Groundwater in the Cities – its past and present –

Kasumi YASUKAWA
Institute for Geo-Resources and Environment,
Geological Survey of Japan, AIST

Abstract

Remarkable land subsidence phenomena, caused mainly by domestic groundwater pumping and natural gas mining, took place in major plains in Japan. Since the middle 1950s, Japanese government and local authorities enforced lows and regulations for land subsidence control, which contributed to the stop of lowering groundwater table and serious ground sinking.

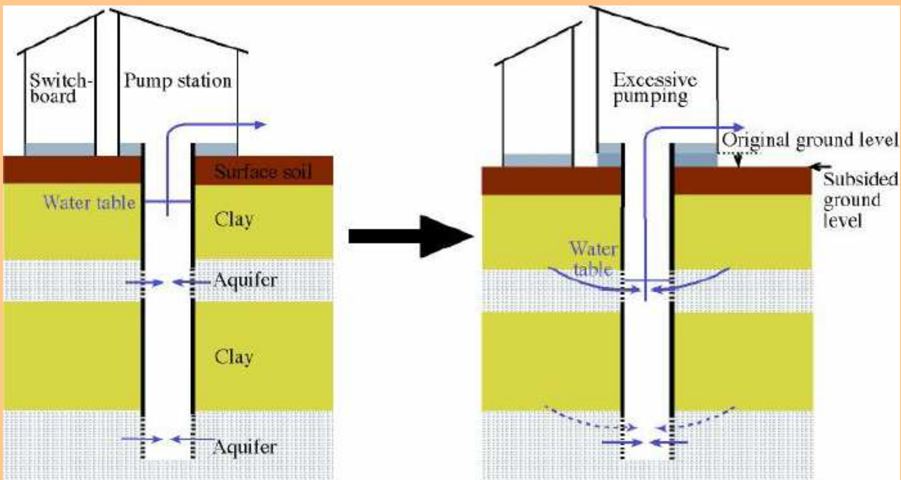
After the land subsidence control was recognized effective, a progressive rise in groundwater levels has been reported in big cities in Japan. The principal cause for the rise is the reduction of groundwater abstraction. Another important cause is leakage from water supply networks. In central Tokyo, over the last forty years more than 30m rise of groundwater table has been observed.

A rising groundwater level gives us benefits such as rebirth of dried springs, supply of emergency water etc. It, however, possibly causes negative effects to our daily life environment. It has already been reported that flooding of building basements, leakage into sewers and subway tunnels, increase in hydrostatic pressures on basement structures actually occurred at several places in Tokyo. We need to establish new groundwater control policy against the rise in water table.

Groundwater in the cities

- its past and present -

Schematic diagram of land subsidence



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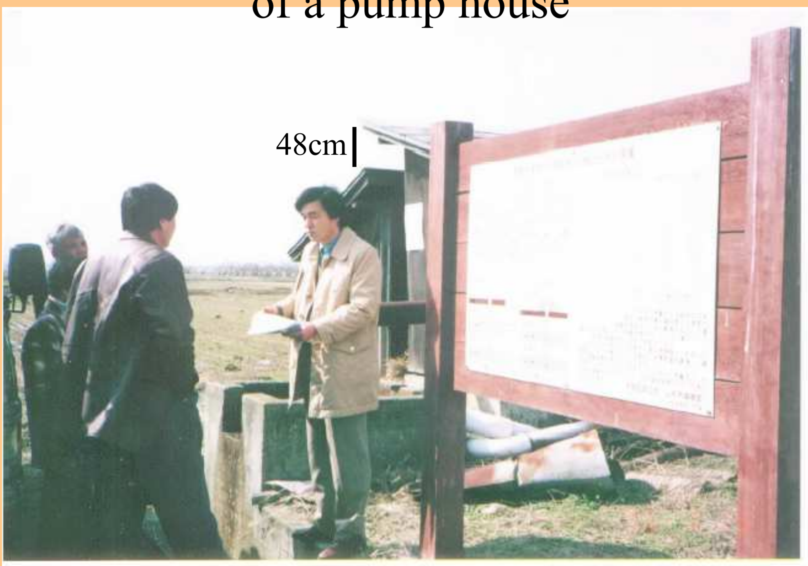
48cm difference occurred at the roof part of a pump house



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Damages by land subsidence

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Two-story or three-story?
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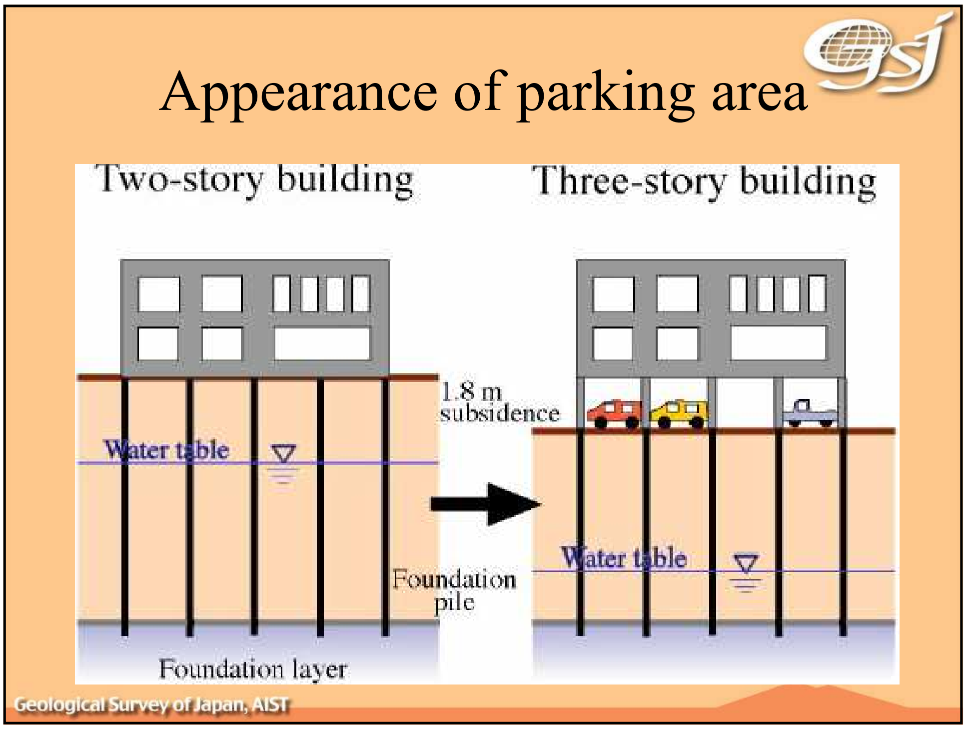
Appearance of parking area
Two-story building
Three-story building
1.8 m subsidence
Water table
Water table
Foundation pile
Foundation layer
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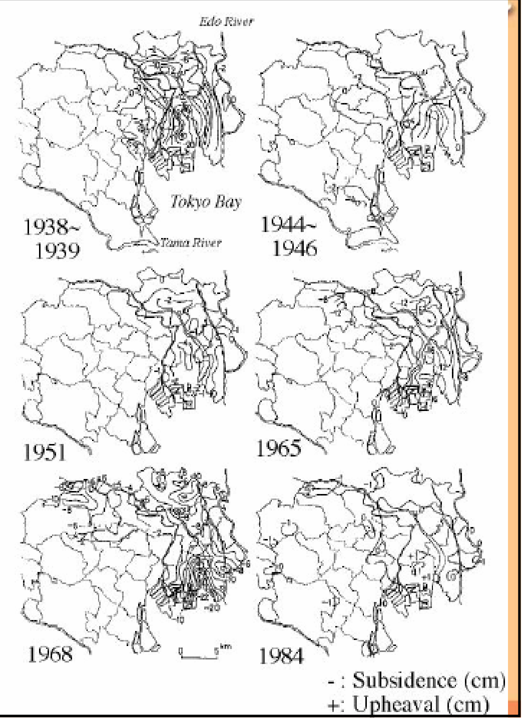
Land subsidence in Tokyo



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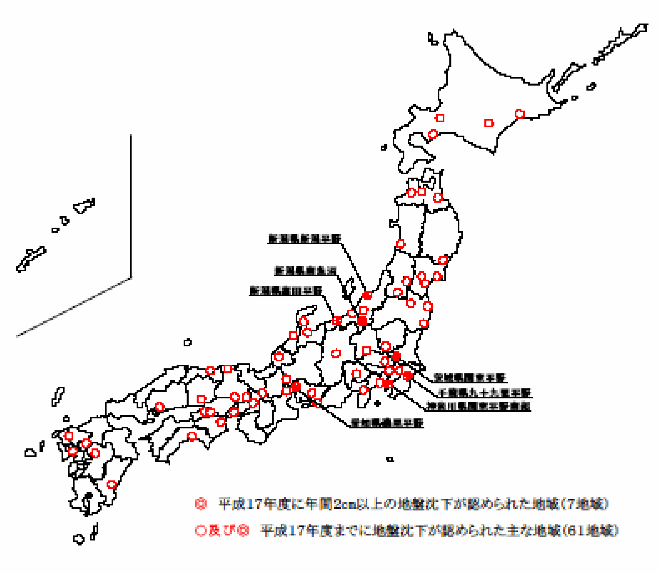
Land subsidence in Japan



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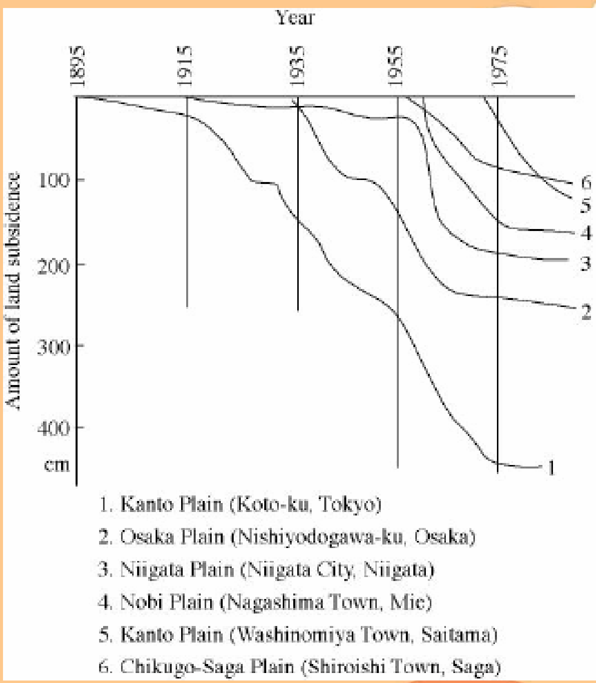
Cumulative curve of land subsidence



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Moderation of land subsidence

Decrease in amount of groundwater use
and stop of the lowering of groundwater level

1. Enactment of laws and regulations
2. Saving and reuse of water
3. Changing water source from groundwater to surface water
4. Use of sea water
5. Leakage from water supply networks

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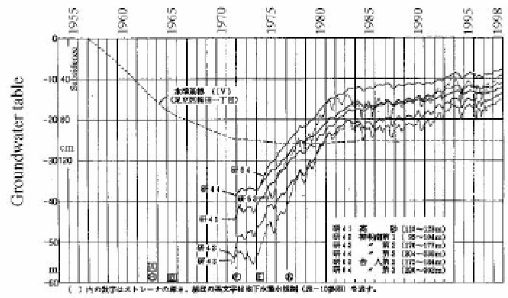
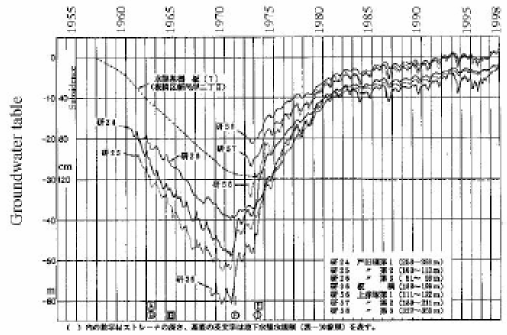
Groundwater observation in Tokyo



Groundwater table change and amount of land subsidence (Adachi and Katsushika, Tokyo)



Groundwater table change and amount of land subsidence (Itabashi, Tokyo)

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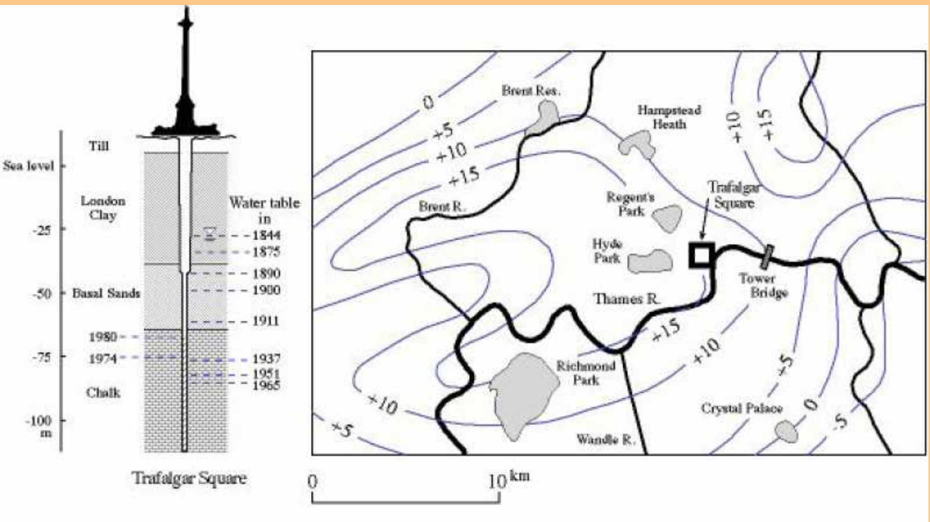
Rising groundwater in London



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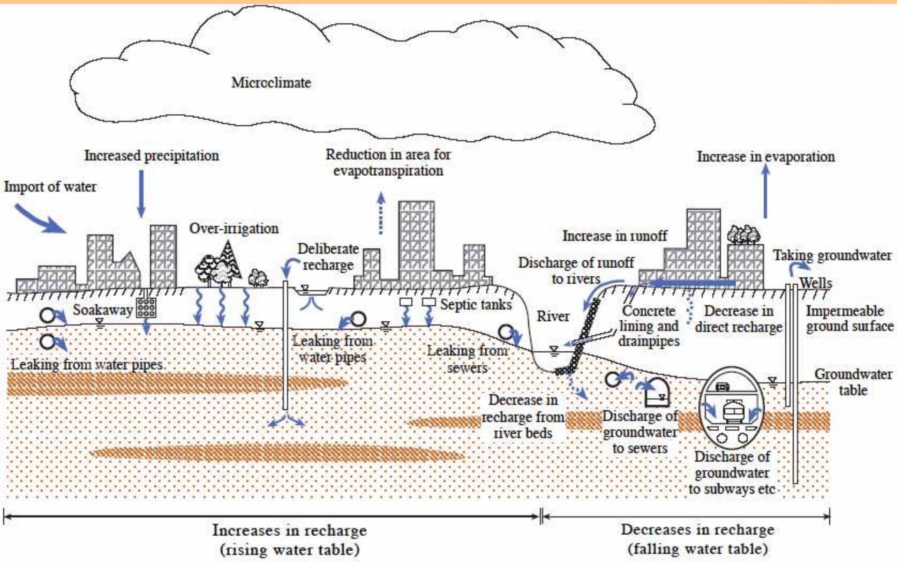
Water flow in urban area



(modified from Lerner, 1989)

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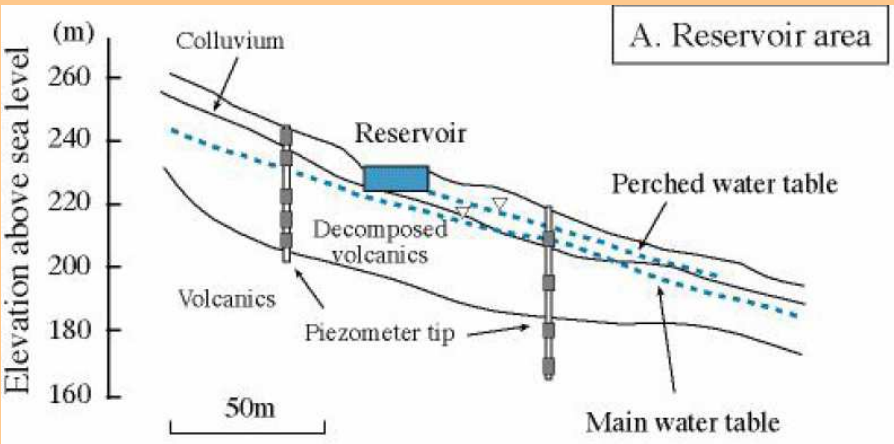
Perched water in Hong Kong



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Groundwater balance in Tokyo

($10^4 m^3$/day)

Region	Ku*	Tama**	Total
Groundwater recharging from :			
Precipitation	23	72	95
Leaking mains	38	6	44
Sub-total(A)	61	78	139
Groundwater discharging to :			
Sewers	27	6	33
Subways	3	0	3
Pumping wells	11	55	66
Sub-total(B)	41	61	102
Balance (A-B)	20	17	37

* Central Tokyo
** Suburban Tokyo

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Recharge and discharge of groundwater in Tokyo

	Recharging from (1,000m3/day)	Discharging to (1,000m3/day)	Total length (km)
Subway		30	240
Water supply	440		22,000
Sewage		330	15,000

Groundwater abstraction for water supply in Tokyo (1,000m3/day)

1989	409
1990	402
1991	395
1992	391
1993	415
1994	415
1995	422
1996	416
1997	445

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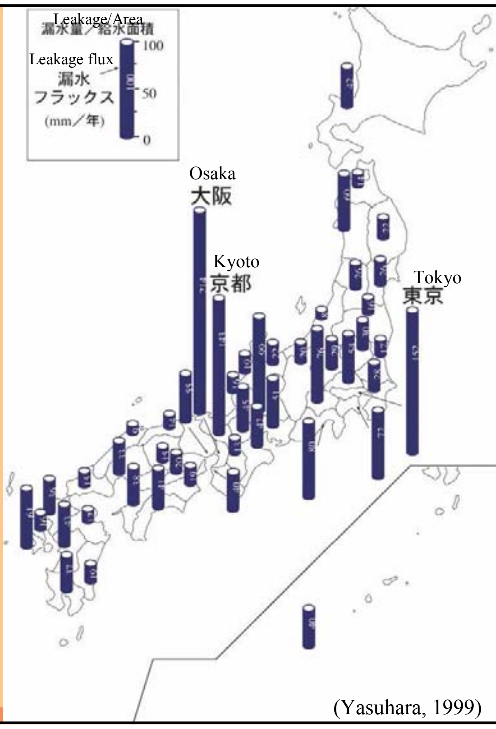
Annual leakage flux of water supply at capital cities in Japan in 1995



(Yasuhara, 1999)

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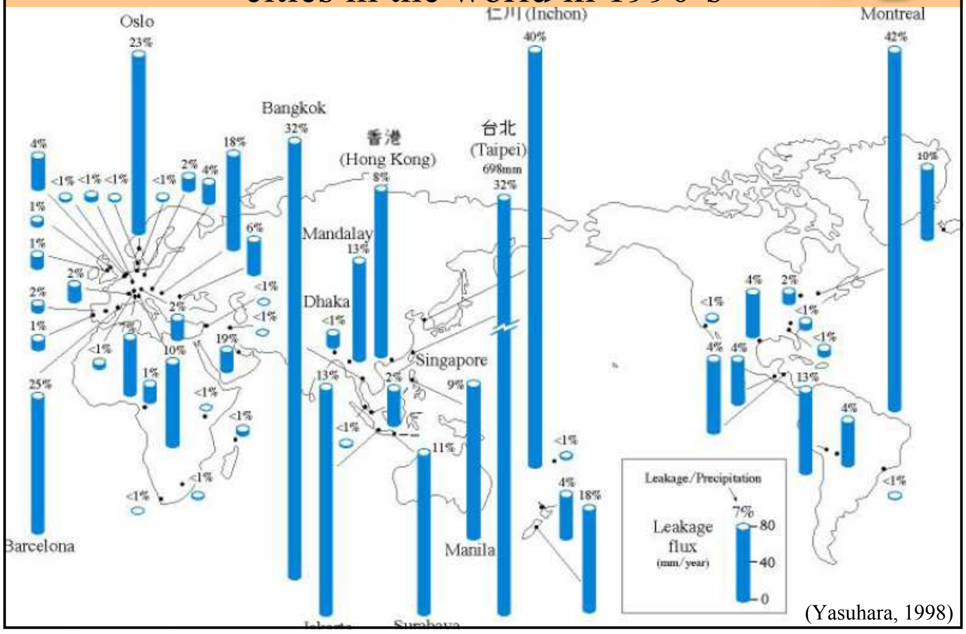
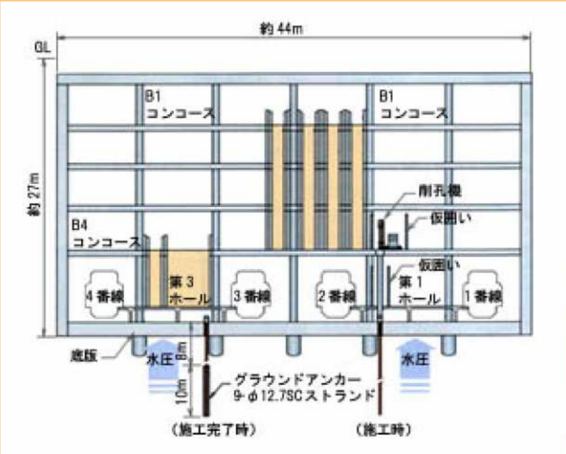
Annual leakage flux of water supply at major cities in the world in 1990's



(Yasuhara, 1998)

Groundwater pressure at the underground level of the JR Tokyo Station



Discharging 1600m^3

Groundwater comes out from the Tokyo Metro subway tunnel

Discharging 290m3

Any new idea for using groundwater in the big cities?

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Groundwater Survey for Geothermal Heat Pump Application in East Asia

Kasumi YASUKAWA

GSJ/AIST, AIST Tsukuba Central 7, Tsukuba, Ibaraki 305-8567, Japan
e-mail: kasumi-yasukawa@aist.go.jp

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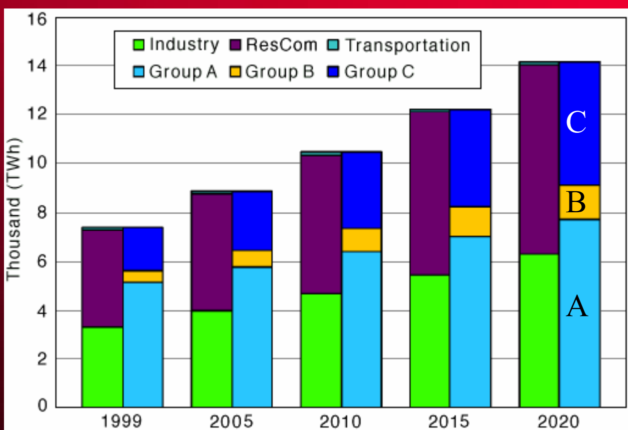
1. Environmental and energy problems in East Asian countries
2. Geothermal heat pump (GHP) system
3. Groundwater temperature study for GHP
4. GHP installation in Thailand

1. Environmental and energy problems in East Asian countries

a) Rapid growth of electricity demand
b) CO_2 and toxic gas emissions
c) Urban Heat-Island phenomenon

a) Rapid growth of electricity demand

-> and shortage of energy supply ?



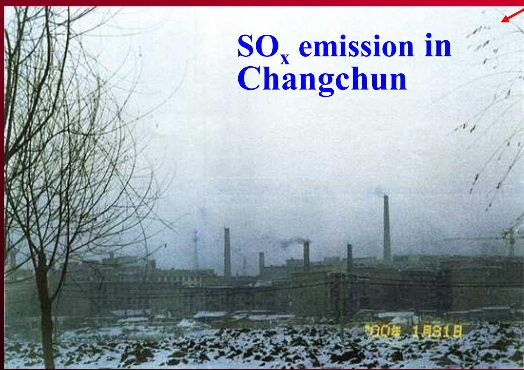
Economical Groups B & C:

Korea, Malaysia, China, Indonesia, Papua N. Guinea, Philippines, Thailand, Viet Num

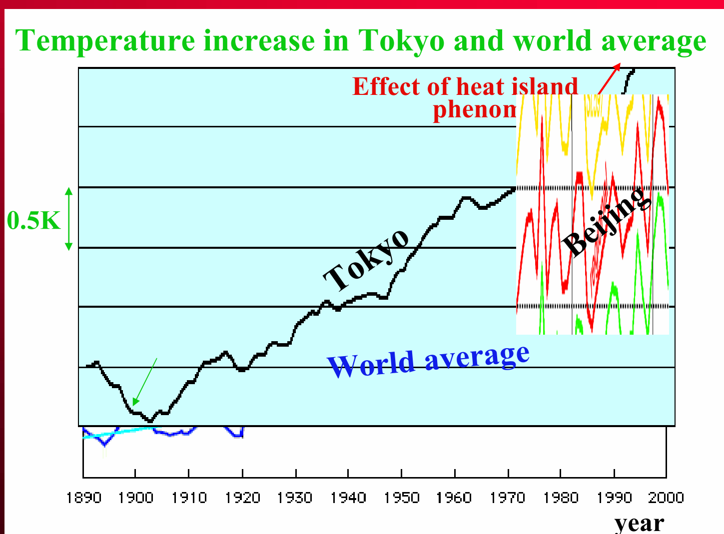
Prospect of electricity demands in APEC countries (APEC, 2002)

b) CO_2 and toxic gas emissions

- Greenhouse gas (CO_2) emission is of great concern over the world
- Toxic gas (NO_x, SO_x) emission by fossil fuels for space heating locally occurs



c) Urban Heat Island (UHI) phenomenon



- Human activity simply releases heat into the atmosphere (local warming problem)

Problems:

a) Rapid growth of electricity demand
b) CO_2 and toxic gas emissions
c) Urban heat-island phenomenon

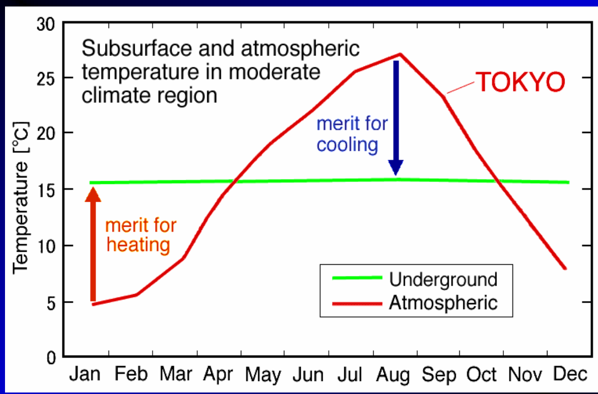
Geothermal heat pump system may be a solution!

What is Geothermal heat pump system?

2. Geothermal heat pump (GHP) system

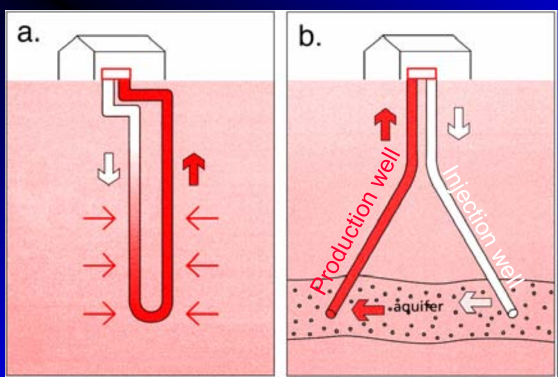
- **Subsurface vs. atmospheric temperature**
- **Heat exchange with underground**
- **Geothermal heat-pump (GHP)**
- **Positive effects of GHP system**

Subsurface vs. atmospheric temperature in moderate climate regions



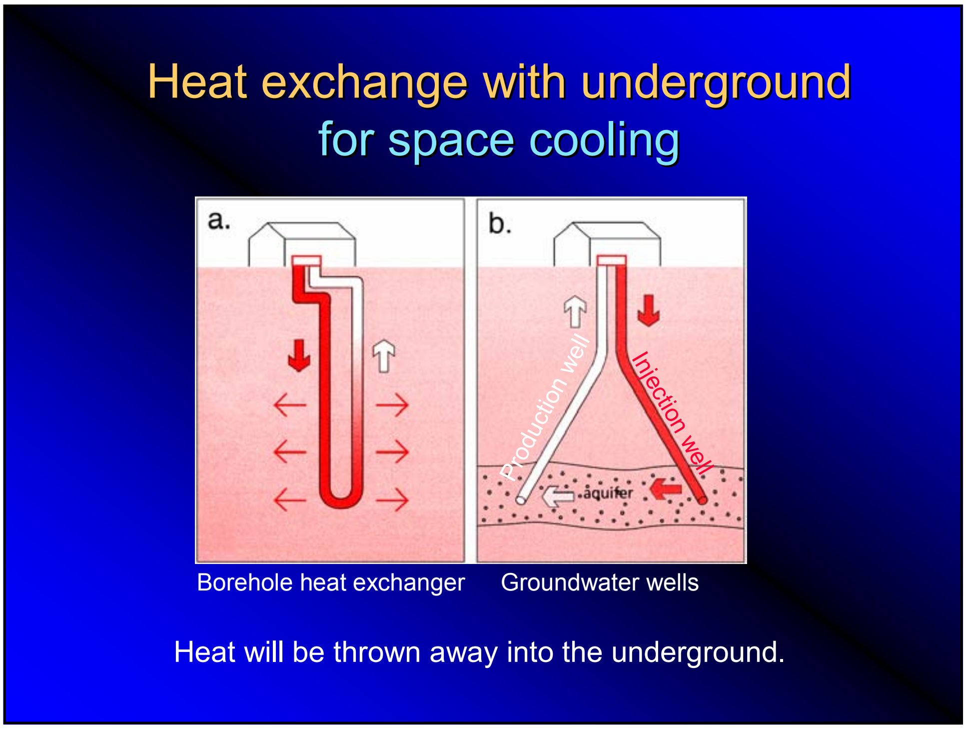
- Subsurface temperature is constant through a year.
- Therefore, it can be used as warm and cool heat sources against atmospheric temperature.

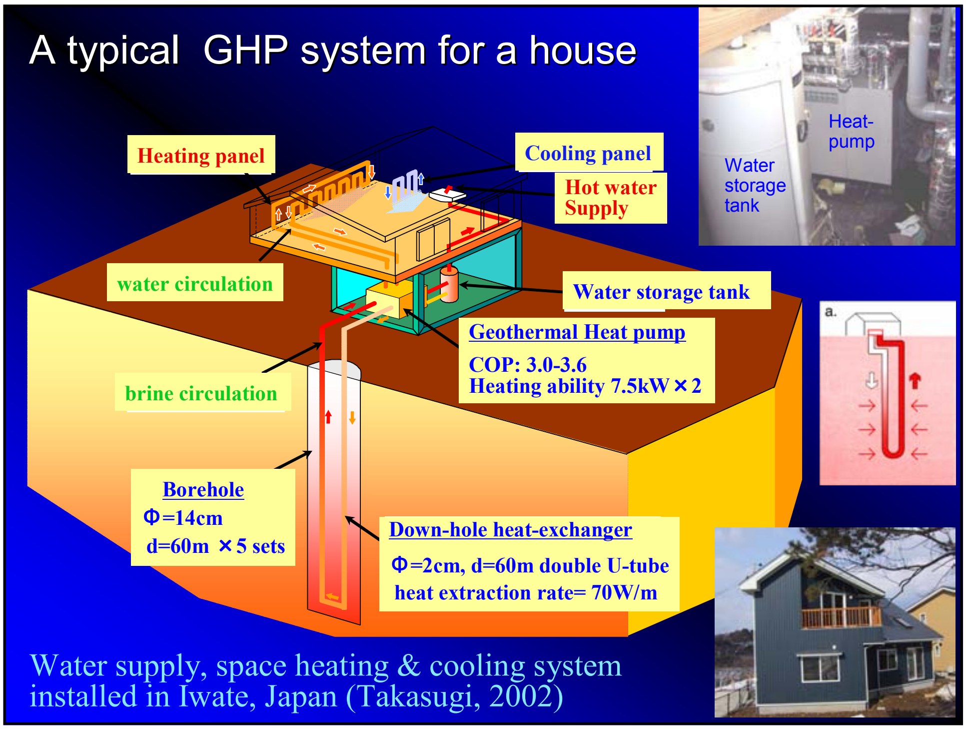
Heat exchange with underground for space heating



Borehole heat exchanger   Groundwater wells

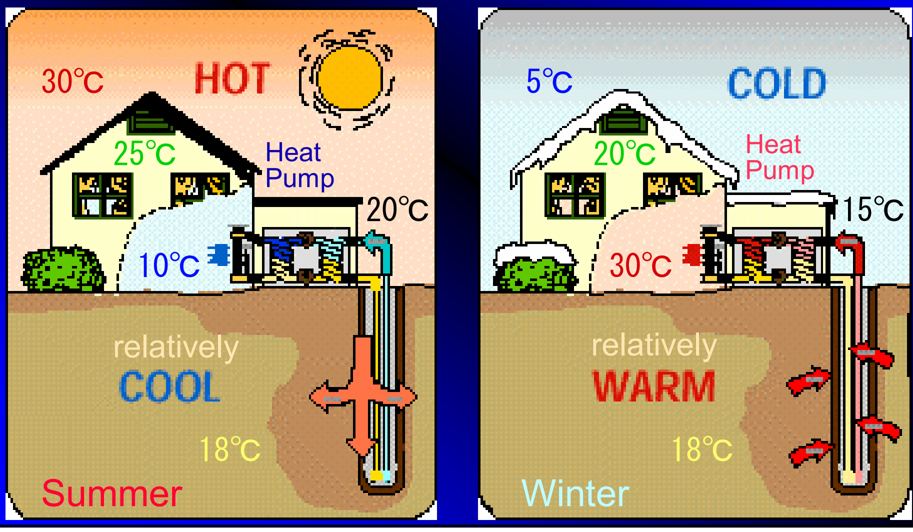
- Heat will be taken out from the underground.
- Hot water supply, snow melting can be also done.


Heat exchange with underground
for space cooling
a.
b.
Production well
Injection well
aquifer
Borehole heat exchanger
Groundwater wells
Heat will be thrown away into the underground.

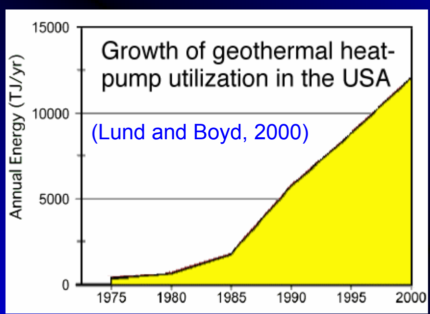

A typical GHP system for a house
Heating panel
Cooling panel
Hot water Supply
Heat-pump
Water storage tank
water circulation
Water storage tank
Geothermal Heat pump
COP: 3.0-3.6
Heating ability 7.5kW×2
brine circulation
Borehole
Φ=14cm
d=60m ×5 sets
Down-hole heat-exchanger
Φ=2cm, d=60m double U-tube
heat extraction rate= 70W/m
Water supply, space heating & cooling system
installed in Iwate, Japan (Takasugi, 2002)

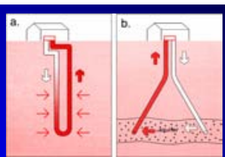
Geothermal Heat-pump (GHP)

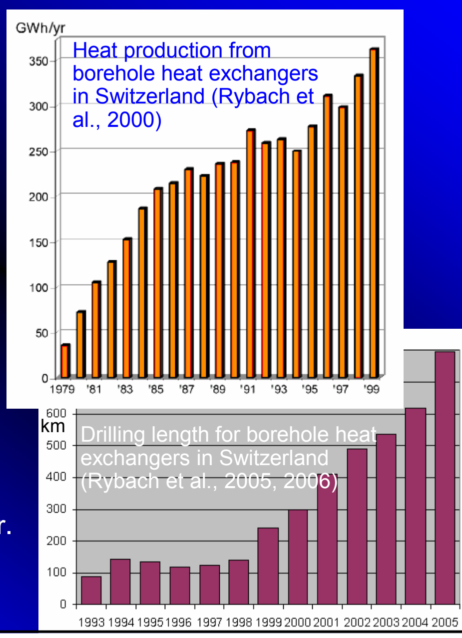
Although subsurface heat can be directly used without heat-pumps, combination with a heat-pump enables to achieve wider temperature range of utilization for air-conditioning, hot-water supply, etc. Subsurface heat exchange system with a heat pump will be called as GHP system.



Growth of GHP in the USA and Switzerland







- GHP saves electricity up to 50 % compared to normal air-conditionar.
- GHP is widely used in European countries and in the USA.

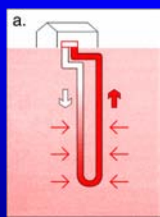
GHP utilization in the world

	Capacity (MWt)	Used heat (GWh/yr)	Number of installation	Capacity factor (%)	Average capacity (kWt)	installation per million people
USA	6,300	6,300	600,000	11.4	10.5	2,048
Sweden	2,000	8,000	200,000	45.6	10.0	22,256
China	631	1,825		33.0		
Germany	560	840	40,000	17.1	14.0	485
Switzerland	440	660	25,000	17.1	17.6	3,355
Canada	435	300	36,000	7.9	12.1	1,107
Austria	275	370	23,000	15.3	12.0	2,814
others	5,082	5,780				
world total	15,723	24,075	>1,000,000	17.5		

Reference: Curtis et al, (2005), Zheng et al.(2005), Lund et al.(2005).

Installation in Switzerland

Construction of an apartment complex and a drilling machine for borehole heat exchanger



U-tube for borehole heat exchanger

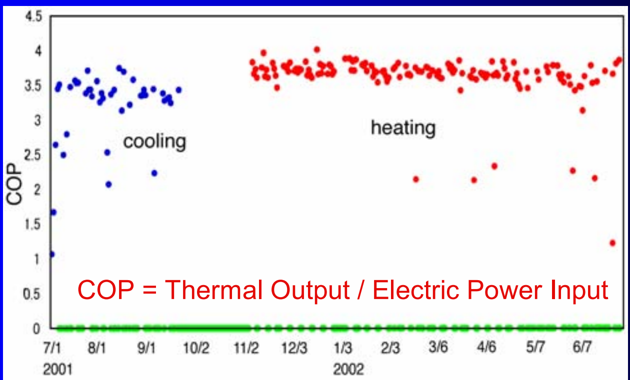
Surface top part of the borehole and double u-tubes. They will be connected to a heat-pump.

Thermal response test: measurement of effective heat conductivity of underground layers. Heated water will be pumped into u-tubes and inlet & outlet temperature will be measured.

Positive effects of GHP system

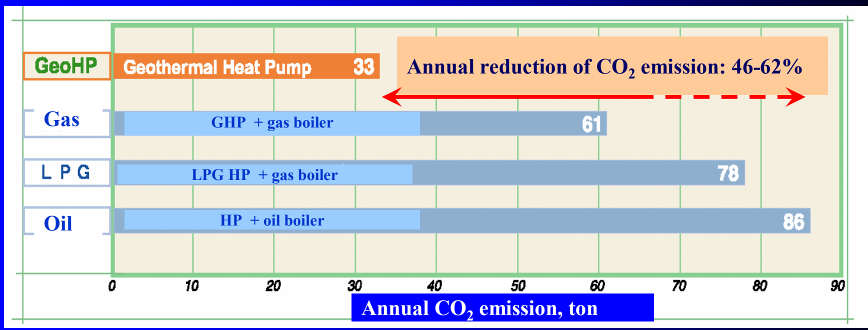
a) Save electricity with high COP
b) Reduce CO_2 and toxic gas emission
c) Reduce urban heat-island phenomenon

a) Save electricity with high COP



COP(Coefficient of Performance) of Geo-HP
Observed for a system in Iwate, Japan (Takasugi, 2002)

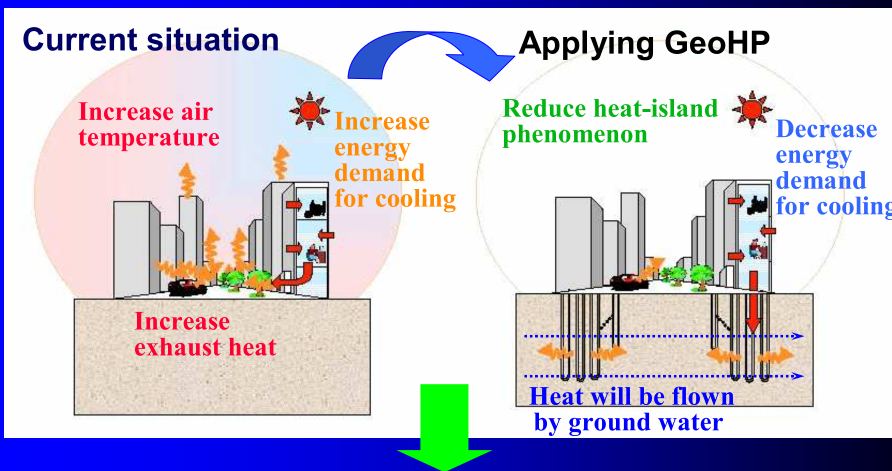
b) Reduce CO_2 and toxic gas emission



GHP installation in Changchun, China

- CO_2 gas emission will be reduced as above.
- SO_x gas emission from space heating in Changchun, China is estimated to be reduced 1.5 tons/year by full installation of GHP system (Takasugi et al., 2001).

c) Reduce urban heat-island phenomenon

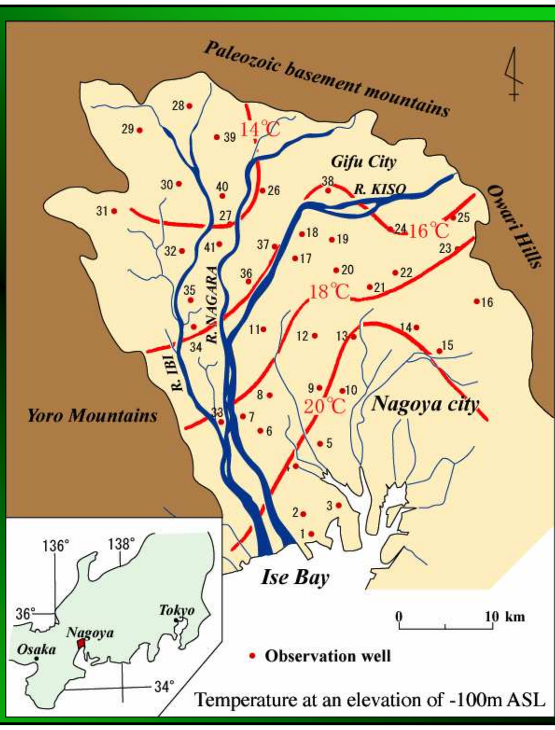


Estimation: GHP system with a 3m pitch, 234m long borehole heat exchanger installed over 0.21km² of Shinjuku, Tokyo would reduce over 100W/m² of sensible heat flux in daytime (Genchi et al., 1999)

3. Groundwater temperature study for GHP

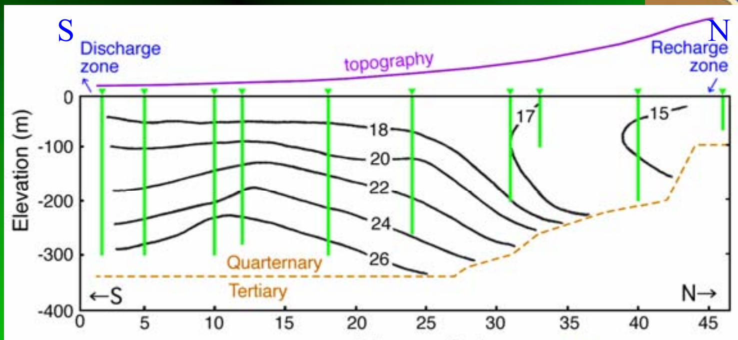
- Subsurface temperature distribution
- Case study at the Sendai plain
- GHP system in tropical countries?

Subsurface temperature distribution at the Nobi plain, Japan



(Uchida and Sakura, 1999)

N-S cross-section of subsurface temperature at the Nobi plain, Japan

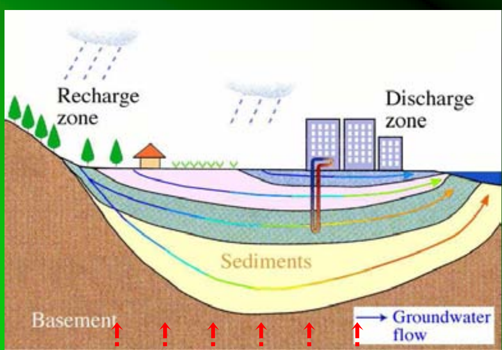


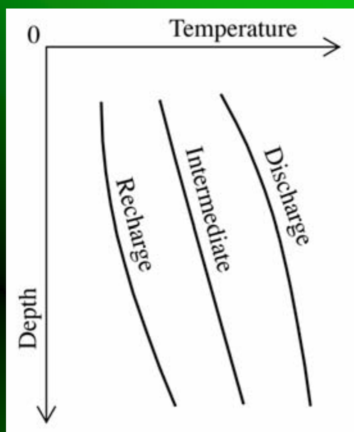
(Uchida and Sakura, 1999)

*Subsurface temperature is one of the natural tracers of the groundwater flow.

Shallow subsurface temperature affected by groundwater flow

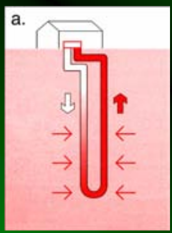
At recharge zones (high elevation), shallow temperature is lower, while it is higher at discharge zones because ground water is heated by heat flow from a depth while flowing laterally.



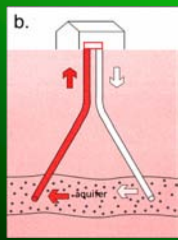


Subsurface temperature profile with groundwater flow

Possible contribution of ground water survey results to GHP promotion



Subsurface information needed for GHP system design:



Borehole heat exchanger

- vertical temperature profiling
- effective thermal conductivity (aquifer depth & velocity)
- effective specific heat (aquifer depth & velocity)

Groundwater wells

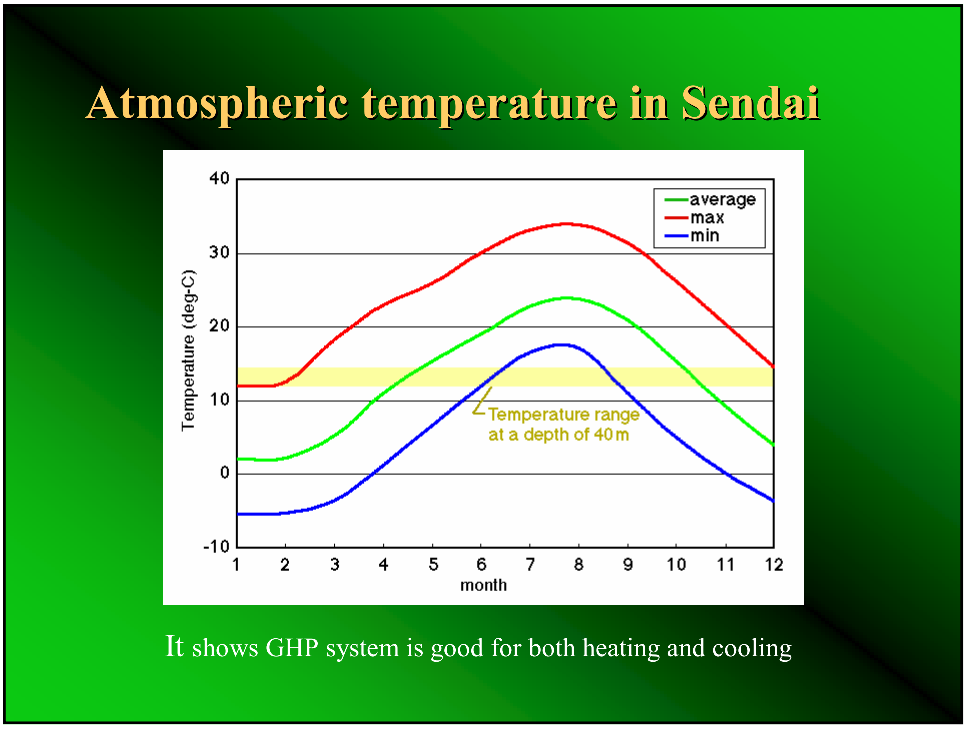
- aquifer temperature
- aquifer depth
- aquifer flow direction (for injection well)

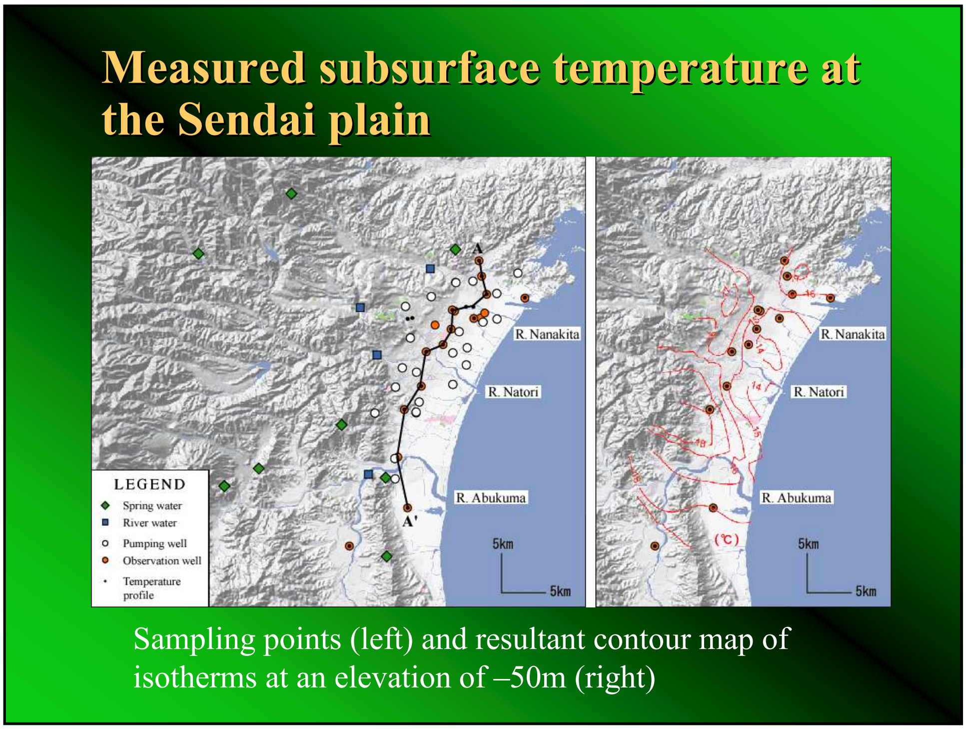
Temperature profiling and aquifer depth can be obtained by measurement at site. 3D numerical modeling enables to estimate temperature profiling, aquifer depth and flow direction & velocity at any point.

Case study at the Sendai plain

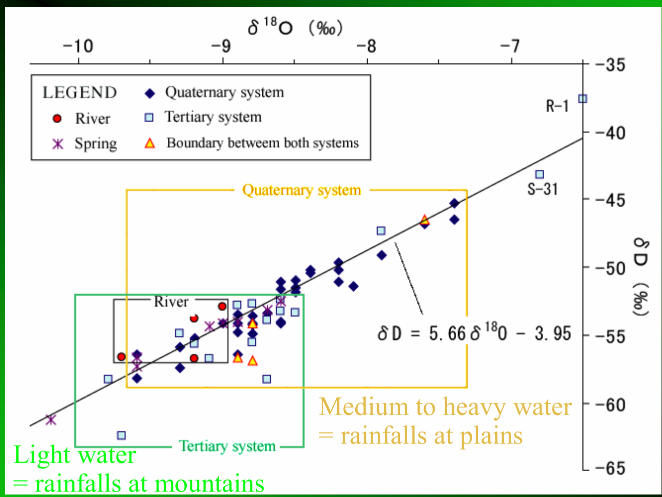
- Since subsurface temperature is largely affected by ground water flows, ground water survey and numerical modeling is needed to get 3-D temperature distribution.
- A case study in Sendai, Japan will be introduced.

Location of the Sendai plain


Atmospheric temperature in Sendai
Temperature (deg-C)
month
average
max
min
Temperature range
at a depth of 40m
It shows GHP system is good for both heating and cooling

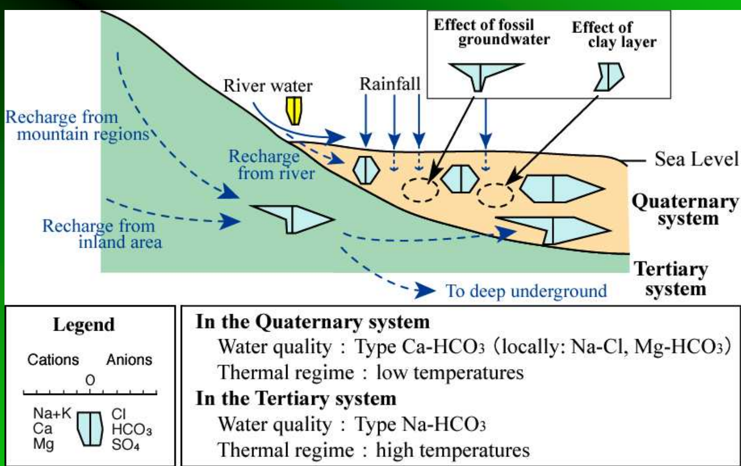

Measured subsurface temperature at the Sendai plain
LEGEND
Spring water
River water
Pumping well
Observation well
Temperature profile
R. Nanakita
R. Natori
R. Abukuma
5km
(℃)
Sampling points (left) and resultant contour map of isotherms at an elevation of –50m (right)

Isotope components of the samples from the Sendai plain



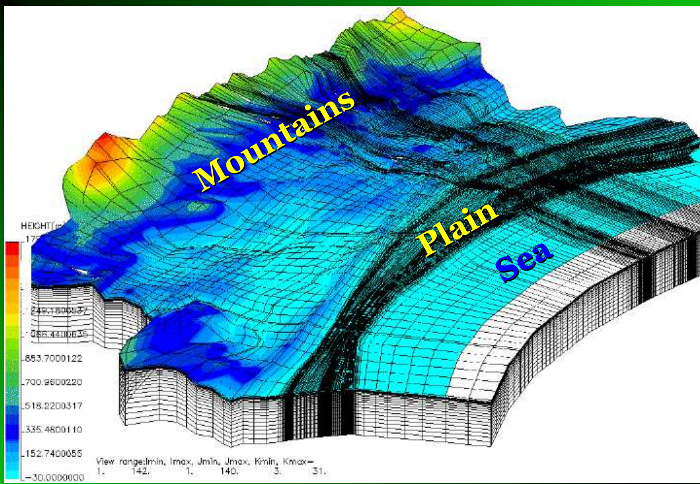
Separate flows in Tertiary and in Quaternary are suggested.

Schematic subsurface flow model of the Sendai plain



*Chemical and isotope components are natural tracer of the groundwater flow.

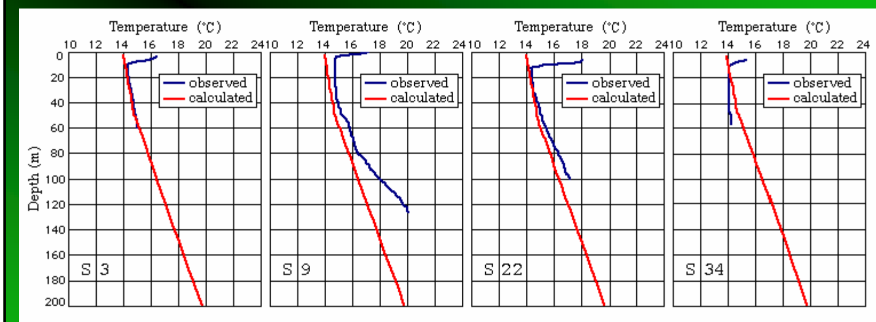
Numerical modeling of the Sendai plain



Mesh for 3D modeling (3D image)

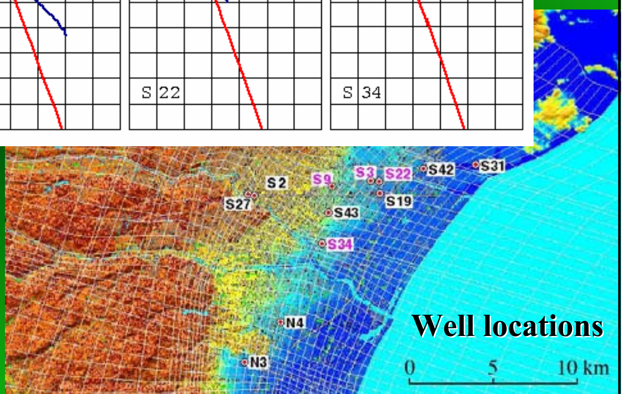
The simulated area is approximately 60 x 60 km^2. The number of grid mesh is 19,599 in plan view and 587,970 in total.

Calculated and observed temperature profiles in wells in the Sendai plain

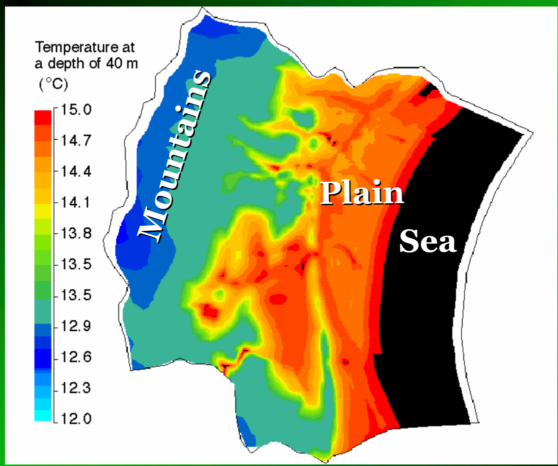


Good match of calculated and observed temperature is obtained.

*Temperature is one of the fitting parameters of a model.



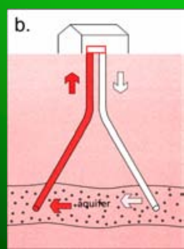
Calculated subsurface temperature distribution



It can be used for system design of geothermal heat pumps at any location in the model region.

Thermal environmental effect of heat exchange: Simulation results for Sendai Plain

Heat exchanges at R1, PL, and 3D are simulated.

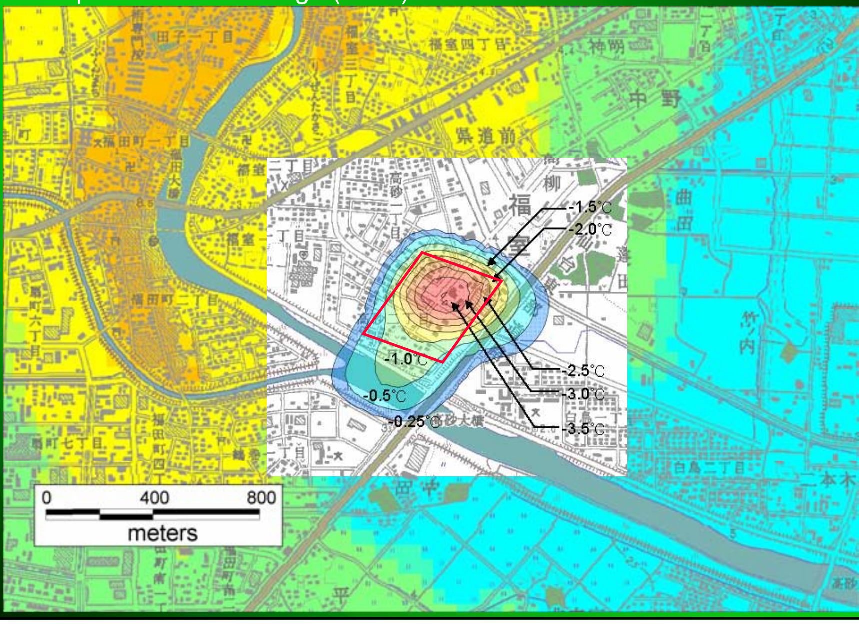


Groundwater well type heat exchange (at a depth of 50 m)

- 50% replacement of traditional heating with GHP for a 900-household district heating/cooling at R1, PL and 3D
- 40 GJ/day (0.463 MW_t) is withdrawn from underground for 4 months for space heating, and 10 GJ/day (0.116 MW_t) is sequestered for 2 months for space cooling each year.
- 30 years of calculation result for 3D will be shown

Temperature change around 3D

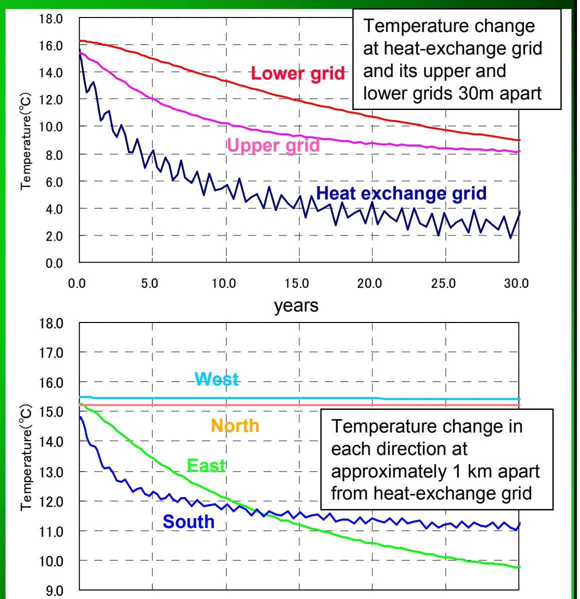
at the depth of heat exchange (50 m)



Temperature change around 3D

- Quasi-steady state at heat exchange grid, after 25 years of gradual temperature decrease with seasonal change
- Relatively high effects on upper and lower grids due to high permeability in Quaternary layer.
- High effects on downstream grids (south & east) with seasonal change at south.
- Almost no change at upstream grids (north & west)

Thus thermally affected region is estimated by detailed subsurface flow simulation.

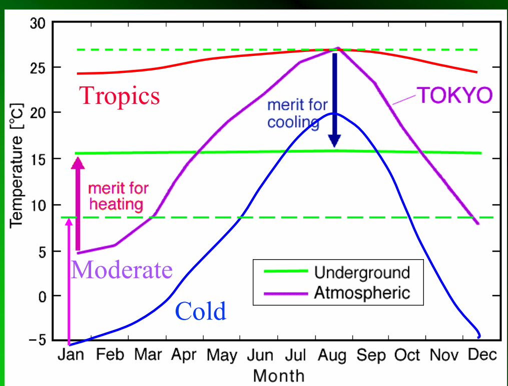


Geothermal heat-pump in east Asia?

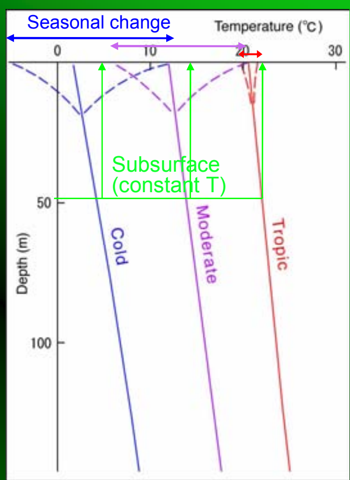
- In east-Asia, where significant economical growth in this century is expected, energy saving and environmental protection will be major matters of importance.
- Intensive installation of geothermal heat-pump may contribute to energy (electricity) savings and protection of the environment.
- However, generally in tropics where air cooling system is needed, subsurface temperature is higher than atmospheric one through a year and underground is not suitable as a cool heat source.
- Nevertheless in tropical regions, underground may be used as cold source if there exist slight change of atmospheric temperature and subsurface temperature is rather low.
- Therefore, subsurface temperature measurement was conducted in Thailand to investigate the possibility of geothermal heat-pump application in tropical regions.

Atmospheric and subsurface temperature changes at different climatic regions

Is geothermal heat-pump applicable everywhere? **Not really in tropics…**

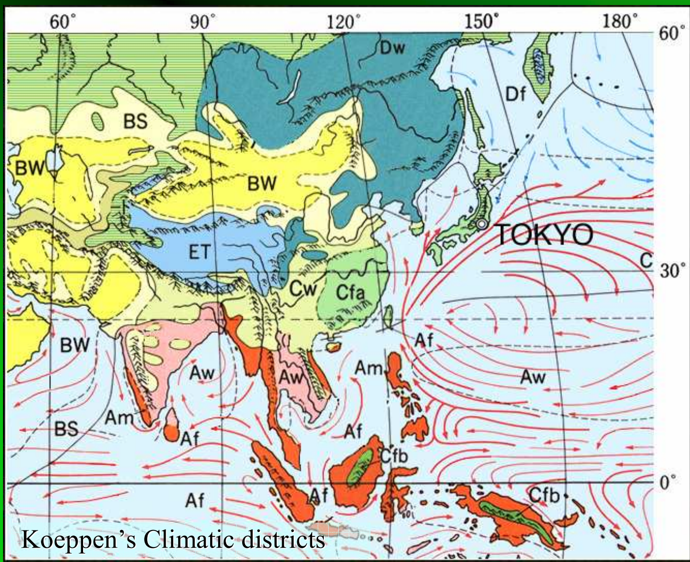


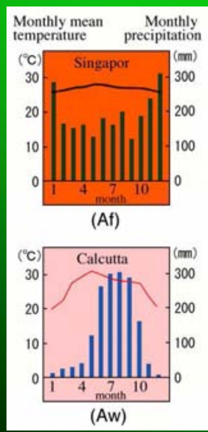
Monthly mean atmospheric and subsurface temperature



Subsurface temperature profiles without groundwater flow

Geothermal Heat Pump in Tropics?

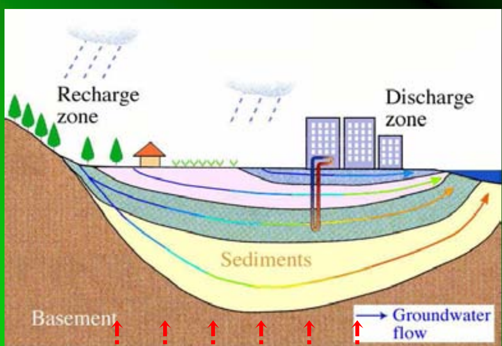


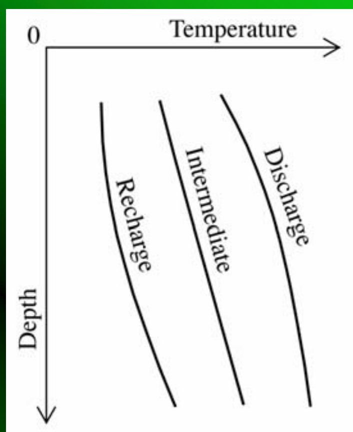


Impossible in Af (rainforest) and Am (monsoon), But possible in Aw (savannah)?
THAILAND??

Shallow subsurface temperature affected by groundwater flow

- At recharge zones (high elevation), shallow temperature is lower, while it is higher at discharge zones.
- At recharge zone, underground may be used as cold source in tropics?

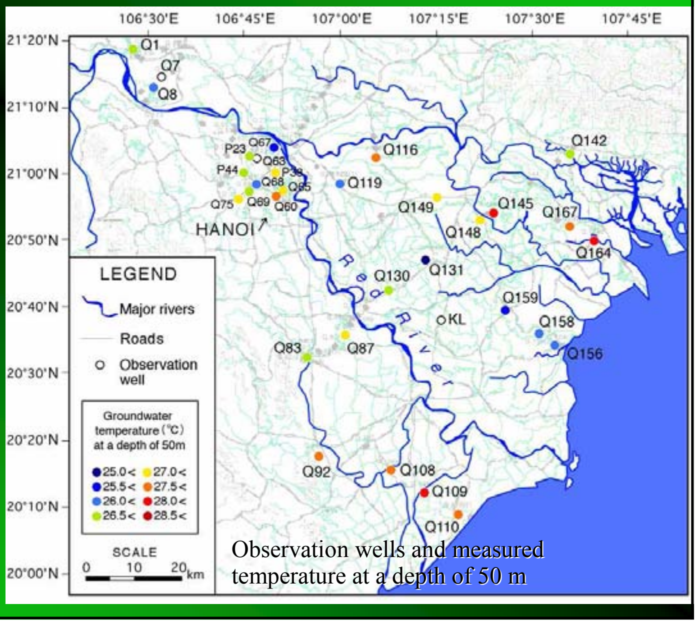




Subsurface temperature profile with groundwater flow

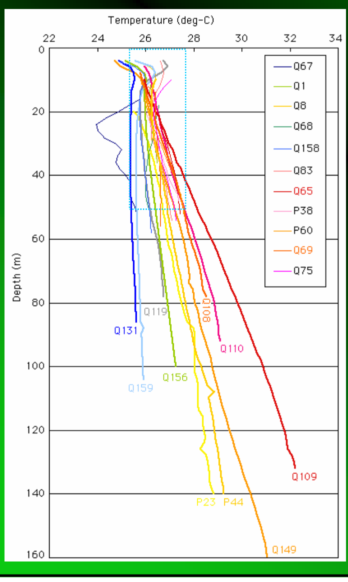
Temperature measurement in Vietnam

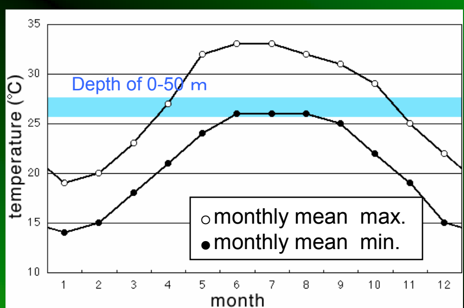
Along the Red River near Hanoi



Observation wells and measured temperature at a depth of 50 m

Subsurface temperature in Hanoi



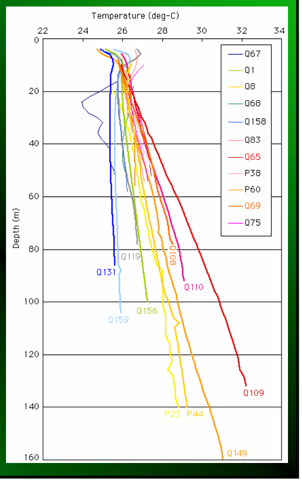


Summary of the Red River Plain

Regional variation of subsurface temperature at depths from 20 to 50 m of 2.0K was observed in the whole Red River plain.

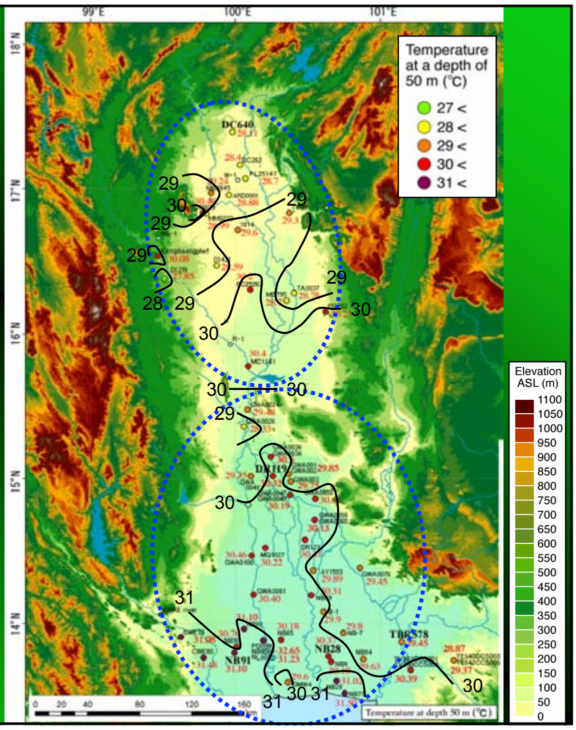
Generally the wells near the sea has higher temperature. However, in the region between the Red River and another river in the north has lower temperature even near the sea, suggesting different subsurface flow system from that along the Red River.

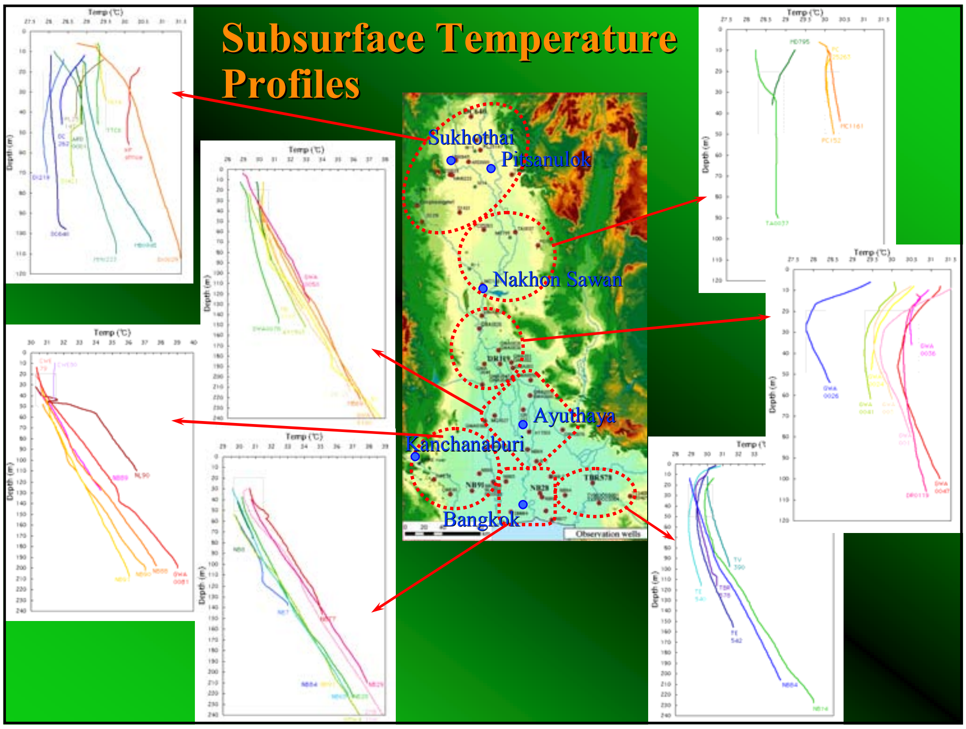
In Hanoi, subsurface temperature is lower than surface monthly mean max for 5K or more over 6 months.



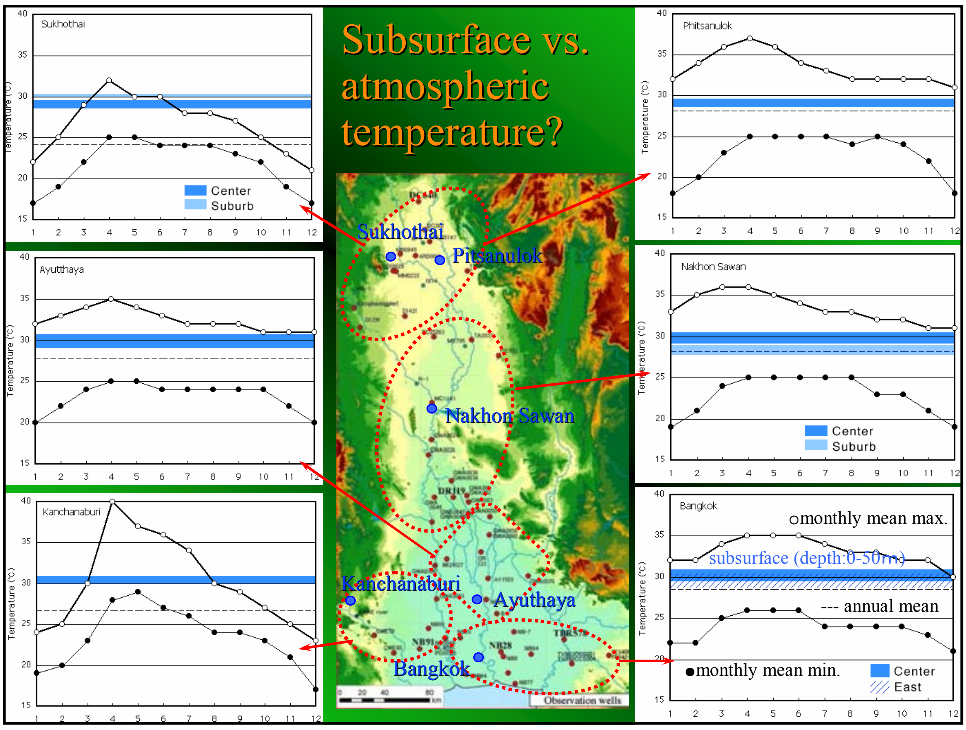
Temperature measurement in Thailand

Chao Phraya river





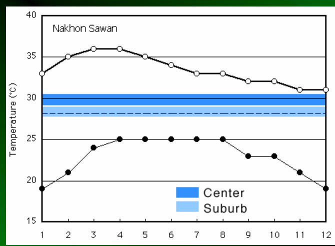
Subsurface Temperature Profiles
Sukhothai
Pitsanulok
Nakhon Sawan
Ayuthaya
Kanchanaburi
Bangkok
Observation wells



Subsurface vs. atmospheric temperature?
Sukhothai
Phitsanulok
Ayutthaya
Nakhon Sawan
Kanchanaburi
Bangkok
Sukhothai
Pitsanulok
Nakhon Sawan
Kanchanaburi
Ayuthaya
Bangkok
Observation wells
Center
Suburb
East
monthly mean max.
subsurface (depth:0-50m)
--- annual mean
monthly mean min.
Temperature (°C)

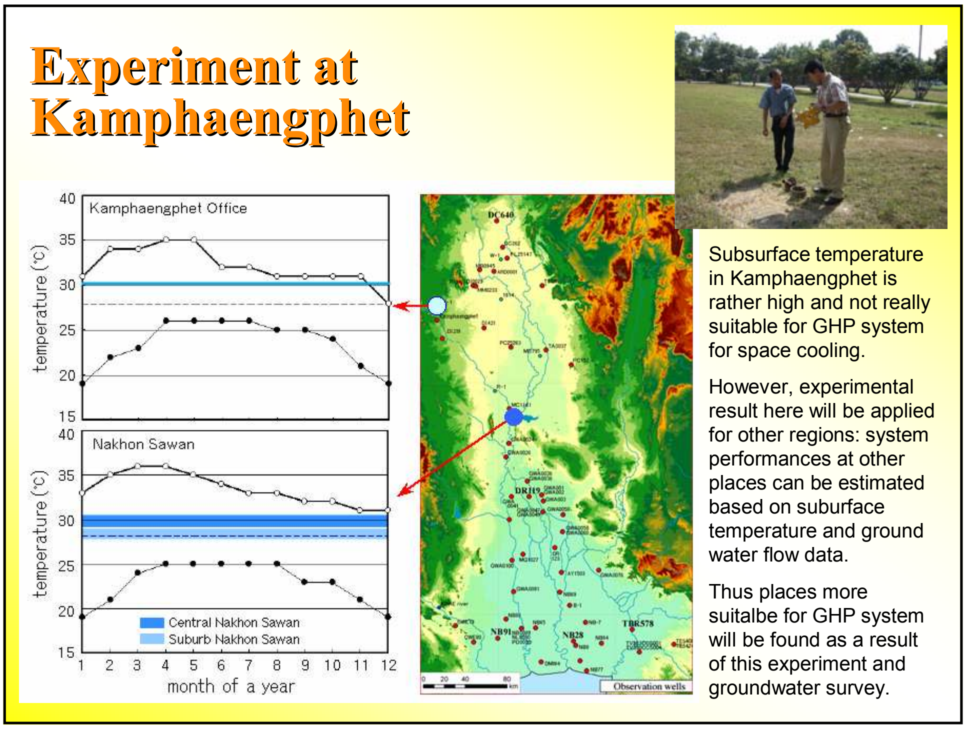
Summary of the Chao-Phraya plain

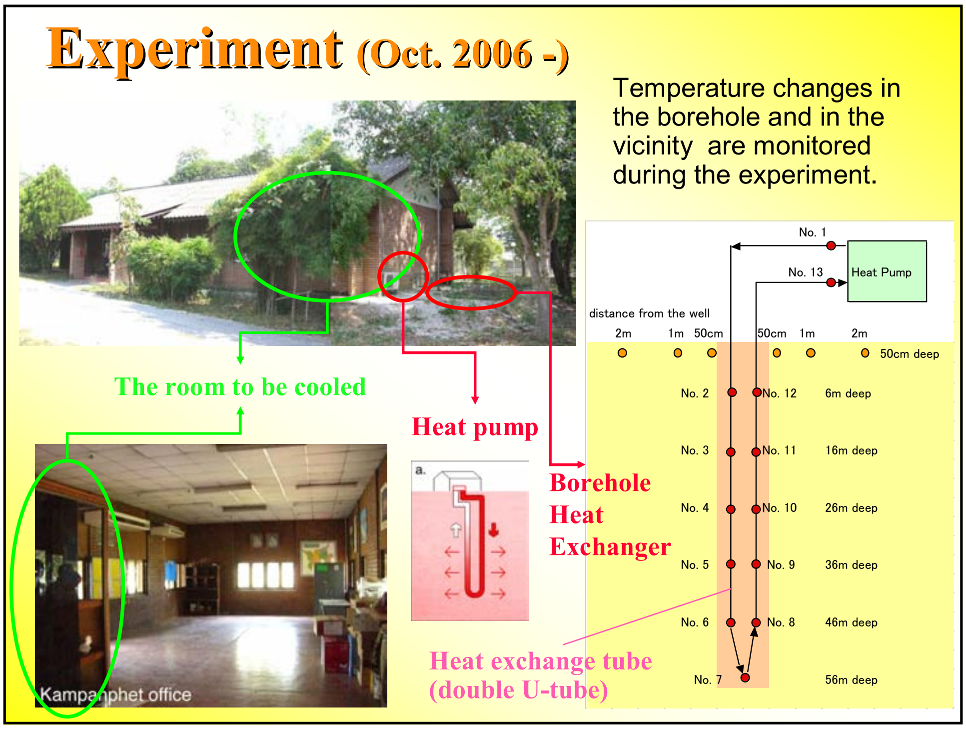
- Temperature profiles in observation wells are widely measured in the Chao-Phraya plain, Thailand.
- As a result, subsurface temperature becomes lower than atmospheric one soundely in hotter season in some places, suggesting the possibility of geothermal heat-pump application in tropics.



4. GHP installation in Thailand

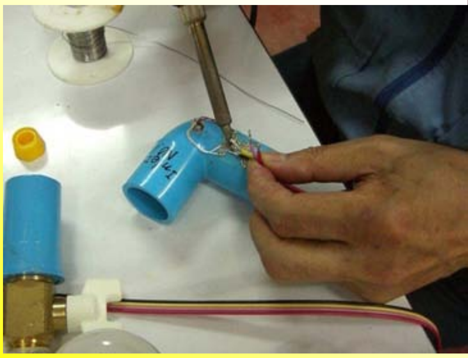
- Borehole heat-exchanger and heat-pump was installed for a room air-conditioner.
- System performance and capacity of the subsurface heat exchange system will be measured over a year.

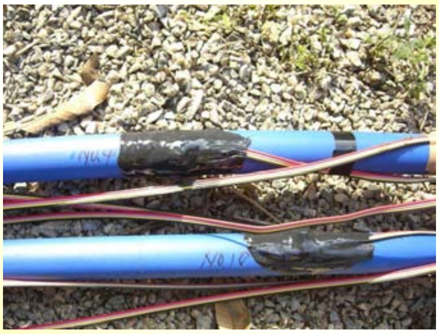

Experiment at Kamphaengphet
Kamphaengphet Office
Nakhon Sawan
temperature (℃)
month of a year
Central Nakhon Sawan
Suburb Nakhon Sawan
Observation wells
Subsurface temperature in Kamphaengphet is rather high and not really suitable for GHP system for space cooling.
However, experimental result here will be applied for other regions: system performances at other places can be estimated based on suburface temperature and ground water flow data.
Thus places more suitalbe for GHP system will be found as a result of this experiment and groundwater survey.


Experiment (Oct. 2006 -)
Temperature changes in the borehole and in the vicinity are monitored during the experiment.
The room to be cooled
Heat pump
Borehole Heat Exchanger
Heat exchange tube (double U-tube)
Kampaphet office
Heat Pump
distance from the well
2m 1m 50cm 50cm 1m 2m
50cm deep
No. 1
No. 13
No. 2 No. 12 6m deep
No. 3 No. 11 16m deep
No. 4 No. 10 26m deep
No. 5 No. 9 36m deep
No. 6 No. 8 46m deep
No. 7 56m deep

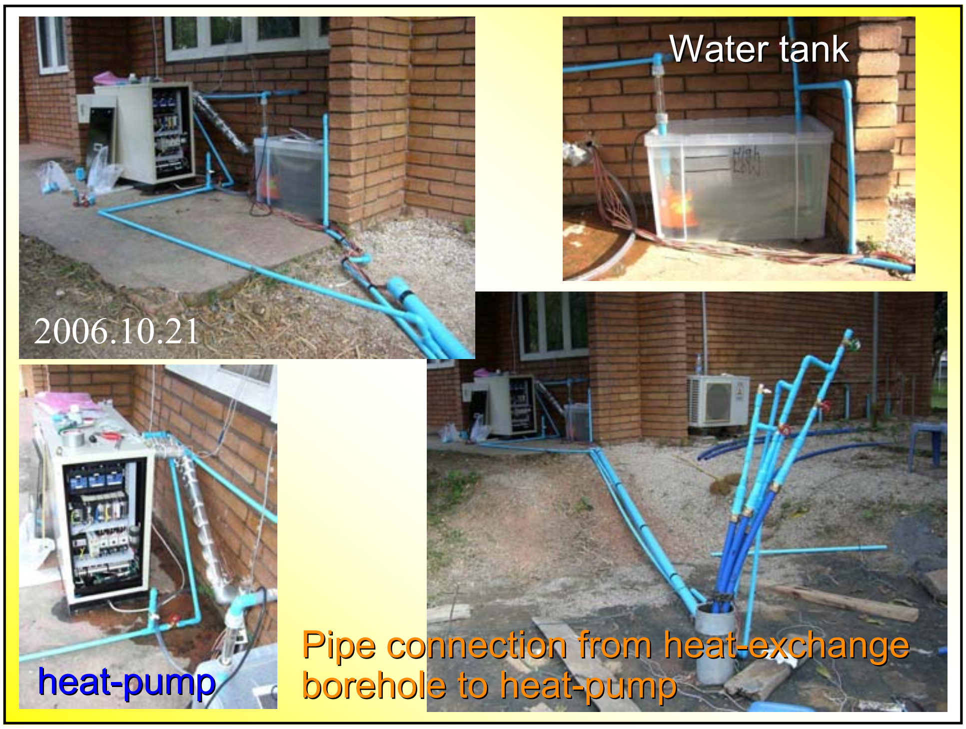
Drilling of heat exchange borehole, 2006.10.17

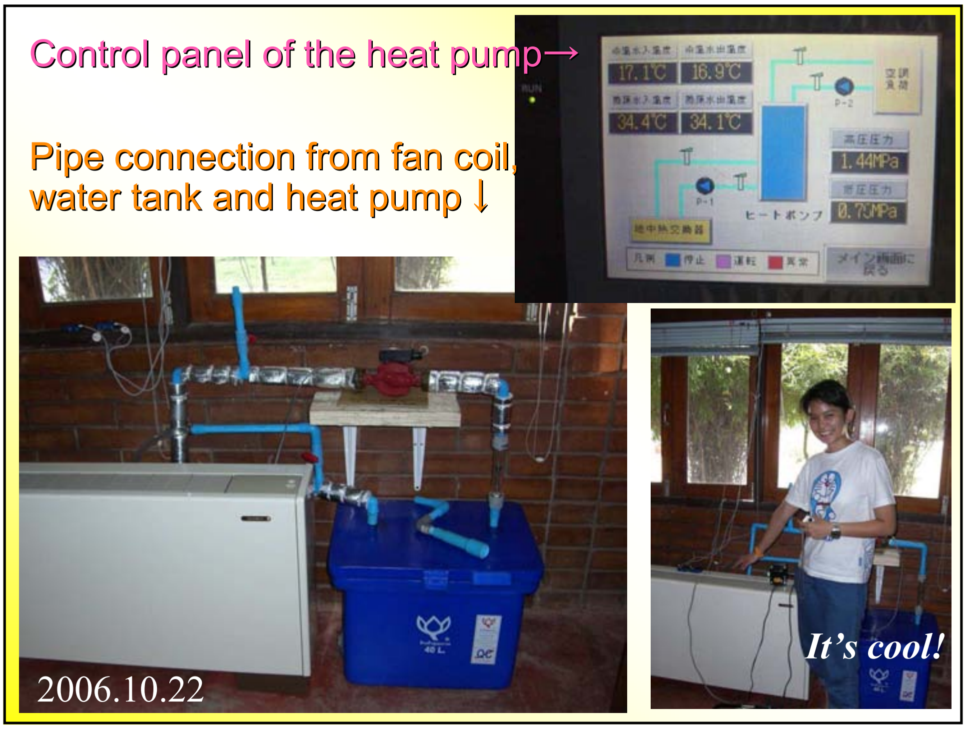
Putting temperature sensors inside/outside heat exchange tube (U-tube)

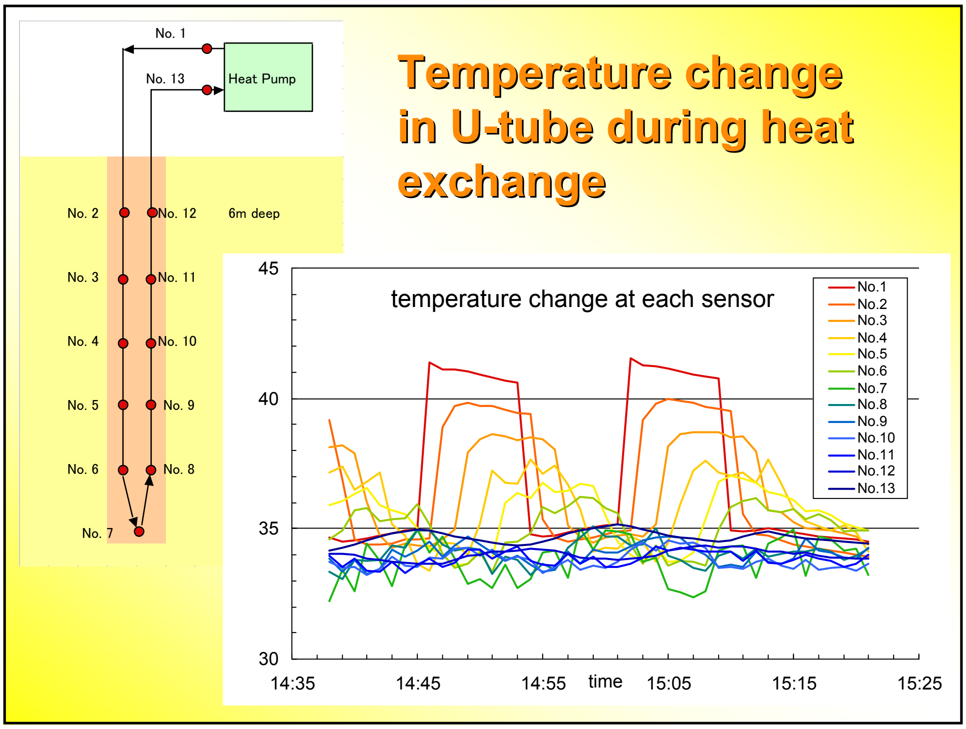





2006.10.20
Installation of U-tube


Water tank
2006.10.21
heat-pump
Pipe connection from heat-exchange borehole to heat-pump


Control panel of the heat pump→
Pipe connection from fan coil, water tank and heat pump ↓
2006.10.22
It's cool!


Temperature change in U-tube during heat exchange
Heat Pump
No. 1
No. 13
No. 2
No. 12
6m deep
No. 3
No. 11
No. 4
No. 10
No. 5
No. 9
No. 6
No. 8
No. 7
temperature change at each sensor
45
40
35
30
14:35
14:45
14:55
time
15:05
15:15
15:25
No.1
No.2
No.3
No.4
No.5
No.6
No.7
No.8
No.9
No.10
No.11
No.12
No.13

ACKNOWLEDGEMENTS

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Thank you!