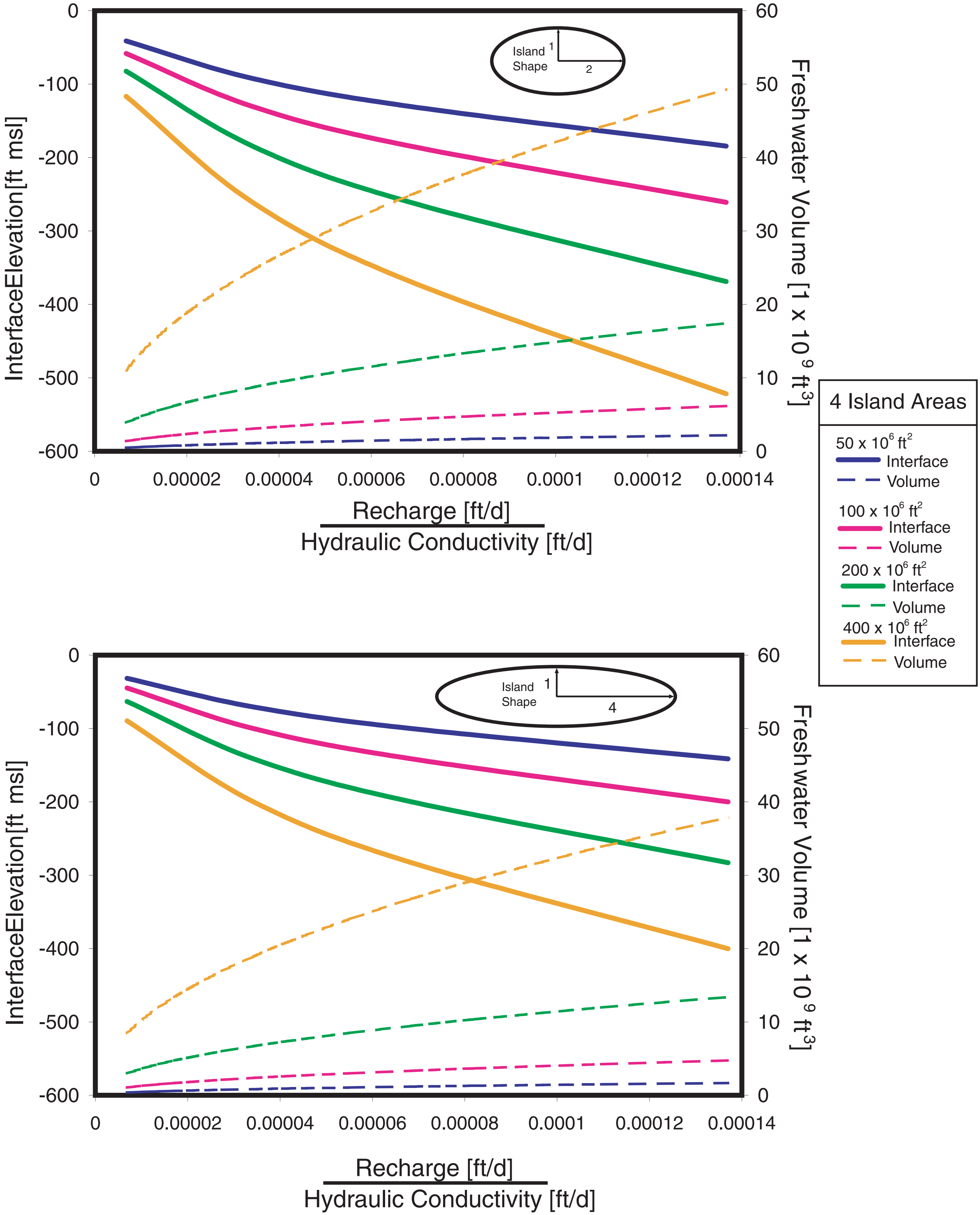
Typical Values of $\frac{\text{Recharge [ft/d]}}{\text{Hydraulic Conductivity [ft/d]}}$

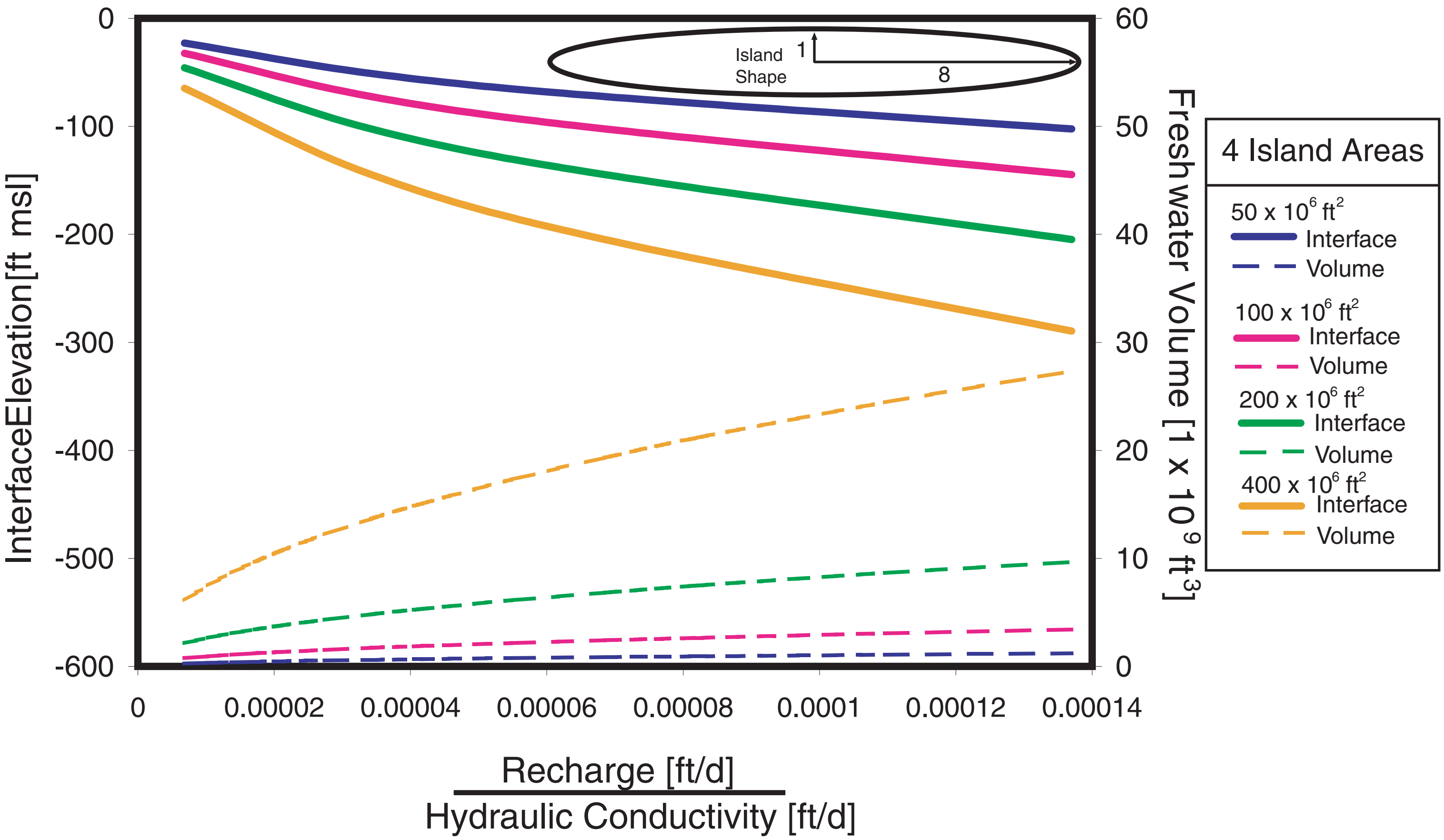
Recharge		Hydraulic Conductivity [ft/d]			
in/yr	ft/d	50	100	200	400
30	0.006845	0.000137	0.000068	0.000034	0.000017
24	0.005476	0.000110	0.000055	0.000027	0.000014
18	0.004107	0.000082	0.000041	0.000021	0.000010
12	0.002738	0.000055	0.000027	0.000014	0.000007

Interface Elevation at Center of Island and Freshwater Lens Volume for Various Aquifer Properties and Pumping Rates



$\frac{\text{Recharge [ft/d]}}{\text{Hydraulic Conductivity [ft/d]}}$


0
-100
-200
-300
-400
-500
-600
InterfaceElevation[ft msl]
60
50
40
30
20
10
0
Freshwater Volume [1 x 10 9 ft3]
Island Shape
1
2
0
0.00002
0.00004
0.00006
0.00008
0.0001
0.00012
0.00014
Recharge [ft/d]
Hydraulic Conductivity [ft/d]
4 Island Areas
50 x 10 6 ft2
Interface
Volume
100 x 10 6 ft2
Interface
Volume
200 x 10 6 ft2
Interface
Volume
400 x 10 6 ft2
Interface
Volume
0
-100
-200
-300
-400
-500
-600
InterfaceElevation[ft msl]
60
50
40
30
20
10
0
Freshwater Volume [1 x 10 9 ft3]
Island Shape
1
4
0
0.00002
0.00004
0.00006
0.00008
0.0001
0.00012
0.00014
Recharge [ft/d]
Hydraulic Conductivity [ft/d]



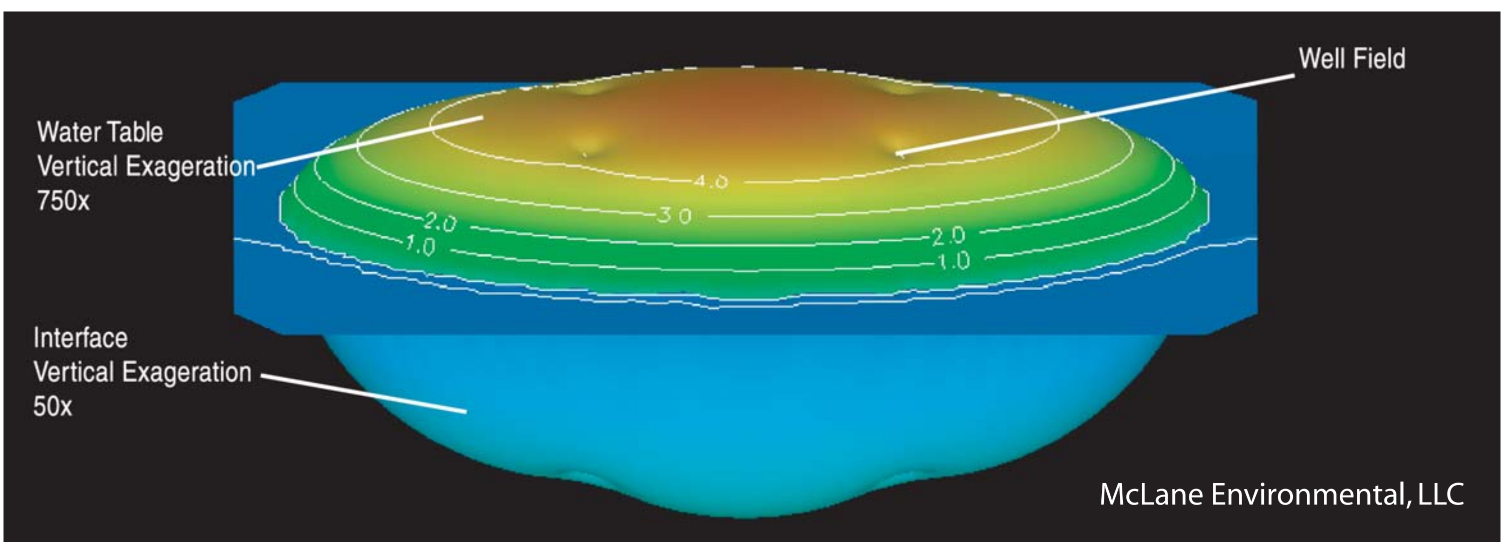
0
-100
-200
-300
-400
-500
-600
InterfaceElevation[ft msl]
60
50
40
30
20
10
0
Freshwater Volume [1 x 10⁹ ft³]
Island Shape
1
8
0
0.00002
0.00004
0.00006
0.00008
0.0001
0.00012
0.00014
Recharge [ft/d]
Hydraulic Conductivity [ft/d]
4 Island Areas
50 x 10⁶ ft²
Interface
Volume
100 x 10⁶ ft²
Interface
Volume
200 x 10⁶ ft²
Interface
Volume
400 x 10⁶ ft²
Interface
Volume

Effects of Pumping

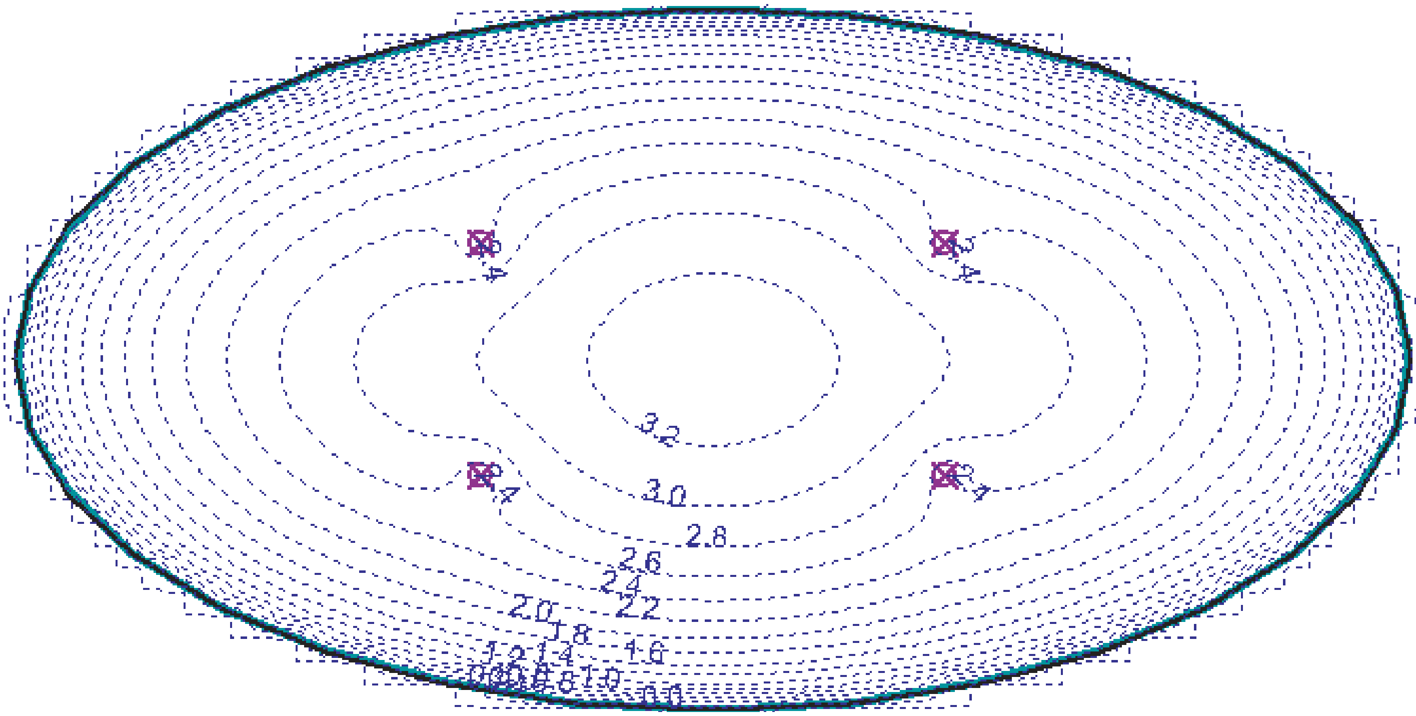
Elliptical Island with Pumping

Parameter	Value
Area	400 x 10^6 ft^2
Aspect Ratio	2:1
Recharge	24 in/yr
Hydr. Conductivity	50 to 400 ft/d
Total Withdrawals	0 to 2 MGD*
Porosity	0.35

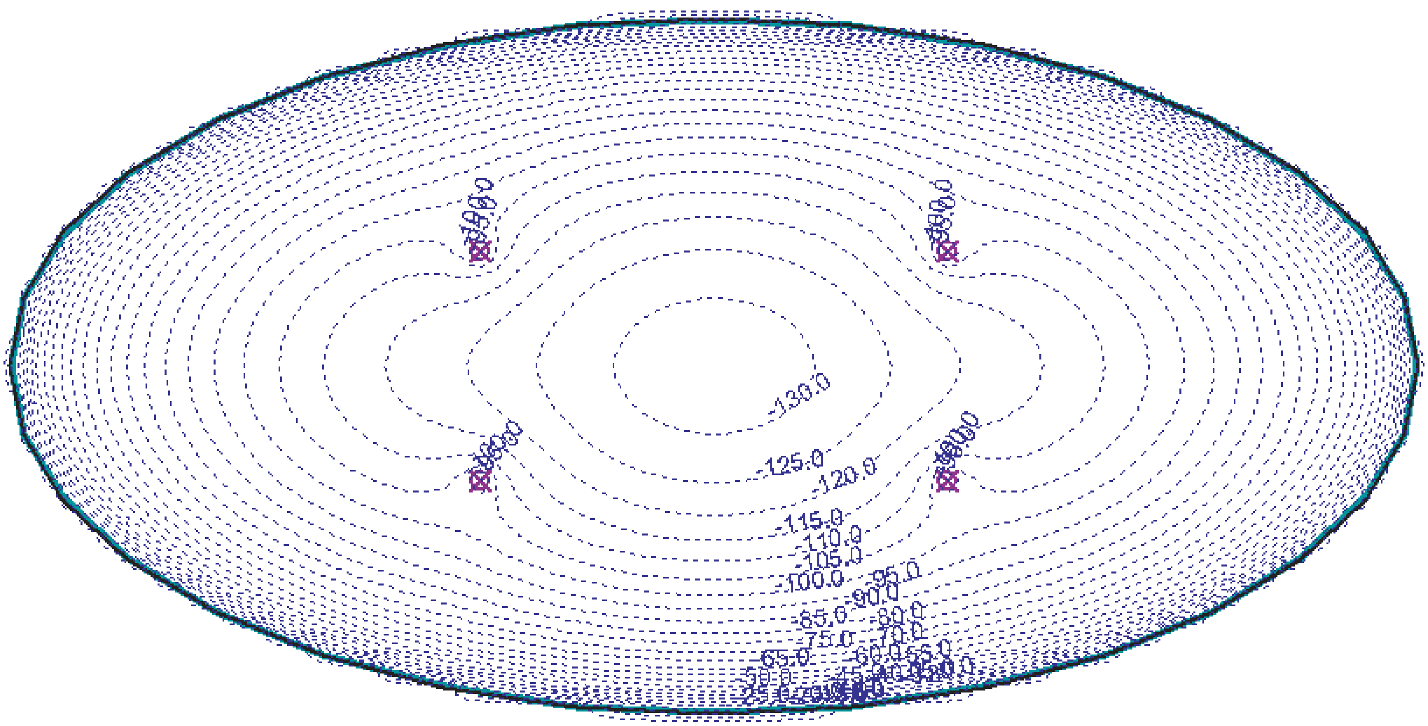
* Divided among 4 well fields; each circular well field area has a radius of 500 ft



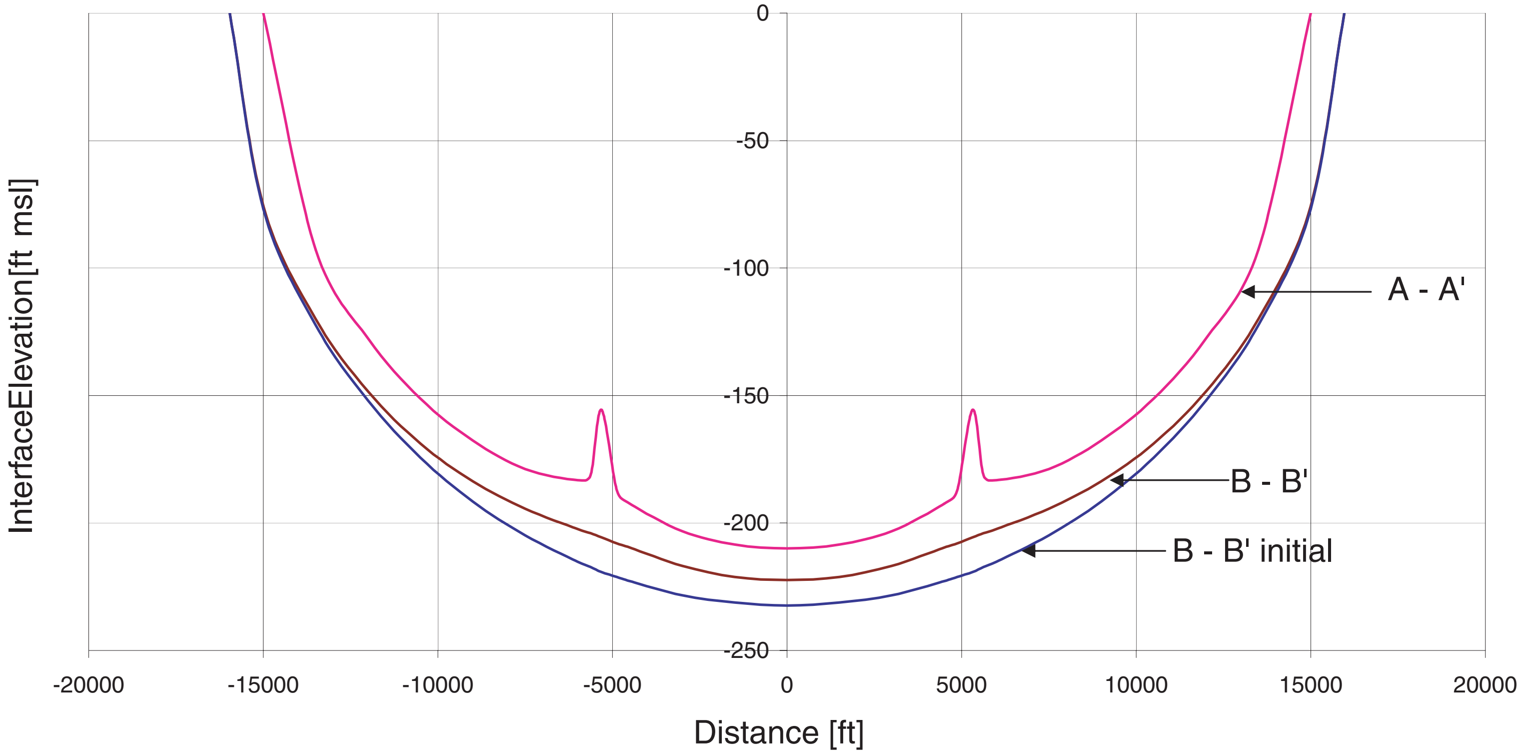
Water Table Elevation [ft msl]



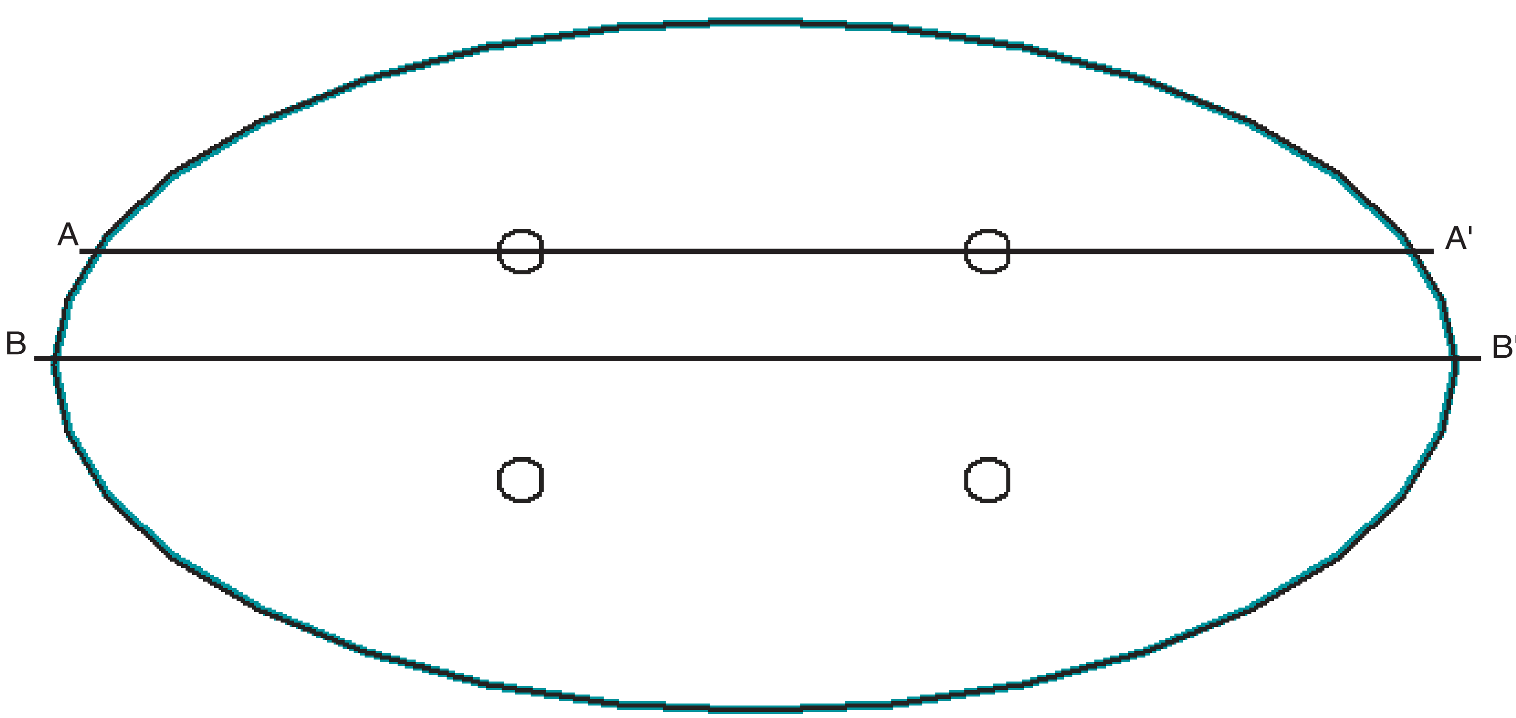
Saltwater Interface Elevation [ft msl]

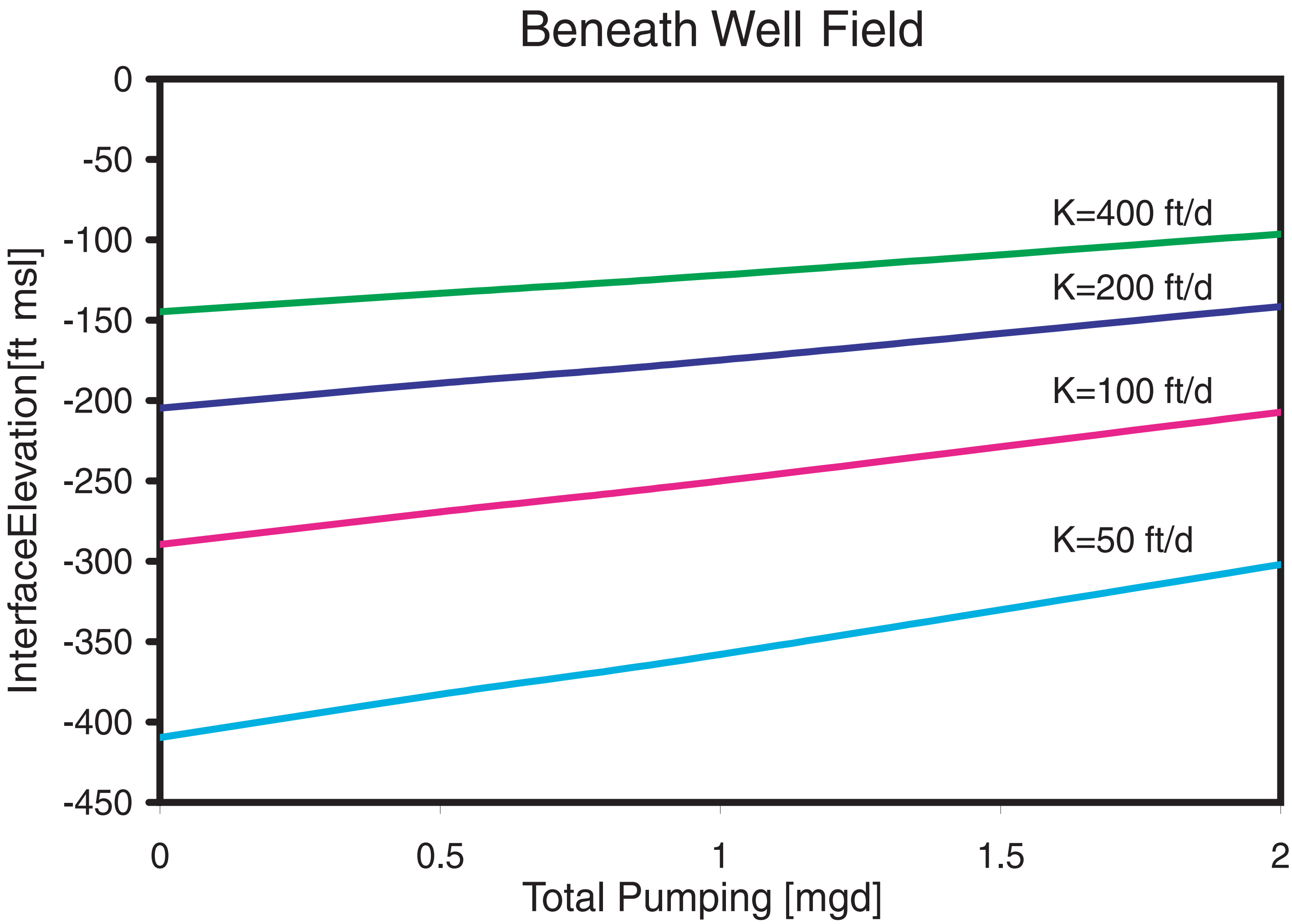


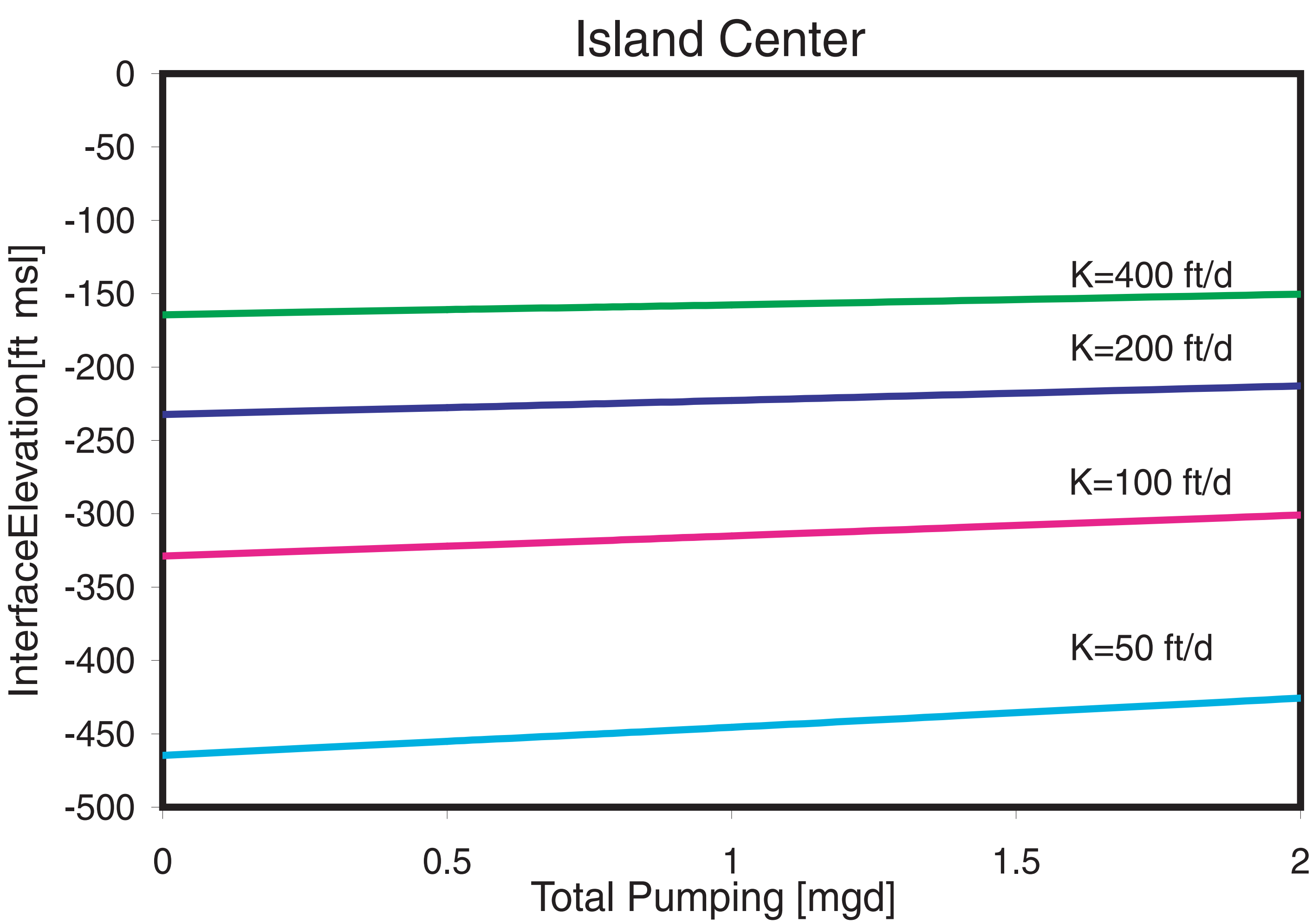
Interface Rise in Response to Pumping
$Q_{Total} = 1$ MGD Distributed Among Four Well Fields

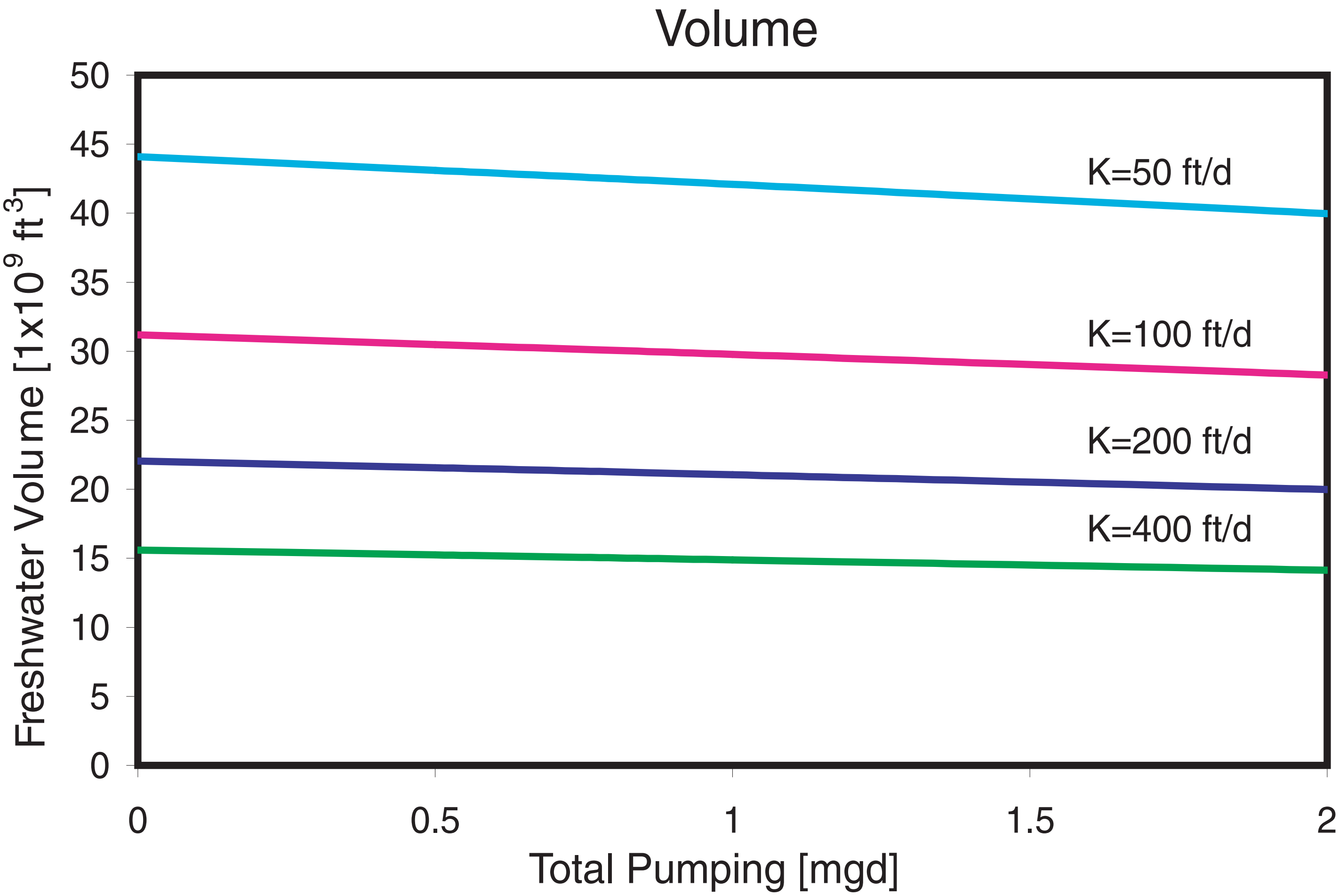


Transect Locations




Beneath Well Field
InterfaceElevation[ft msl]
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
K=400 ft/d
K=200 ft/d
K=100 ft/d
K=50 ft/d
0
0.5
1
1.5
2
Total Pumping [mgd]


Island Center
InterfaceElevation[ft msl]
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
K=400 ft/d
K=200 ft/d
K=100 ft/d
K=50 ft/d
0
0.5
1
1.5
2
Total Pumping [mgd]


Volume
Freshwater Volume [1x10^9 ft^3]
50
45
40
35
30
25
20
15
10
5
0
K=50 ft/d
K=100 ft/d
K=200 ft/d
K=400 ft/d
0
0.5
1
1.5
2
Total Pumping [mgd]

CONCLUSIONS

This study has generated a number of interesting findings regarding natural freshwater lens hydraulics and interface dynamics in response to pumping, including:

1) Natural freshwater lens depth is greater for conditions of greater recharge and/or lower hydraulic conductivity, and greater island area;
2) Higher aspect ratio elliptical island shape (long and thin like a barrier island) results in a thinner freshwater lens (other factors being equal).
3) Interface rise is greatest directly beneath a pumping well or well field;
4) Interface rise beneath a well field is the result of regional interface rise (lens thinning) and localized upconing;
5) Interface elevation (at steady state) in response to pumping increases linearly with pumping rate;
6) Lens volume (at steady state) in response to pumping decreases linearly with pumping rate; and
7) Greater island aquifer hydraulic conductivity results in both lesser drawdown near wells and a lesser interface rise (other factors such as recharge and pumping rate held equal), but the thin freshwater lens produced in high conductivity aquifers can limit well field yields to values below those for lower hydraulic conductivity aquifers.

DISCUSSION

GFLOW 2000 proved to be a flexible and efficient tool with which to analyze i dealized freshwater lens aquifer. The modeling analyses showed some expected results; for example that greater recharge and/or larger island size produces deeper freshwater lenses with greater volumes. The modeling also revealed some less obvious results; for example that any combination of recharge hydraulic conductivity that yield the same N/K ratio (for example 12 inches recharge per year in a 100 ft/day aquifer, or 24 inches of recharge per year 200 ft/day aquifer) produce the same lens geometry. Model results also indicate that a more permeable aquifer does not always allow the greatest yields from well field because the lower hydraulic gradient governing discharge to the creates a thinner lens from which to pump, thereby placing the starting interface elevation closer to the well screen.

GFLOW could also be used to examine aquifers of nonidealized geometry (irregular coastal boundary) with hydraulically connected surface water features (e.g. streams or wetlands). The effects of sea level rise on lens characteristics could be analyzed by generating a series of steady-state approximations future times of interest.

The method of freshwater lens analysis using GFLOW is attractive because models are relatively easy to set up, and computational times are a small of the times required for large sharp-interface or variable-density numerical models for a similar lens. This is especially true when one considers that the numerical model would require a very fine computational grid to produce level, interface elevation, or particle tracking information at a spatial resolution approaching that achievable with an analytic element model.

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REFERENCES

Fetter, C.W. 1994. Applied Hydrogeology, 3rd ed. , Macmillan, New York, 691

GFLOW 2000. Haitjema Software, Bloomington, IN. Vers. 1.3.1, June 9, 2002.

Haitjema, H.M. 2002. Freshwater and salt water interface flow in GFLOW 2000, April 24, 2002. http://www.haitjema.com/interface.pdf