Assessing sustainability of groundwater resources on Jeju Island, South Korea, under climate change, drought, and increased usage

Aly El-Kadi

Acknowledgements

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Introduction

Sophocleous (2000):

Sustainable development should "*meet the needs of the present without compromising the ability of future generations to meet their own needs.*"

Sustainable groundwater use requires setting upper limits on water withdrawal (defined as sustainable yield) to avoid compromising the source (Mink 1992; Mink and Lau 1990; Takasaki and Mink 1985).

- Sustainable yield is not always easy to estimate or utilize in practice.
- Estimation problems arise due to poor assumptions in models and the lack of reliability of available data.
- For example, although water use in Hawaii is subjected to regulations regarding sustainable yield, studies have shown rising salinity and decreasing fresh water resources (Oki, 2005)

- On islands, where potable water resources are limited, an accurate and reliable estimate of sustainable use or yield is critical.
- Estimates have to address not only decreasing water availability, as manifested by declining water levels, but also deterioration of water quality caused by, e.g., seawater intrusion (Kim et al. 2006; Kim et al. 2003b) or agro-chemical use (Koh et al. 2007).

- On Jeju Island, as is the case for many islands, sustainability of groundwater resources is especially important given the increasing water demands from urban and agricultural development and the island’s lack of reliable surface water resources (Hagedorn et al. 2011; Won et al. 2006).
- The island has experienced tremendous growth over the past 30 years and now supports a residential population of 583,000 and 8.7 million visitors annually.

- Groundwater aquifers supply 92% of fresh water consumed on Jeju (Kim et al., 2003).
- Because of the rapid growth and increased demand for potable water, saltwater intrusion has become a persistent problem particularly in the eastern portion of the island (Kim et al., 2003; Kim et al., 2006).

- In Hawaii, the sustainable yield of an aquifer is defined by the Hawaii State Water Commission (1979) as the "*water supply that may normally be withdrawn from a source at the maximum rate, which will not severely impair source utility.*"
- The clearest expression of sustainable yield is that of allowable net draft for a selected equilibrium head (Mink,1980) .
- Mink (1981) developed the Robust Analytical Model (RAM) for estimating the sustainable yield of a basal aquifer. .

- The analytical RAM2 model was developed as an extension of the original RAM model to include the simulation of the salinity distribution in a transition zone (Liu 2007).
- The RAM and RAM2 models are currently used to estimate the sustainable yield of basal aquifers in the Hawaiian Islands (Wilson Okamoto Corporation, 2008).
- However, these analytical models are limited in their ability to evaluate spatio-temporal effects of climate and withdrawal scenarios on groundwater resources.

- Based on detailed analysis of aquifer testing data on Jeju Island, Hahn et al. (1997) estimated sustainable yield by combining mass balance with Darcy’s law.
- An upper limit for the ratio between the equilibrium water level to be maintained and the initial water level in the pre-development time for each area under consideration.
- This approach is subjected to significant uncertainty due to data limitations, considering that initial water-level data for pre-development times are rarely available.

- Koh et al. 84 (2006b) reported the most recent estimate of sustainable yield by KOWACO as 1.77 x 10^6 m^3/d.
- KOWACO also specifies a maximum allowable aquifer withdrawal rate (MAWR) of 1.48 x 10^6 m^3/d for domestic, industrial, and irrigation purposes (KOWACO 2003a), which is roughly 84% of the estimated sustainable yield.

Estimates of groundwater recharge on Jeju range from 4.09 x 10^6 to 4.80 x 10^6 m^3/d (Hahn et al. 1997; KOWACO 2003b; Koh et al. 2006b; Won et al. 2006). Thus, the limits on aquifer pumping as a percentage of groundwater recharge range from 37 to 43% for the sustainable yield and from 31 to 36% for the MAWR.

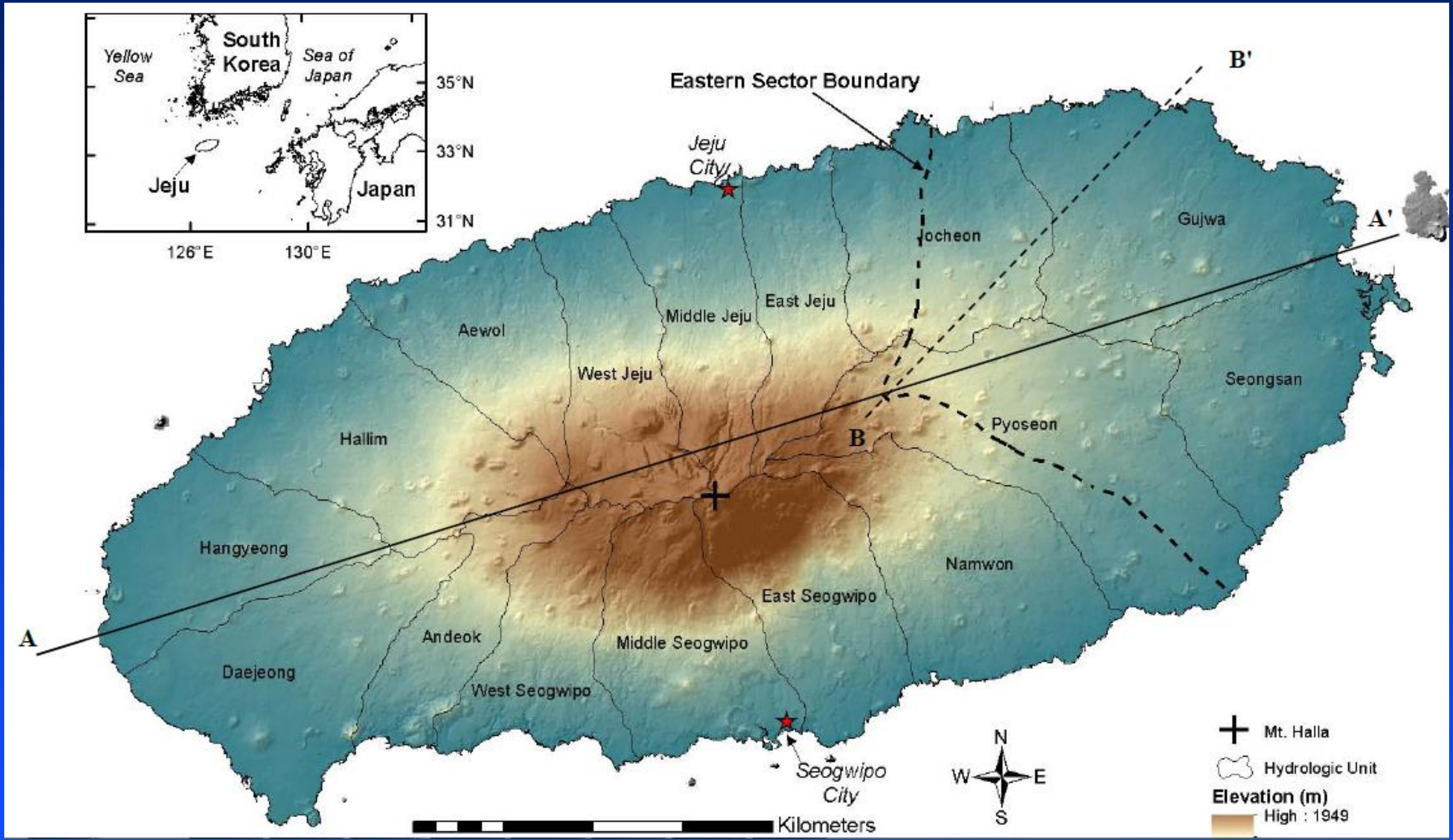
- By 1993, total daily pumping averaged 0.66 x 10^6 m^3/d from all of Jeju’s domestic, municipal, and irrigation water supply wells (Hahn et al. 1997).
- These data imply that pumping from Jeju’s aquifers by the mid-1990s was already at 37% of the sustainable yield and 45% of the MAWR.

- Although accurate estimates of pumping rates from all sources on Jeju in recent years are lacking, it is highly likely that total pumping now exceeds the rate in 1993 of 37%.
- Based on discussion with various government groups, a value of a total use of 64% of the sustainable yield was adopted in the current study based on a best estimate.

Objective

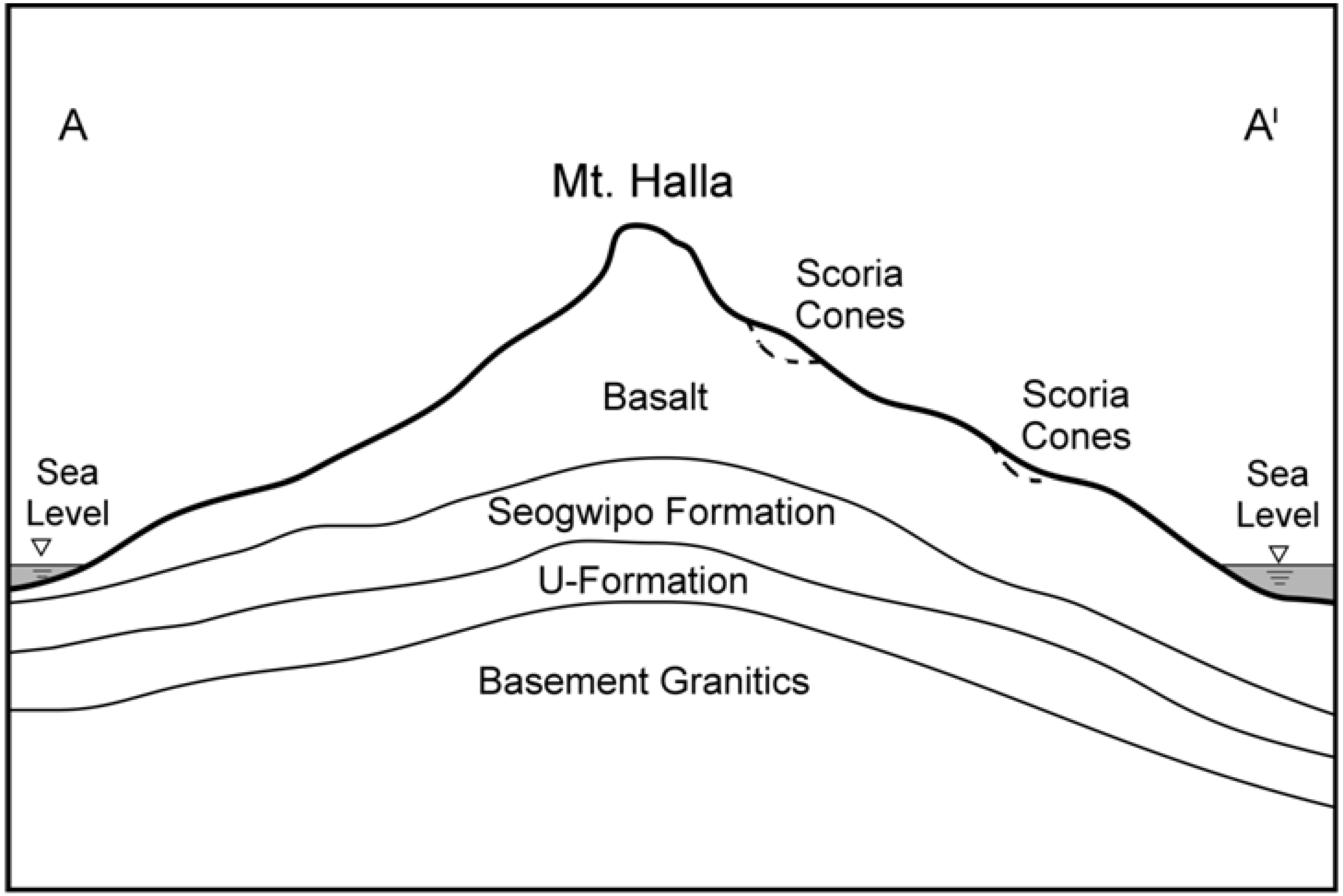
- Assessing sustainable groundwater use for Jeju Island under projected climate, land-use, and increased-pumping conditions.
- Numerical modeling is used in assessing the sustainability by evaluating the response of the groundwater system to different climate, land use, and pumping scenarios.
- The results for each scenario are evaluated by assessing negative effects on groundwater sustainability indicators, namely, hydraulic head, spring flow, and salinity.

Study Site



Yellow Sea
South Korea
Sea of Japan
Jeju
Japan
35°N
33°N
31°N
126°E
130°E
Eastern Sector Boundary
B'
A'
B
A
Jeju City
Seogwipo City
Jocheon
Gujwa
East Jeju
Middle Jeju
Aewol
West Jeju
Seongsan
Pyoseon
Hallim
Hangyeong
Namwon
East Seogwipo
Andeok
Middle Seogwipo
Daejeong
West Seogwipo
Kilometers
N
W
E
S
Mt. Halla
Hydrologic Unit
Elevation (m)
High : 1949

Geology



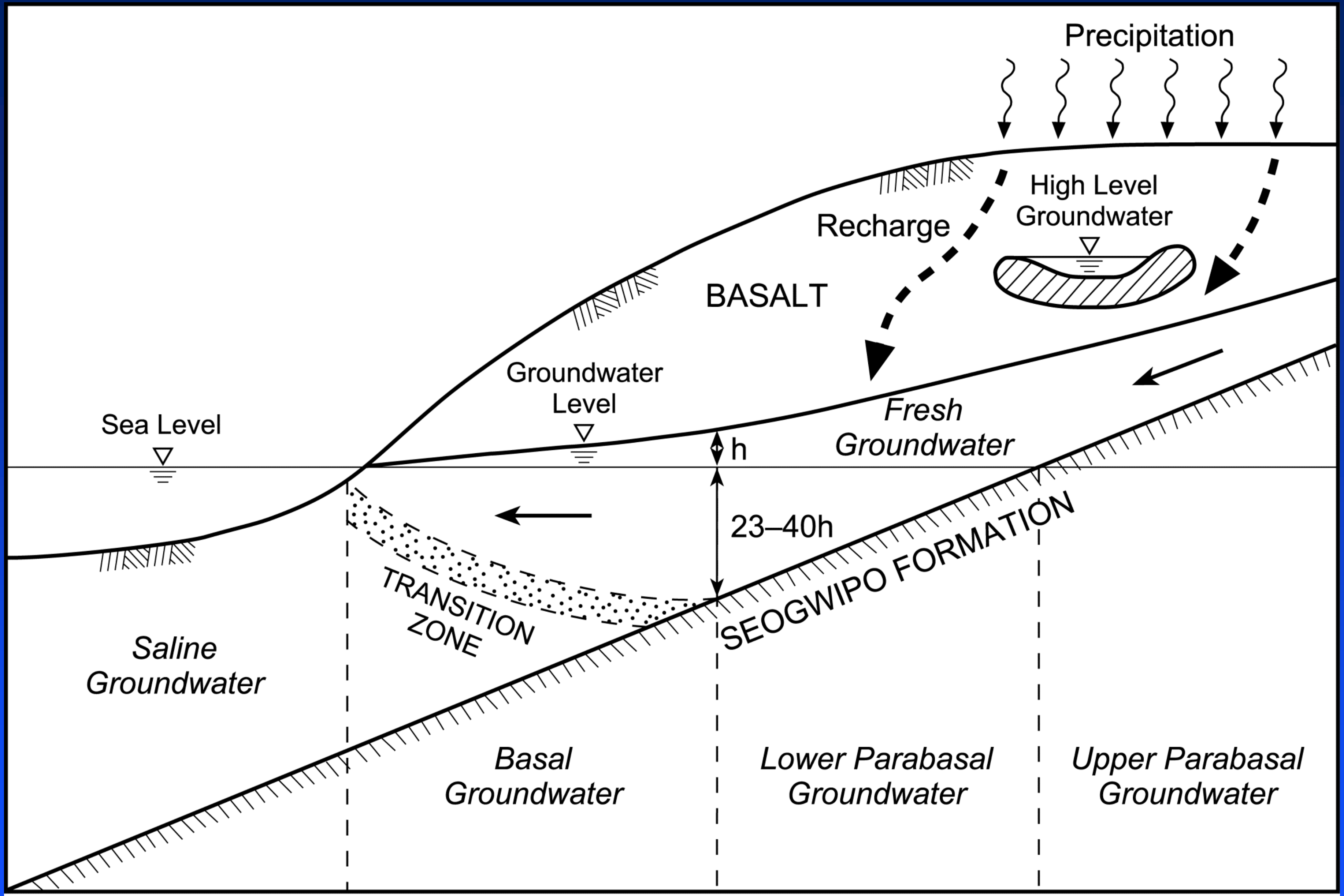
Not to scale.

Geology

1. the main volcanic lithologies consisting of permeable basalt, andesite and trachyandesite lavas, with numerous flow units and abundant fractures;
2. the Seogwipo Formation, comprising low permeability volcanic sediments with an average thickness of about 100 m (Nam et al. 2009);

Geology

3. the U-Formation, including low permeability unconsolidated silt and sand deposits with an average thickness of approximately150 m (Nam et al. 2009); and,
4. the relatively impermeable basement, which is mainly composed of welded tuffs 134 and granite occurring at depths of about 250-300 m below sea level (Nam et al. 135 2009).


Precipitation
High Level
Groundwater
Recharge
BASALT
Groundwater
Level
Sea Level
h
Fresh
Groundwater
23–40h
SEOGWIPO FORMATION
TRANSITION
ZONE
Saline
Groundwater
Basal
Groundwater
Lower Parabasal
Groundwater
Upper Parabasal
Groundwater

Not to scale.

Methods

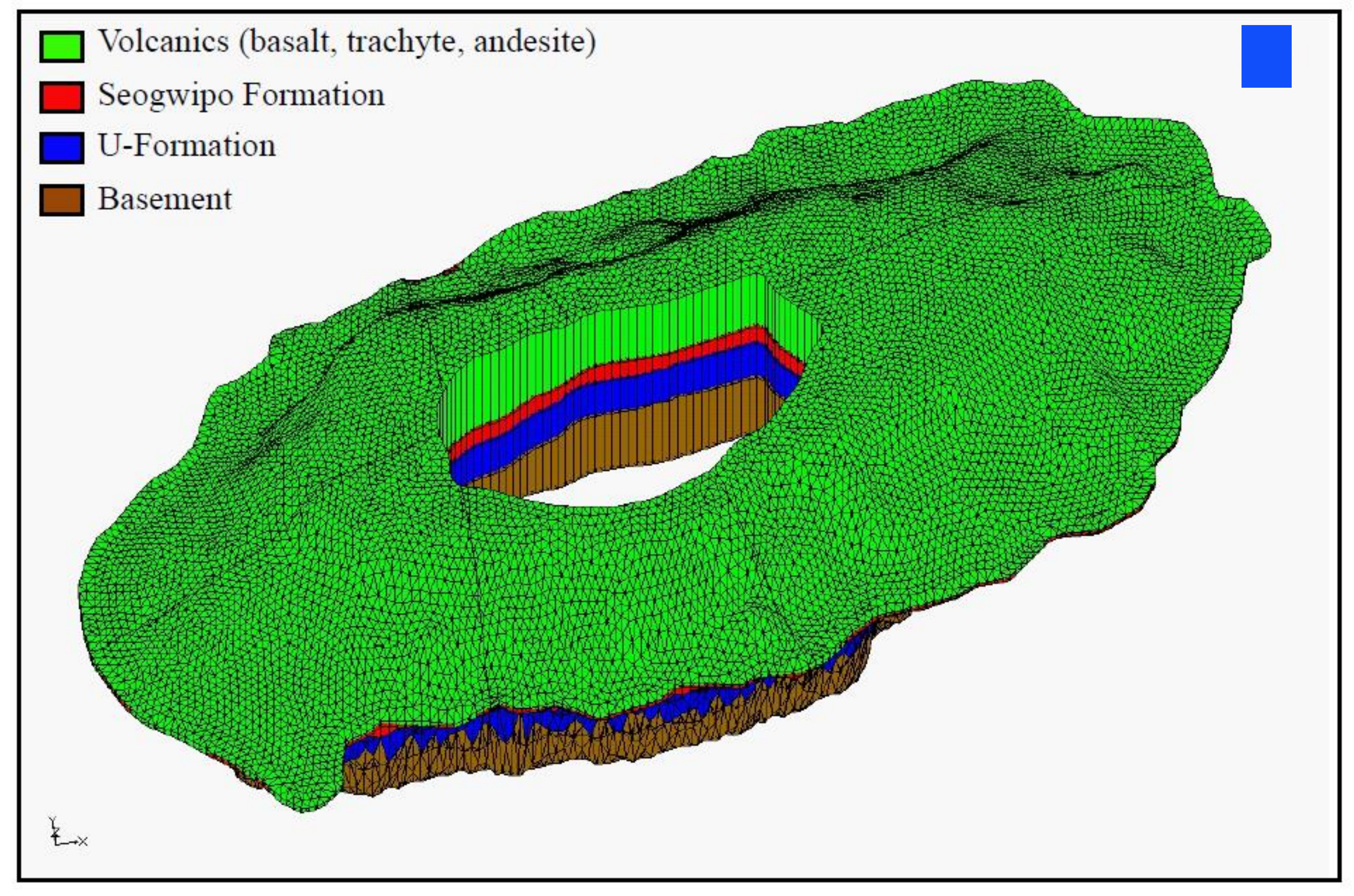
- MODFLOW: to assess water levels and spring flows for the whole island
- SEAWAT: to assess water salinity for the eastern sector where significant saltwater intrusion occurs

MODFLOW Model

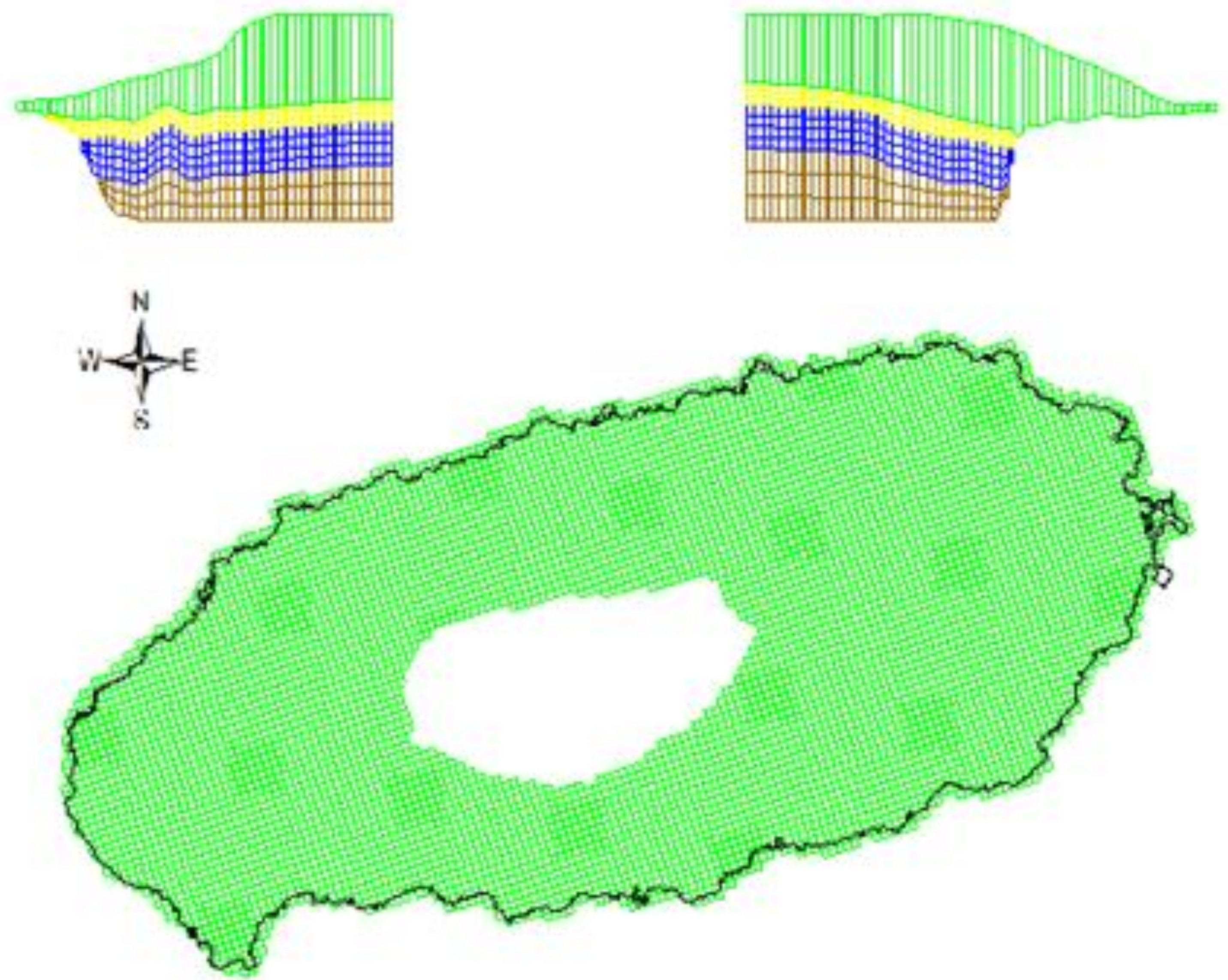
The donut model

The analysis was simplified by excluding the area of the island above the 600 m asl, because of:

1. lack of understanding of the spatial distribution of low permeability volcanic sequences impeding vertical flow and perch groundwater,
2. lack of information on the subsurface distribution of the Seogwipo Formation in the area,
3. lack of water elevation data needed for calibration.



Modeled view Jeju Island


N
W
E
S

Springs

- MODFLOW calibration was done through matching the simulated hydraulic heads to contour values taken from Won et al. (2006), and matching average spring flows at the coast, for which each spring should be treated as a point drain.
- Modeling parameters for a drain include drain-bed elevation and a conductance parameter, which is combined with the groundwater elevation to compute the amount of spring flow. Hence, the drain acts as a head-dependent source that will dry-up if the water table declines below a certain level.

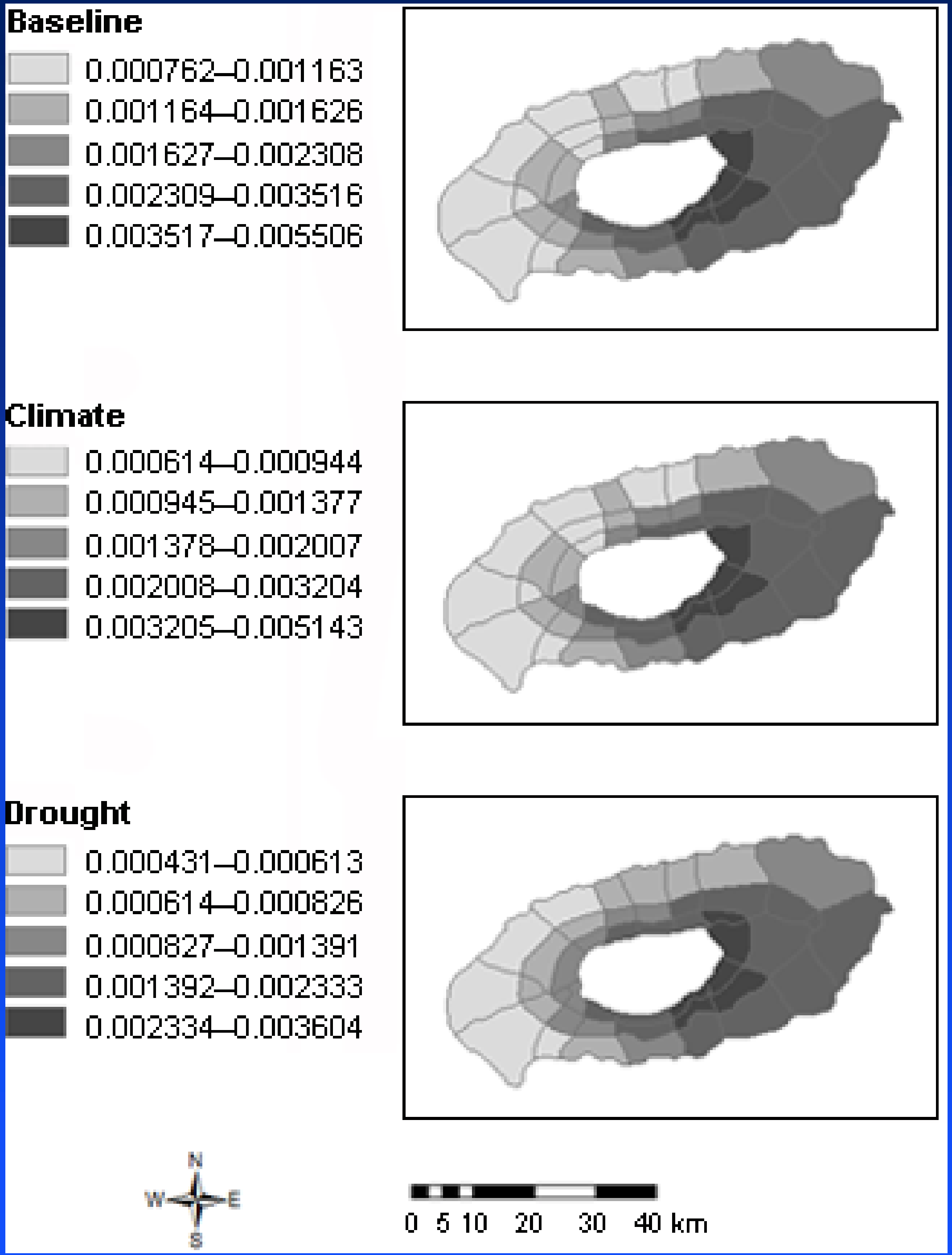
- Calibration was done by the tedious process of adjusting the drain-bed elevation of each drain until the resulting simulated spring flow approximately matched the average value.
- However, due to the large number of springs, only springs with flows larger than 1,000 m^3/d were treated as drains. The springs with flows less than 1,000 m^3/d (with total flow of about 10% of the total) were simulated as constant flux sources, which always withdraw their specified amount of water from the system.

- MODFLOW modeling: steady-state conditions for the baseline and climate scenarios, representing presumed permanent management decisions.
- The initial conditions of head for the models were assigned based on average water levels reported by Won et al. (2006).
- Drought was assessed for a transient condition at the end of 5 and 10-year duration periods, with the baseline-calibrated head-values representing the initial condition.

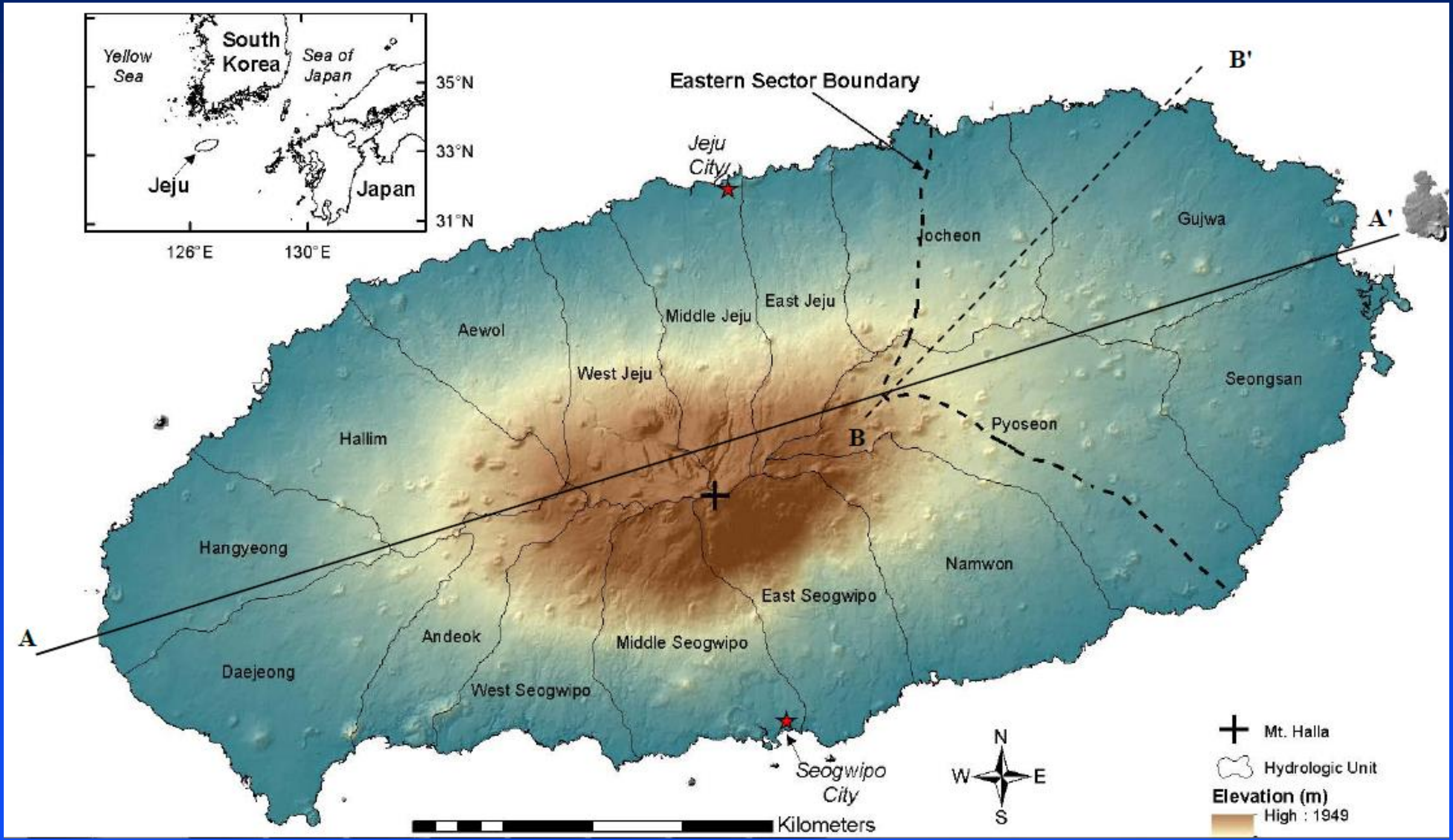
- The transient simulations were done for variable time steps starting at about two days with an expansion by a factor of 1.05 for the duration of the simulation.
- All cases were run with constant recharge at the pertinent average daily rate computed for each of the three recharge scenarios.

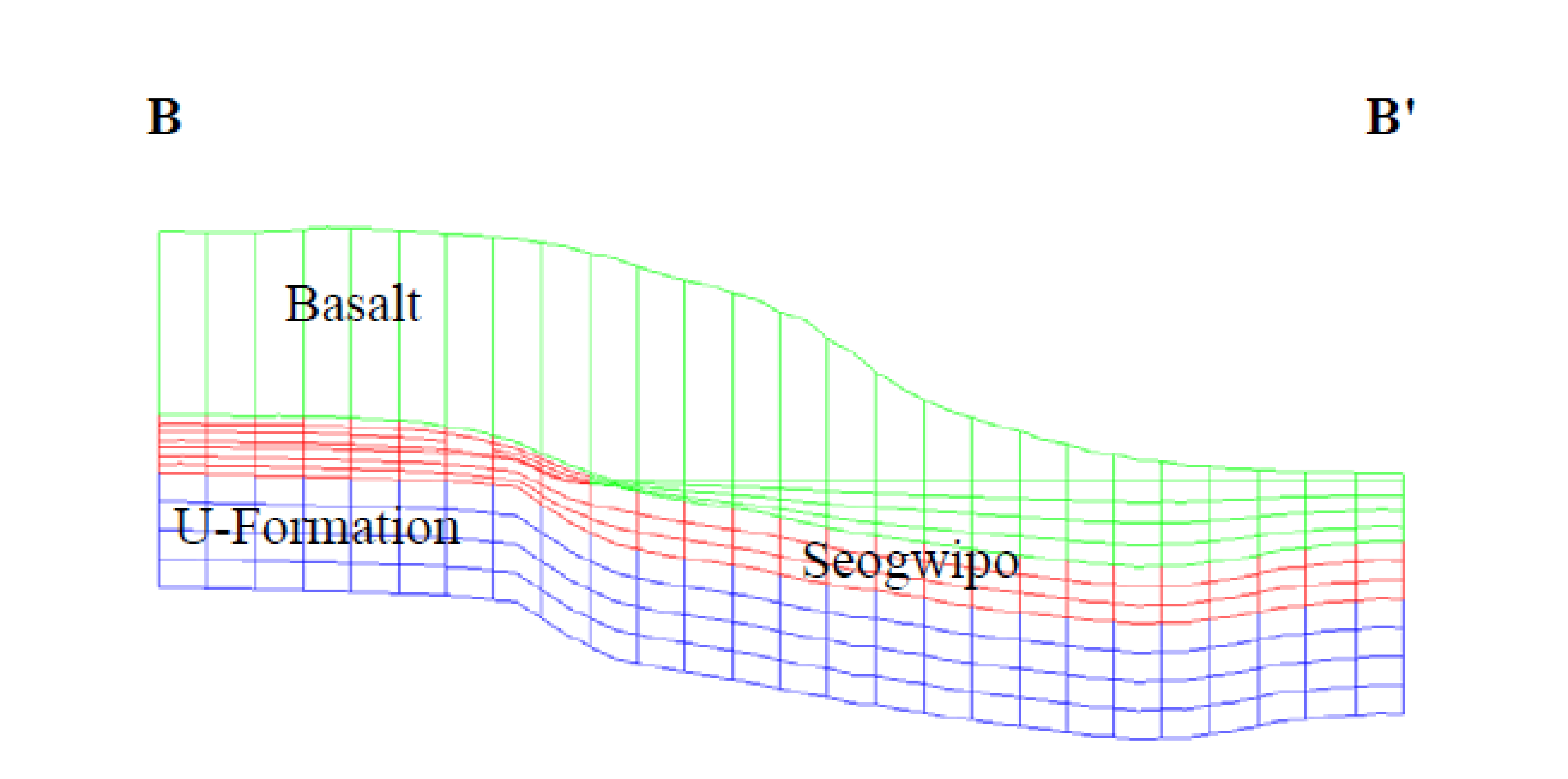
Recharge

- Grid cell values of recharge for baseline, drought, and climate scenarios as computed by Mair et al. (2013b) were transformed into an average recharge rate within the hydraulic-conductivity calibration zones.
- The greatest recharge occurs under a baseline scenario during 1992- 2009 (883 mm/yr or 1,605 x 10^6 m^3/yr) followed by the climate scenario (788 mm/yr or 1,432 x 10^6 m^3/yr) and drought scenario (591 mm/yr or 1,073 x 10^6 m^3/yr).

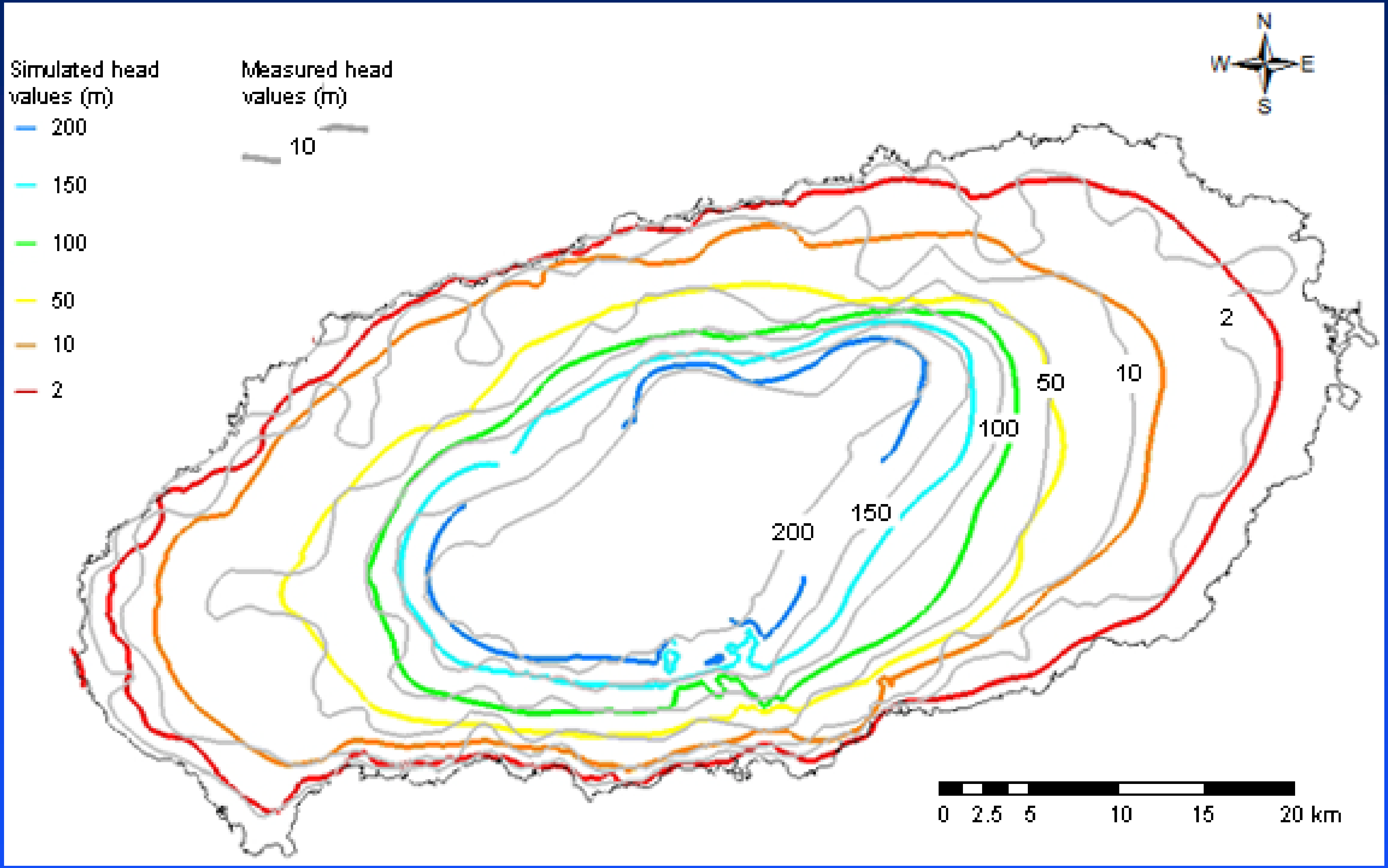

Baseline
0.000762–0.001163
0.001164–0.001626
0.001627–0.002308
0.002309–0.003516
0.003517–0.005506
Climate
0.000614–0.000944
0.000945–0.001377
0.001378–0.002007
0.002008–0.003204
0.003205–0.005143
Drought
0.000431–0.000613
0.000614–0.000826
0.000827–0.001391
0.001392–0.002333
0.002334–0.003604
N
W
E
S
0 5 10 20 30 40 km

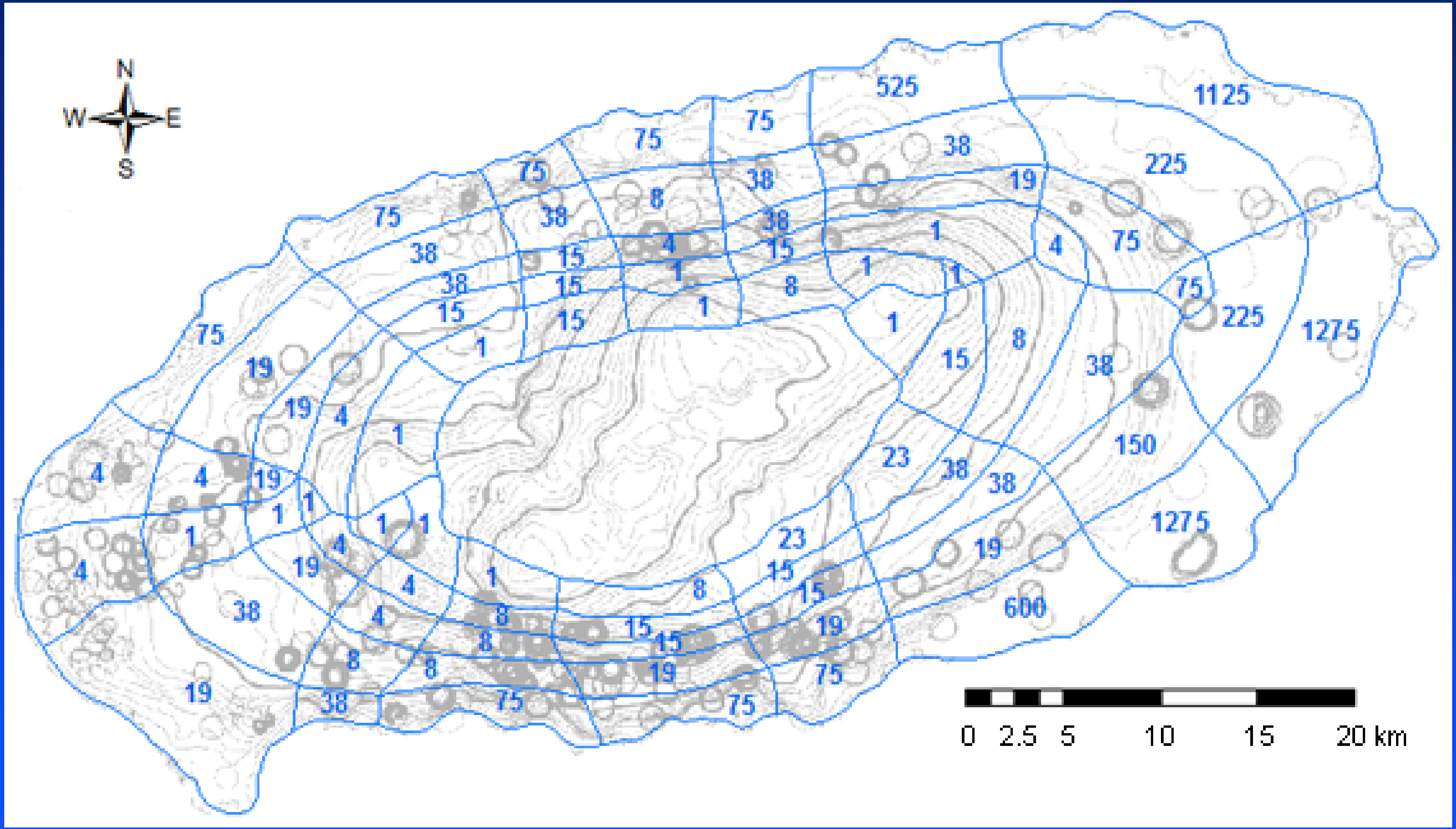
SEAWAT


South Korea
Yellow Sea
Sea of Japan
Jeju
Japan
35°N
33°N
31°N
126°E
130°E
Eastern Sector Boundary
B'
A'
Jeju City
Jocheon
Gujwa
East Jeju
Middle Jeju
Aewol
West Jeju
Seongsan
Pyoseon
B
Hallim
Hangyeong
Namwon
East Seogwipo
A
Andeok
Middle Seogwipo
Daejeong
West Seogwipo
Seogwipo City
Kilometers
N
W
E
S
Mt. Halla
Hydrologic Unit
Elevation (m)
High : 1949


B
B'
Basalt
U-Formation
Seogwipo

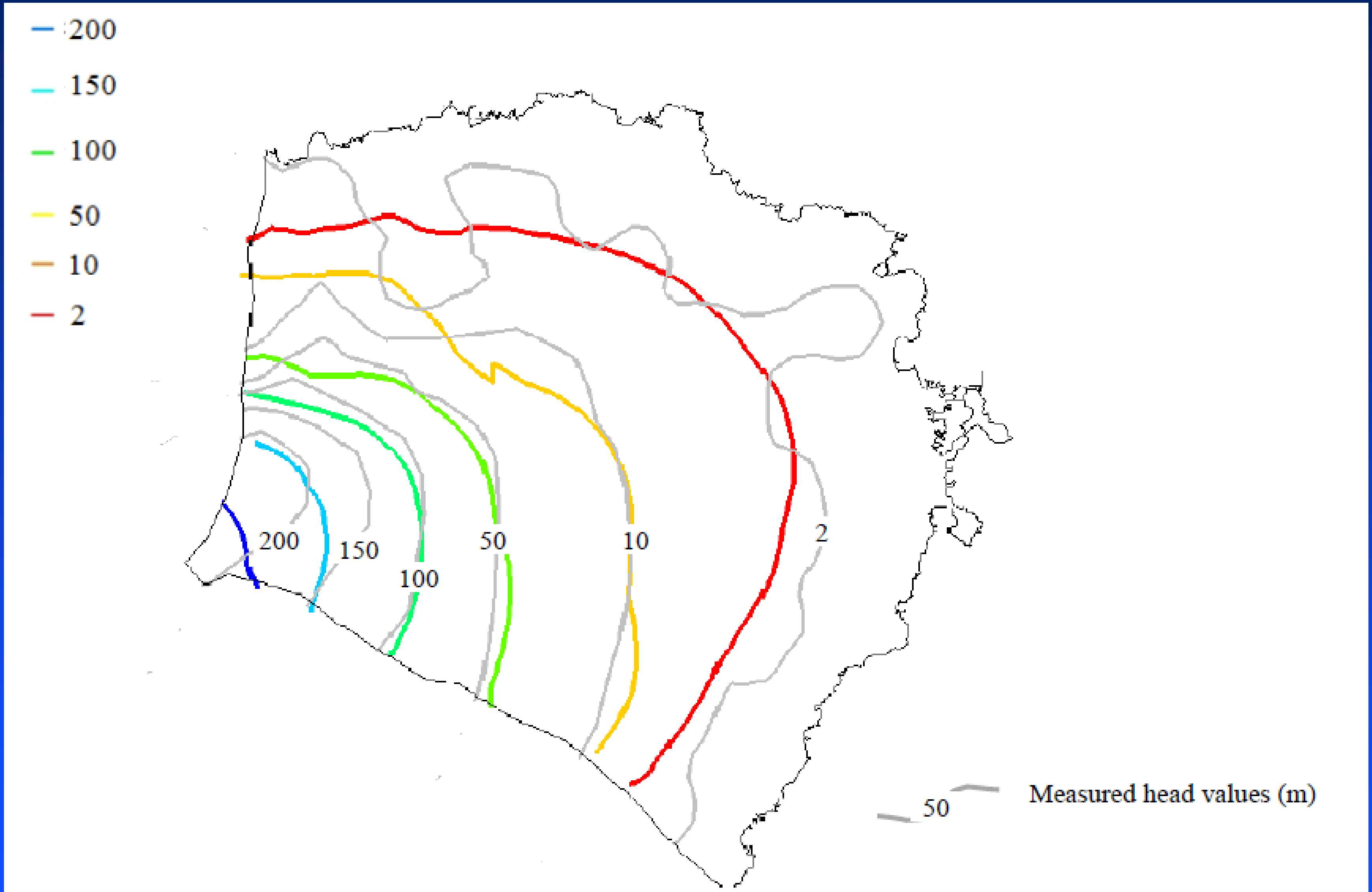
MODFLOW Calibration


Simulated head values (m)
200
150
100
50
10
2
Measured head values (m)
10
N
W
E
S
2
10
50
100
150
200
0 2.5 5 10 15 20 km


N
W
E
S
525
1125
75
75
75
75
38
225
38
19
8
38
75
38
4
75
38
15
1
4
15
38
1
1
75
15
1
8
225
1275
15
15
1
1
75
1
15
8
38
19
19
4
1
150
4
4
19
23
38
38
1
1
1
1
1
1
1275
4
4
19
23
1
19
15
38
4
8
15
19
1
600
4
8
15
15
19
8
4
8
8
19
75
19
38
75
75
0
2.5
5
10
15
20 km

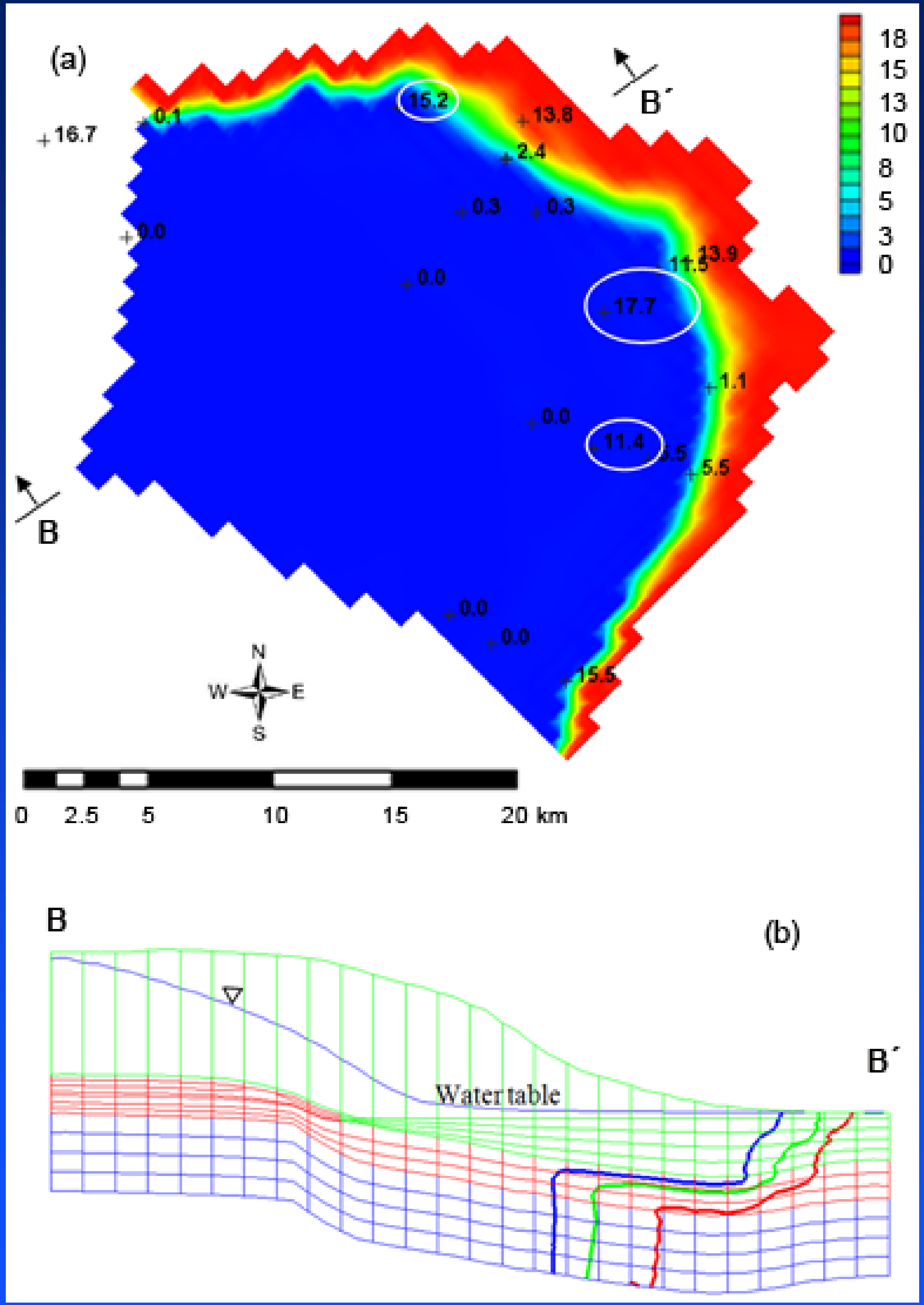
SEAWAT Calibration

- Head


200
150
100
50
10
2
200
150
100
50
10
2
50
Measured head values (m)

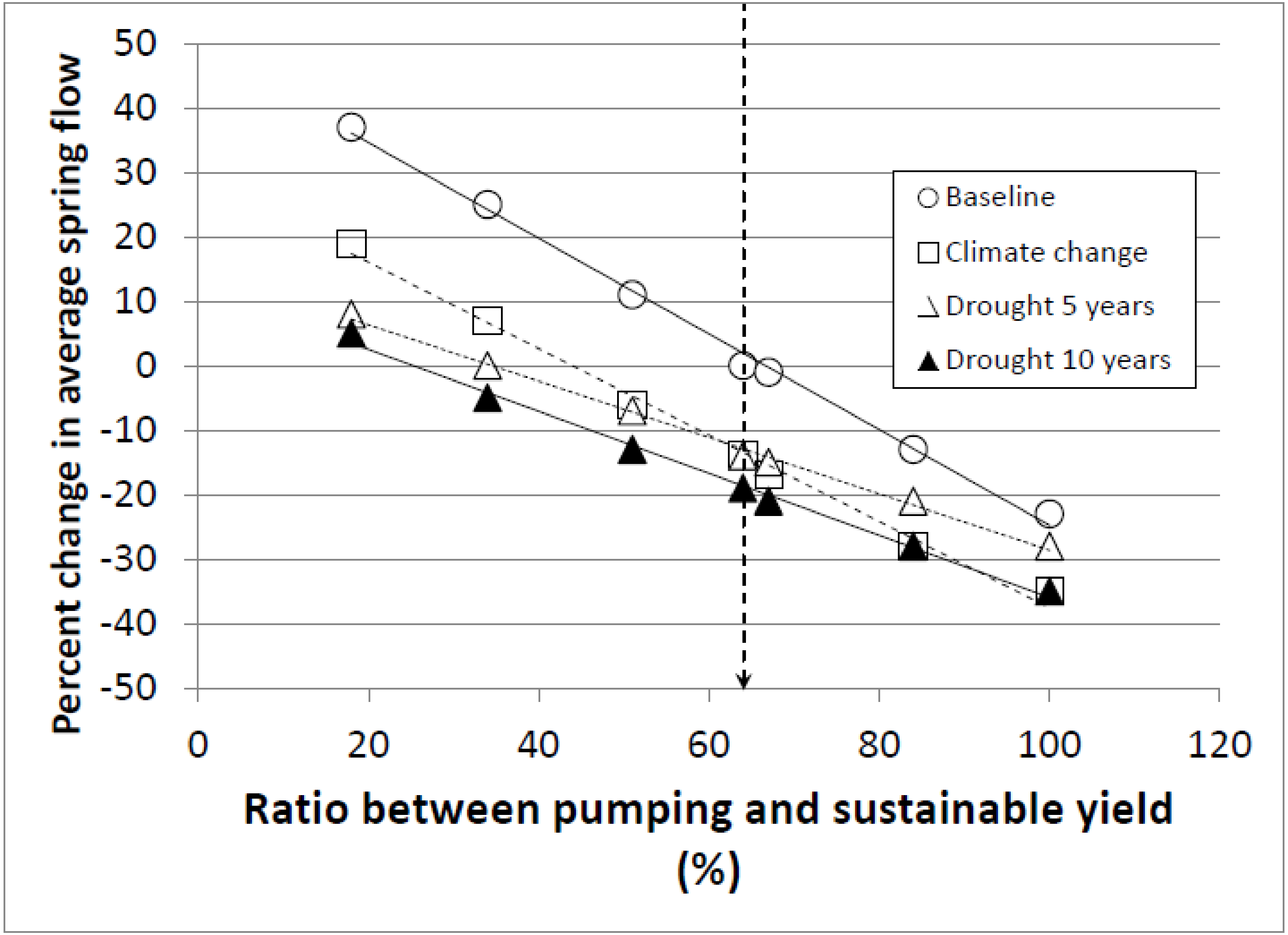
SEAWAT Calibration

- Salinity

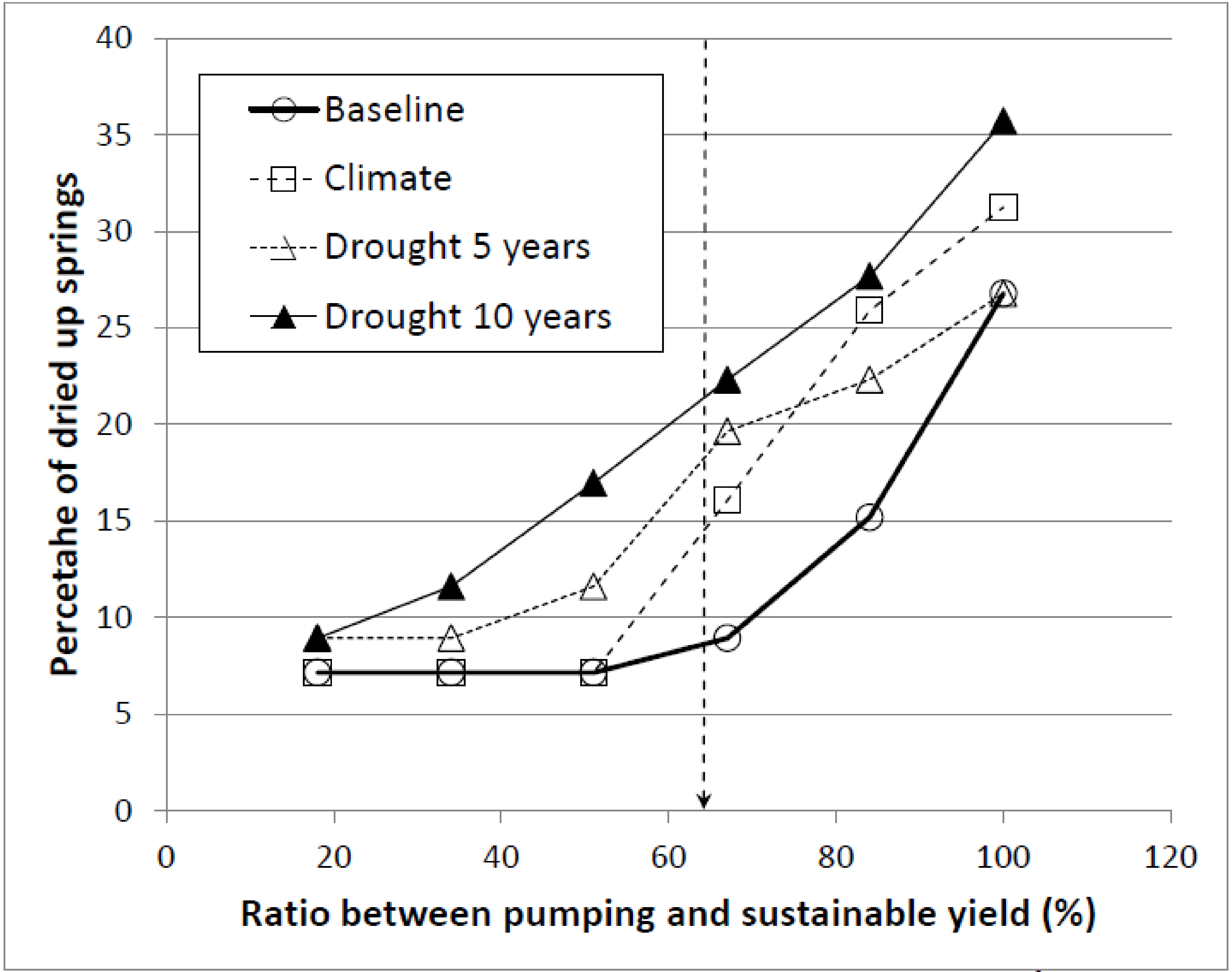


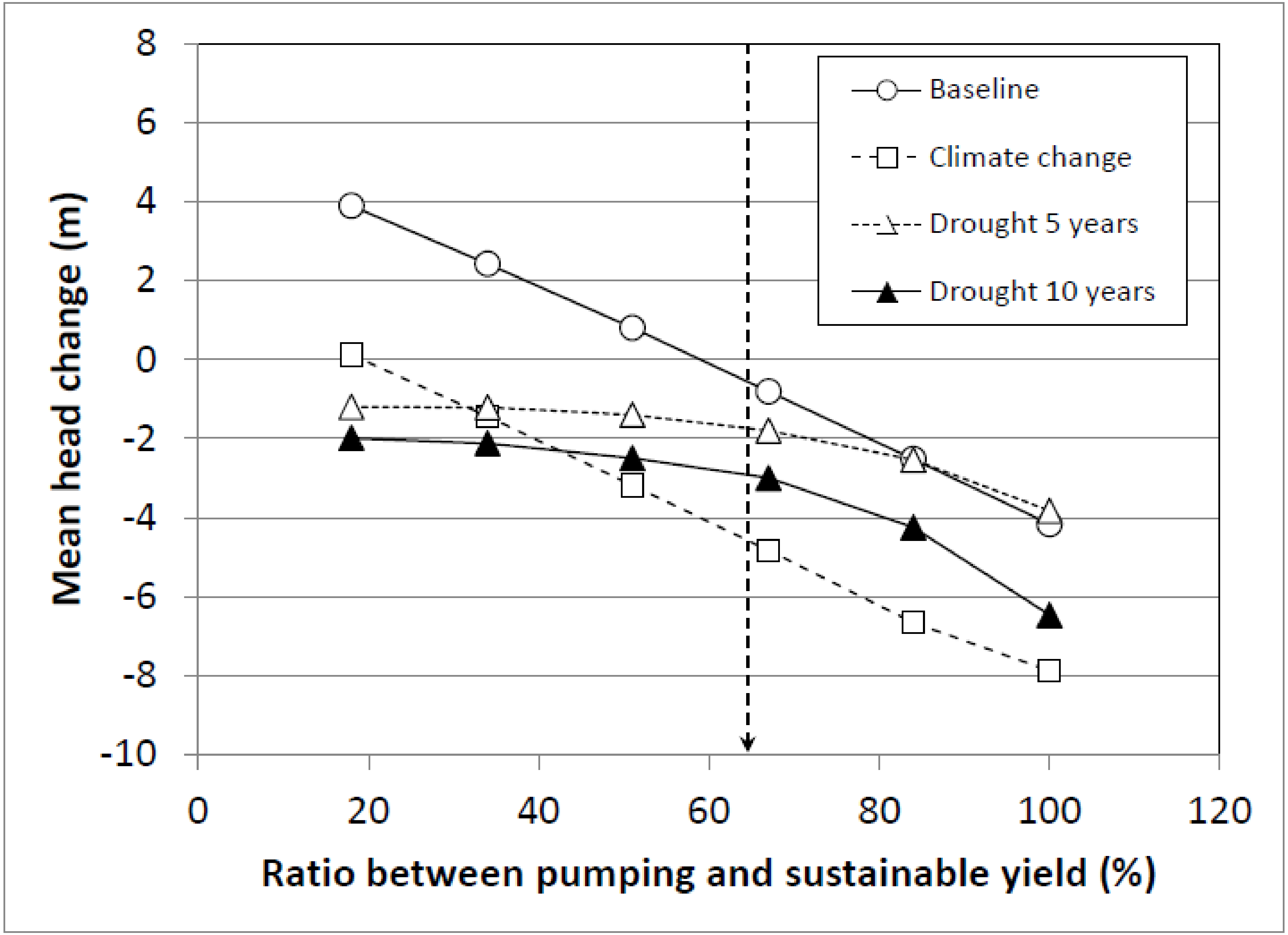
(a)
18
15
13
10
8
5
3
0
B´
16.7
0.1
15.2
13.8
2.4
0.3
0.3
0.0
0.0
13.9
11.5
17.7
1.1
0.0
11.4
5.5
5.5
0.0
0.0
15.5
B
N
W
E
S
0
2.5
5
10
15
20 km
B
(b)
B´
Water table

Scenario Simulations



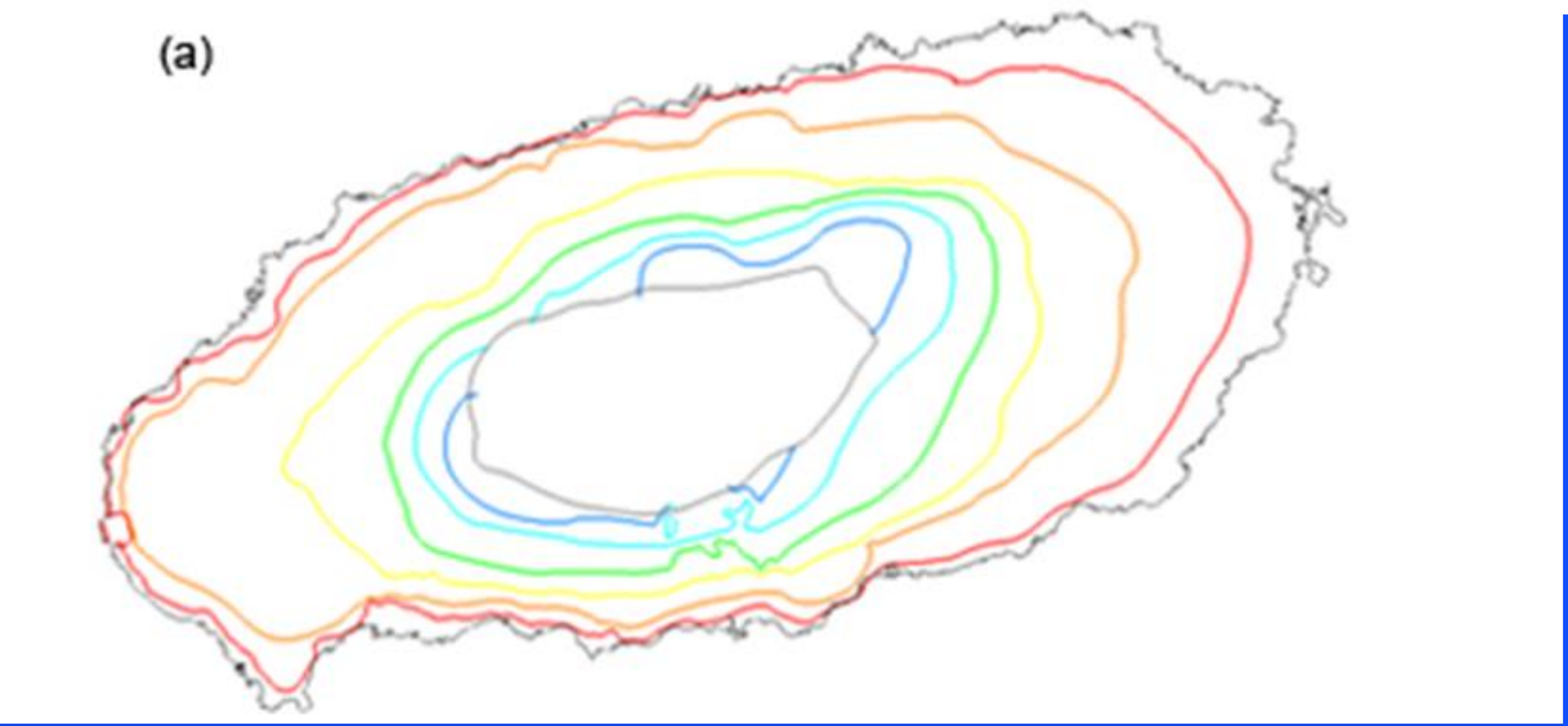
Percent change in average spring flow
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
20
40
60
80
100
120
Baseline
Climate change
Drought 5 years
Drought 10 years
Ratio between pumping and sustainable yield (%)

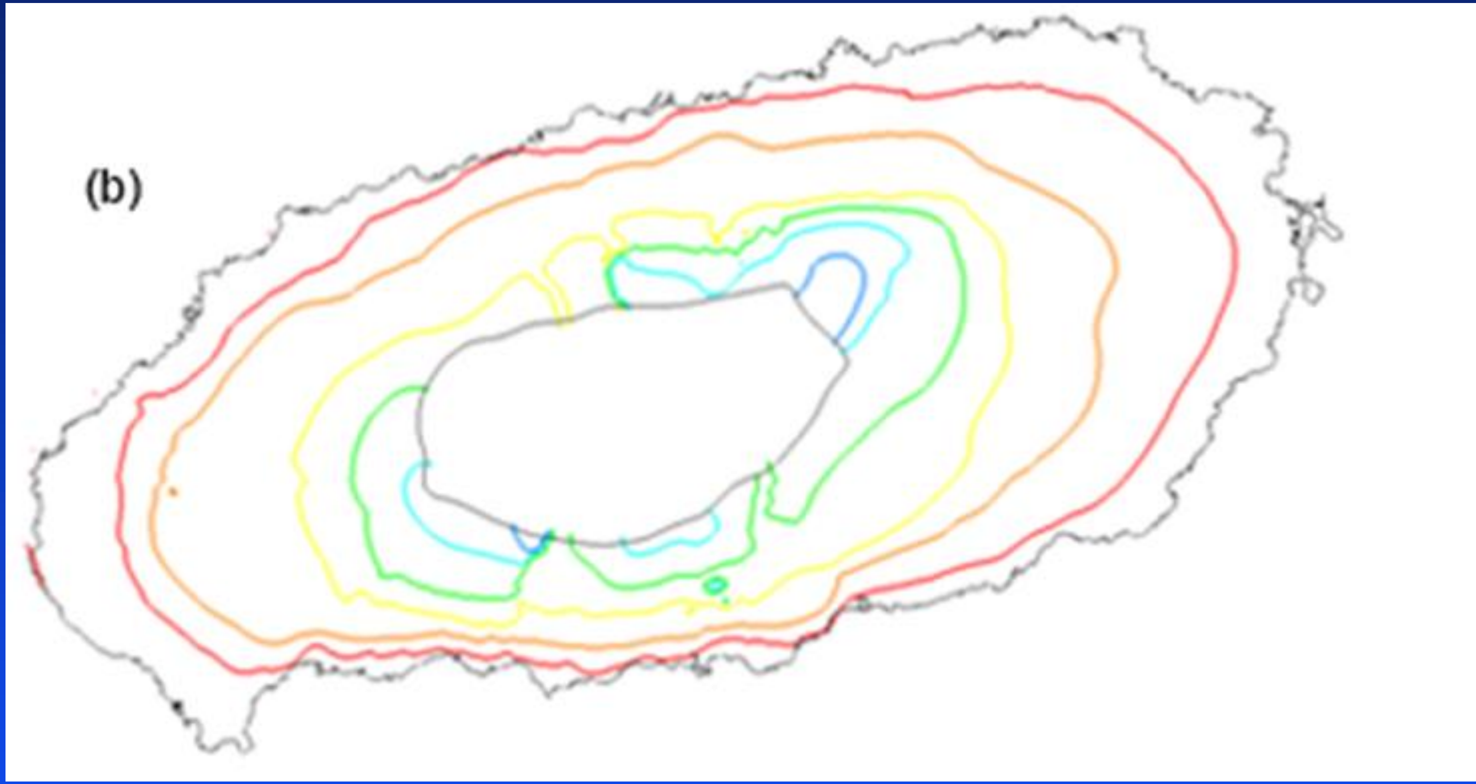

Baseline
Climate
Drought 5 years
Drought 10 years
Percetahe of dried up springs
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Ratio between pumping and sustainable yield (%)

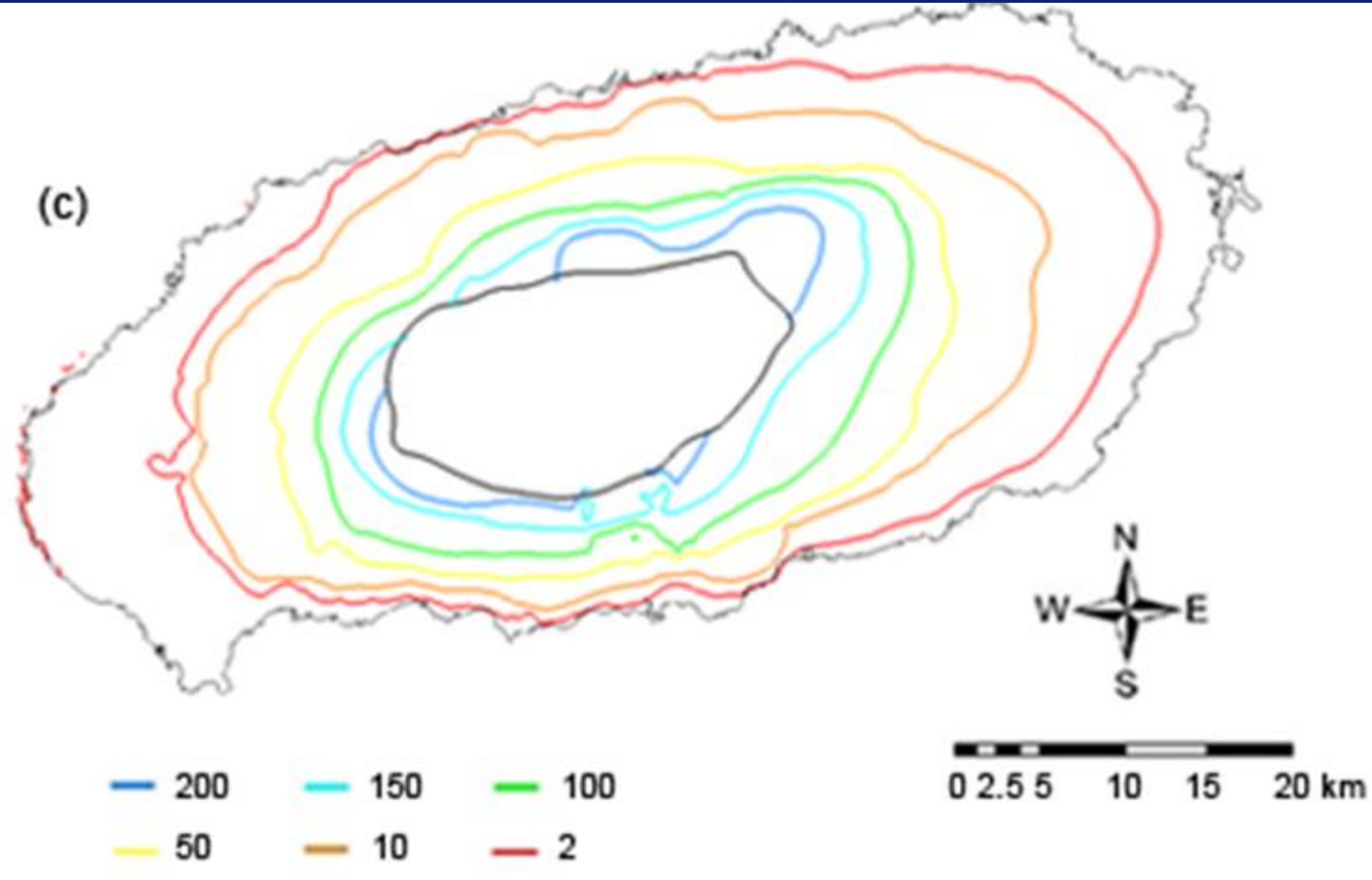


Mean head change (m)
8
6
4
2
0
-2
-4
-6
-8
-10
0
20
40
60
80
100
120
Ratio between pumping and sustainable yield (%)
Baseline
Climate change
Drought 5 years
Drought 10 years

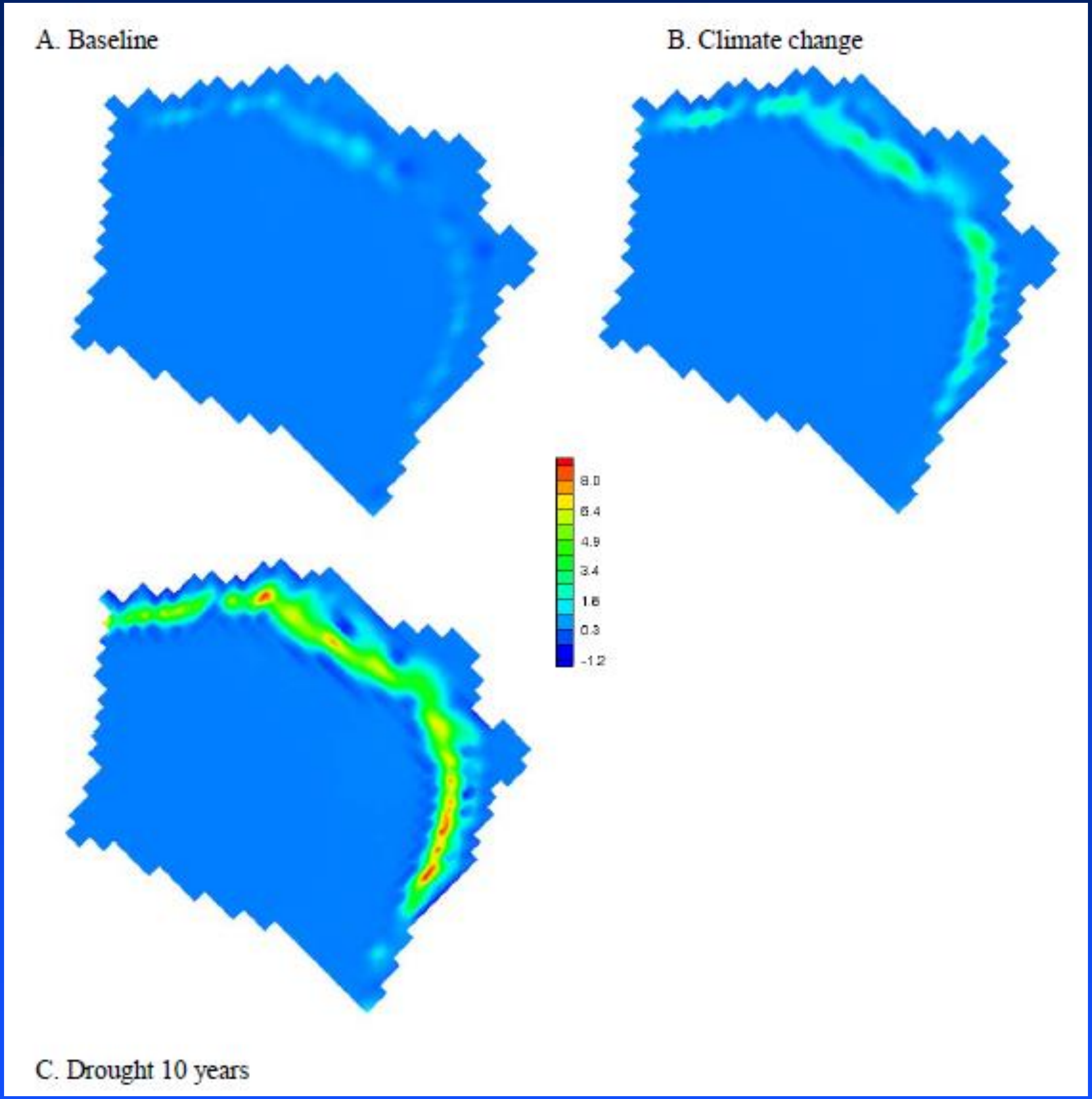
Hydraulic head contours (m asl.) for the climate change case under pumping scenarios of 18, 51, and 84% of sustainable yield


(a)


(b)


(c)
N
W
E
S
0 2.5 5 10 15 20 km
200
150
100
50
10
2

Expected changes in salinity (in g/L) for the three scenarios after 10 years


A. Baseline
B. Climate change
C. Drought 10 years
8.0
6.4
4.9
3.4
1.8
0.3
-1.2

Management Recommendations

- Future management decisions should take into consideration the fact that long sustained drought and climate change has serious adverse effects on sustainability indicators.
- Without even drought or climate change, the current estimated P-SY ratio of 64% can cause long-term strains on groundwater resources.
- Results can provide appropriate total pumping rates based on a certain acceptable total spring flow. The study also provides suitable total pumping rates based on acceptable number of dried-up springs.

Management Recommendations

- New water use policies should be implemented in the western part of the island where head declines can be excessive under various scenarios of recharge and water use.
- The location of the 2 m head contour should be adopted as an indicator of sustainability, regarding both its relative location from the shoreline and salinity level near such a line.

Management Recommendations

- Collection of lithologic data and monitoring information should be emphasized in the eastern side for future model refinement.
- Restrictive management practices should be developed in such areas to avoid further head decline and seawater intrusion.

Conclusions

- Reasonable matches were obtained despite uncertainties in the model data and the absence of detailed characterization of parameter variability.
- Other factors contributing to uncertainty:
  - lack of information concerning the elevation of the top of the low-permeability Seogwipo Formation,
  - complex migration behavior of groundwater in crystalline-fractured aquifers, data related to spring flows,
  - coastal stratigraphy,
  - vertical migration of perched groundwater in the interior of the island, and
  - large possible range of hydraulic conductivities of the island's volcanic lithologies.

Conclusions

- MODFLOW was calibrated to match the average spring-flow values by treating larger-flow springs as drains, with a calibration error of about 5%.
- Reasonable calibration of hydraulic head was evident by the fact that spatial distribution of hydraulic conductivity values were correlated with various geological features of the island, such as areas with lower conductivities correlating to the locations of tuff cones around the island.

- Hydraulic conductivity estimates based on MODFLOW's calibration seems reasonable for use in SEAWAT. However, additional data collection is needed for a closer match of both hydraulic head and salinity.
- At the baseline pumping, drought has the most pronounced negative effect on spring flows, with a decrease up to 21% relative to average condition at the base pumping. Up to 22% of large-flow springs dried up under these conditions. The deterioration is worse with maxinunrates, with decline of spring flows up to 28% and dry-up percentage of 27%.

- Climate change has lower impact on spring flows considering that the change was mostly related to recharge redistribution from the baseline recharge case.
- However, climate change has the most significant influence on head decline, probably due to the same reason by causing significant local effects.
- At the baseline pumping, the average head declines between about 1 and 5 m. For the maximum pumping case, the decline is between about 3 and 7 m.

- The west side of the Jeju Island is most sensitive to recharge decline, which is most likely related to the relatively lower hydraulic conductivity and higher pumping rates.
- The location of the 2 m contour can be used as a criterion for assessing the decline in head under changing recharges.
- Drought simulations showed the most increase in salinity when compared to other scenarios. Largest increases are mainly confined around the 2 m head-contour line.