Evaluation of groundwater age in a layered aquifer system using analytical and numerical models

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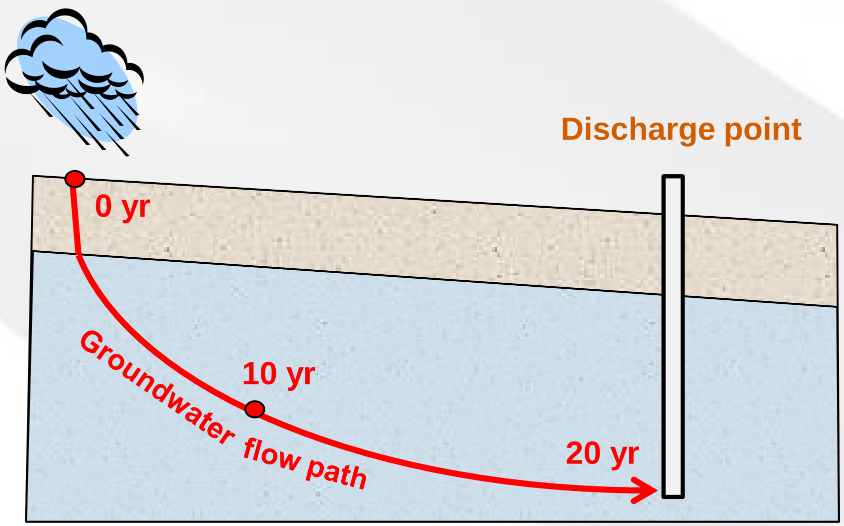
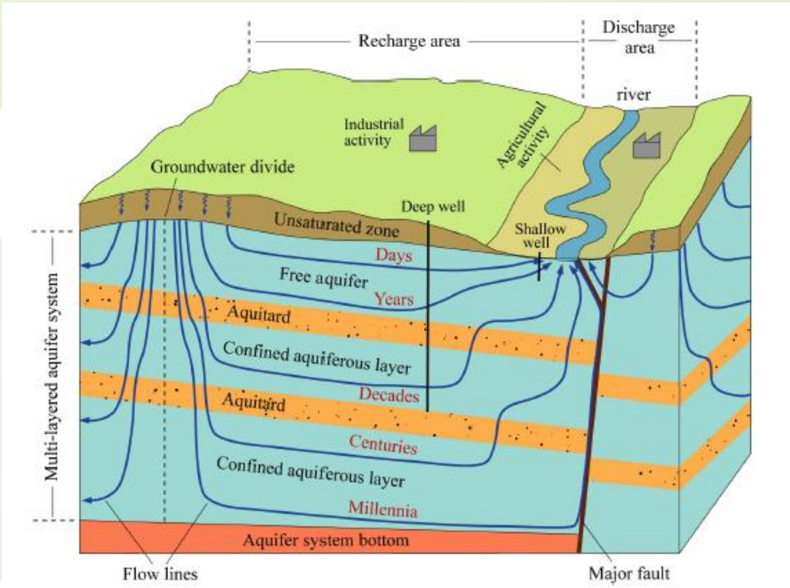
25-29th September 2016
Montpellier, France
CORUM CONFERENCE CENTER
43rd IAH congress

Abstract number: 1606

Introduction

▪ **Groundwater age?**





Cornaton, 2004

- **Groundwater age: the time elapsed since recharge into subsurface.**
- **Groundwater age is composed of water particles with various ages depending on aquifer structure, heterogeneity of the physical parameters and recharge patterns (Cornaton, 2004; Bethke and Johnson, 2008).**
- **Consideration of groundwater age mixing process is needed to understand the aquifer flow characteristics properly.**

Introduction

▪ Groundwater age

- Recharge rates, estimate flow rate, time scale of contaminant transport…

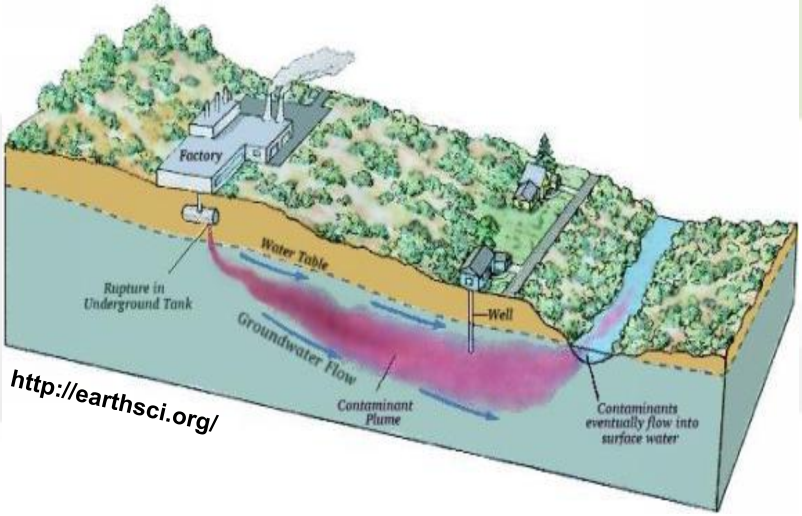
❖ Aquifer vulnerability

- surface contamination sources

: percolating into the subsurface aquifer along with recharged water.

: transporting through the aquifer medium depending on it's geological settings.

→ related to the age distribution of groundwater



❖ Nitrate contamination

- Evaluate the aquifer vulnerability by nitrate contamination associated with interpretation of the groundwater age distribution.
- Böhlke, 2002; Manning et al., 2005; Koh et al., 2006; McMahon et al., 2008; Visser et al., 2013; Alikhani et al., 2016; Jurgens et al., 2016.

Introduction

❖ **Nitrate contamination in groundwater of Gosan area has been reported (Koh et al., 2012)**

▪ **Study area description**

: Gosan ri, Hangyeong myoen, Jeju island

- Located western part of Jeju island

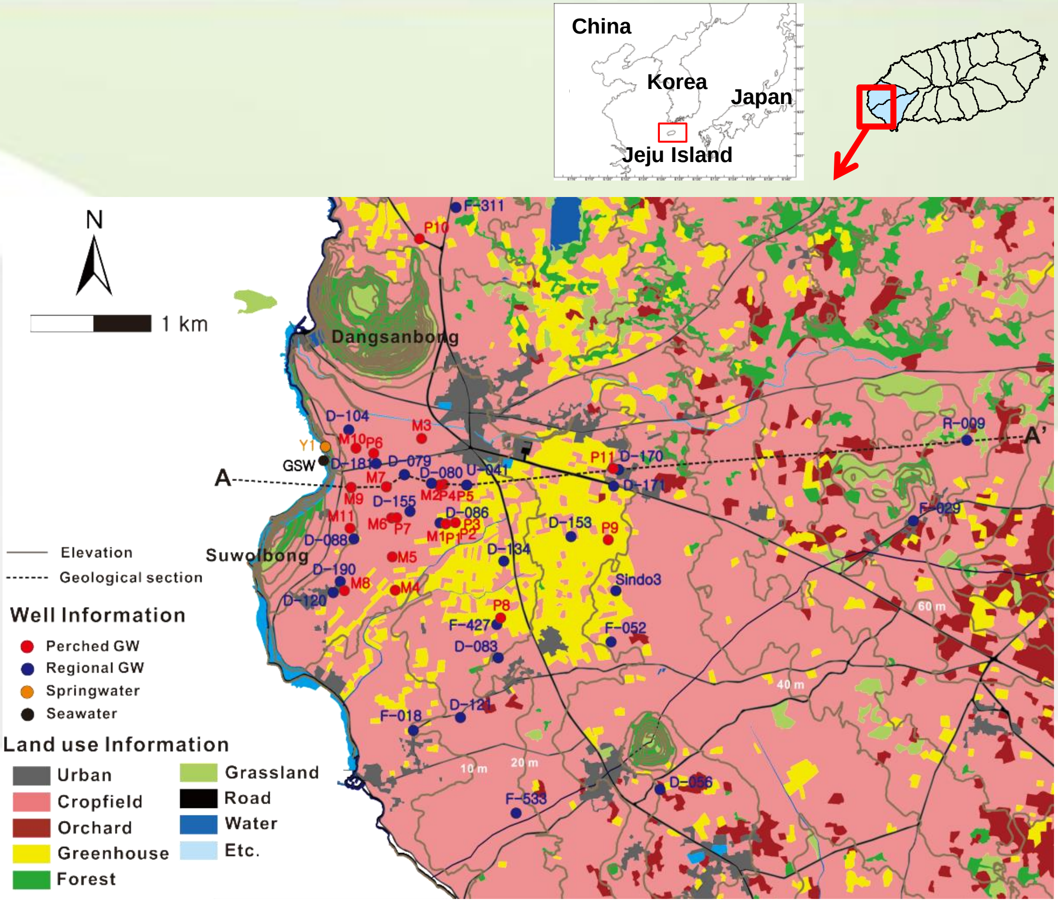
- Readjustment of arable land in 1970s

- Cultivated crops

: rice, bean, sesame (Summer)

: garlic, onion, radish, cabbage (Winter)

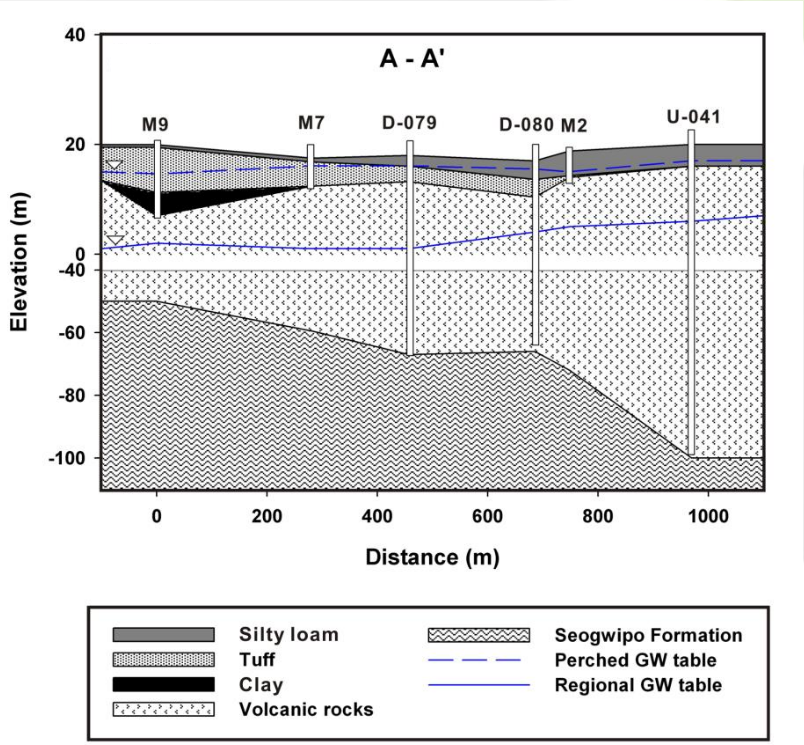
- Annual usage of fertilizers (2010)
: 627 kg-N/ha/yr



Introduction

- **Hydrogeology and nitrate contamination**

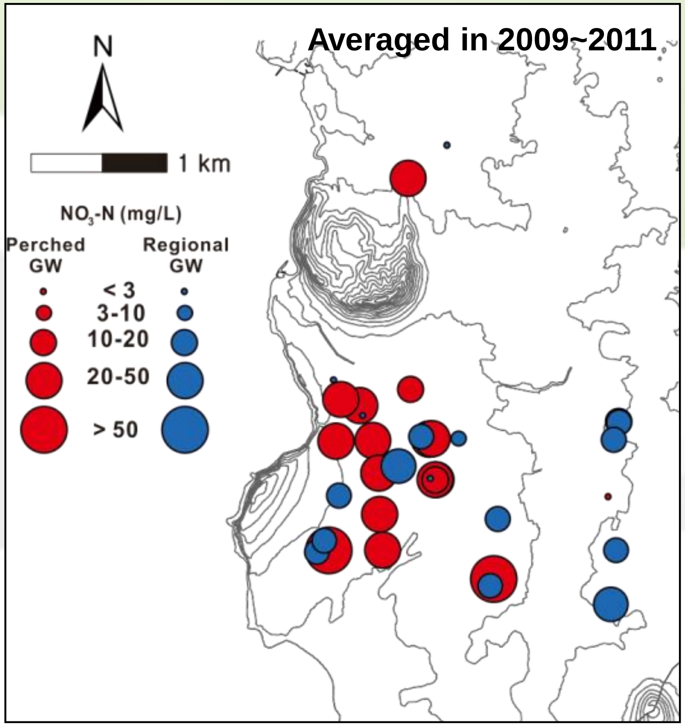
<Groundwater occurrences>



- Perched groundwater is distributed in the upper parts of the clay beds.

-> two aquifer systems
: perched and regional groundwater

<Spatial distributions of NO_3-N>



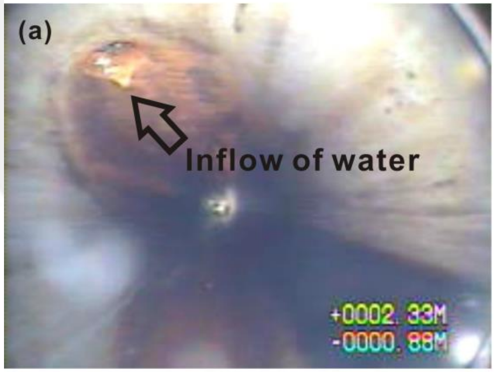
1) Perched GW
: Strongly affected by nitrate contaminant sources

2) Regional GW:
: Group1- naturally occurring groundwater
: Group2- affected nitrate contaminant sources

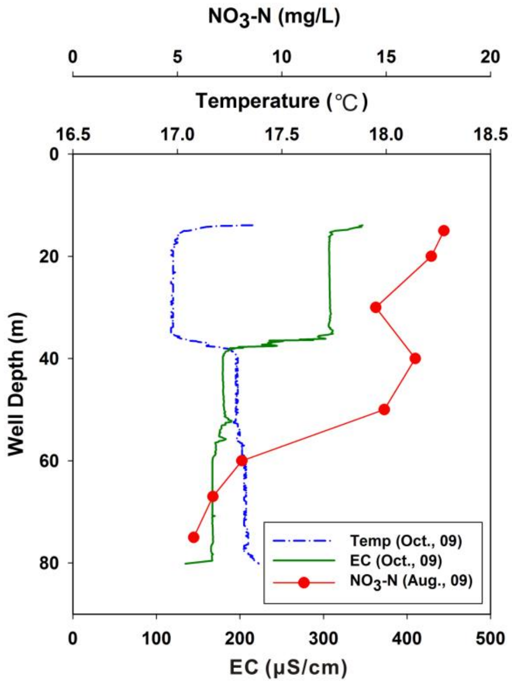
Introduction

❖ **Well leakage impacts on the nitrate contamination**

<Borehole camera image>



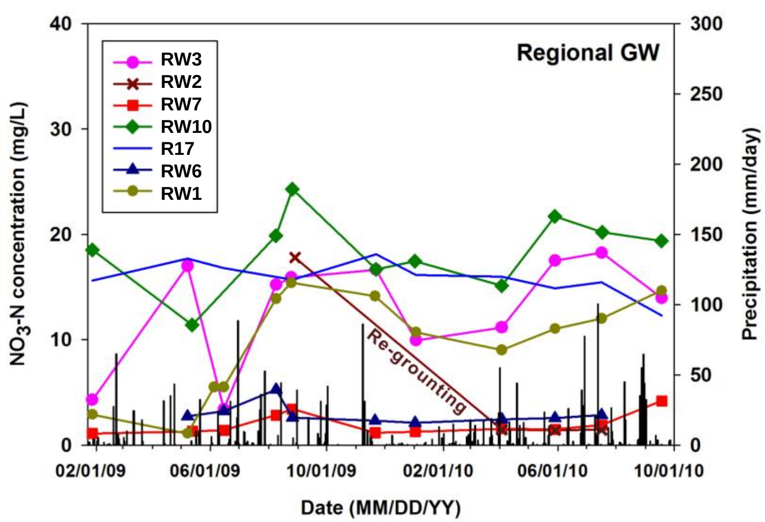
Inflows of the perched groundwater to the RW2 well : depth of 2.33 m



Leakage of perched GW

: elevated NO_3-N (14–18 mg/L) in the upper 50 m of well depth

<Temporal variations of the NO_3-N>



NO_3-N concentrations at the RW2
: 17.8 mg/L → 1.5 mg/L
before and after re-grouting.

✓ **<u>Nitrate-contaminated regional groundwater</u>**

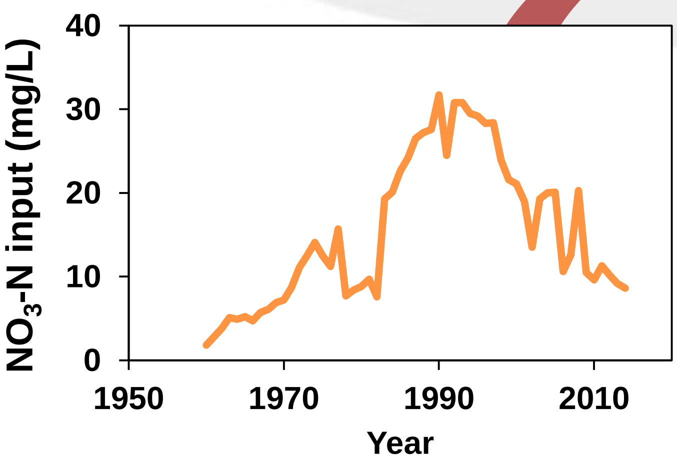
→ Inflow of perched groundwater with high concentration of NO_3-N through improperly completed wells (Koh et al., 2012).

Objectives

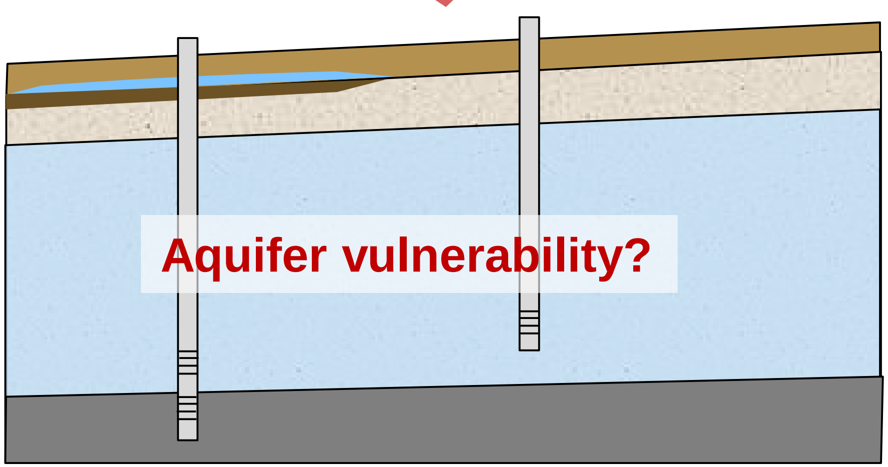
- it is necessary to evaluate aqufer vulnerability to the nitrate loadings before establishing management plans to control the groundwater contamination by nitrate:

1) Applying various methods to estimate the groundwater age in the Gosan area which has complex hydrogeological settings

2) Constraining the timescale of nitrate loading affected by N-input history



Historical
N-fertilizer loading



GW sampling and tracer analysis

- **Groundwater sampling**

1) Oct., 2009

- **Regional GW (15 wells)**

-**^{3}H, CFCs (CFC-11, CFC-12, CFC-113)**

2) June, 2012; Dec., 2013

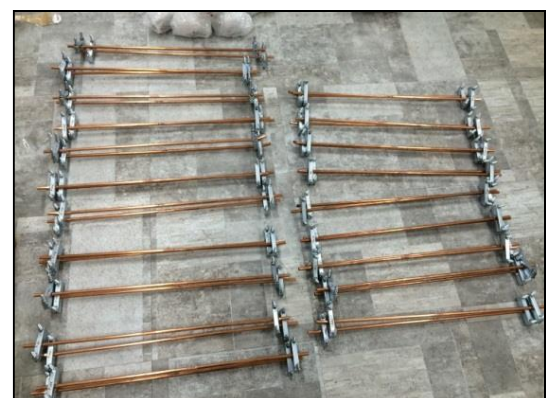
-**Perched (9 wells) & Regional GW (18 wells)**

- **^{3}H, noble gases**

3) Mar., 2014

-**Perched (5 wells) & Regional GW (12 wells)**

- **^{3}H, noble gases, CFCs (CFC-11, CFC-12, CFC-113)**



- **Analysis of environmental tracers**

^{3}H: KIGAM, IT2 Isotope Tracer Technologies

Noble gases: noble gas Lab., university of Utah

CFCs: KIGAM, noble gas Lab., university of Utah

Methods for estimating groundwater age

1) Environmental tracers

- ^{3}H decays by β-decay to $^{3}He_{trit}$ with 12.32 years of half-life (decay constant, $\lambda = \ln(2)/T_{1/2} = 0.0563\ yr^{-1}$)
- $^{3}H/^{3}He$ age (Schlosser et al., 1989)

$$t = \frac{1}{\lambda}\left(1 + \frac{^{3}He_{trit}}{^{3}H}\right)$$

$$^{4}He_{tot} = {}^{4}He_{eq} + {}^{4}He_{ex} + {}^{4}He_{terr}$$

$$^{3}He_{tot} = {}^{3}He_{eq} + {}^{3}He_{ex} + {}^{3}He_{terr} + {}^{3}He_{trit}$$

$^{3}He_{tot}$: total (measured) ^{3}He
$^{3}He_{eq}$: ^{3}He equilibrated with air
$^{3}He_{exc}$: ^{3}He equilibrated with excess air (dissolution of entrapped air bubbles near the water table)
$^{3}He_{terr}$: terrigenic ^{3}He derived from earth's crust and mantle

2) Lumped parameter model (Maloszewski and Zuber, 1982, 1993)

: Applying mixing of tracers using simplified aquifer geometry and flow characteristics

: TracerLPM (Jurgens et al., 2012)

$$C_{out}(t) = \int_{0}^{\infty} C_{in}(t - t')\exp(-\lambda t')\, g(t')dt'$$

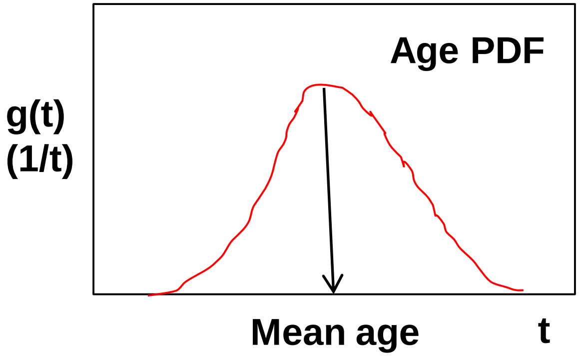
Conc. of age tracer — $C_{out}(t)$
Input conc. — $C_{in}(t - t')$
Decay of radioactive tracer — $\exp(-\lambda t')$
Age distribution functions — $g(t')$

t: sampling date
t': date at which a water parcel entered the system
λ: decay constant
t-t': age of water parcel (=τ)

3) Numerical model (Advection-dispersion model)

-Advective-dispersive transport of travel time distribution (Cornaton and Perrochet, 2006; Park et al., 2008; Lemieux and Sudicky, 2010; McCallum et al., 2014)

-Age PDF (probability density function) ← Age CDF (cumulative distribution function)



Numerical model setting

- <u>HydroGeoSphere</u> (numerical model)

- Variably-saturated groundwater flow and travel time probability transport

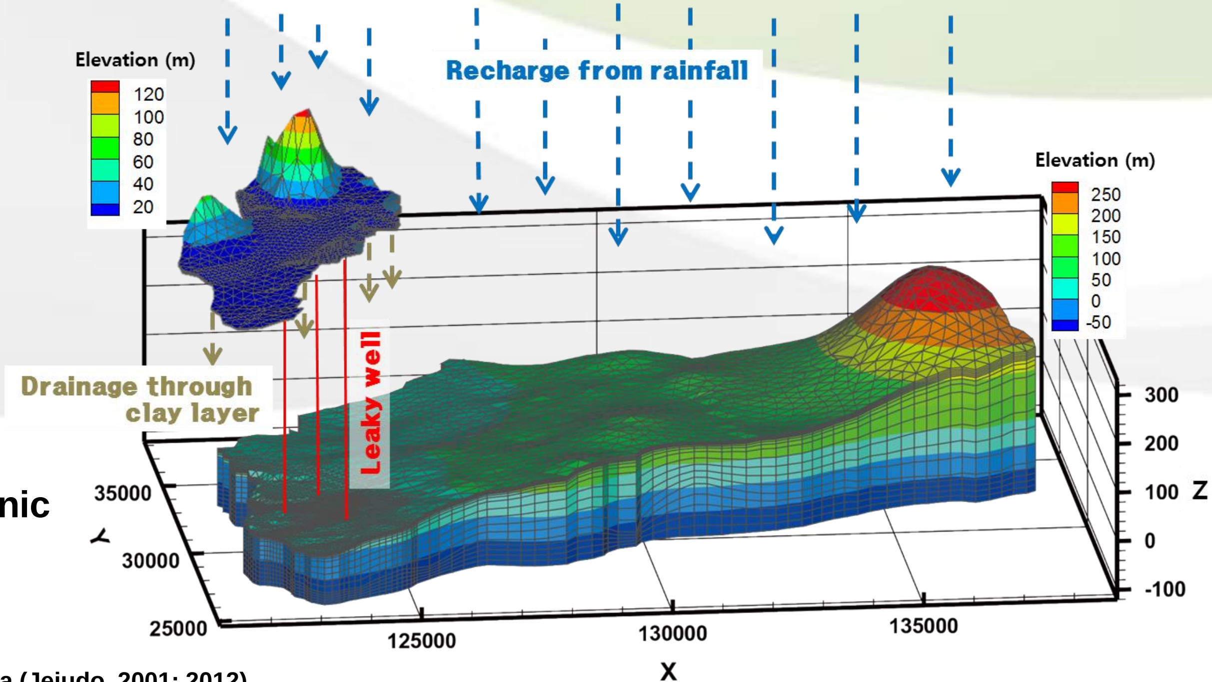
- Two separated domains are developed:

1) perched aquifer

- Total area: 8.22 km^2
- Three hydrogeological layers * (silt loam, tuff, clay)
- Variably-saturated flow

2) regional aquifer

- Total area: 103.11 km^2
- Two hydrogeological layers* (volcanic rocks, Seogwipo Formation)
- Saturated flow

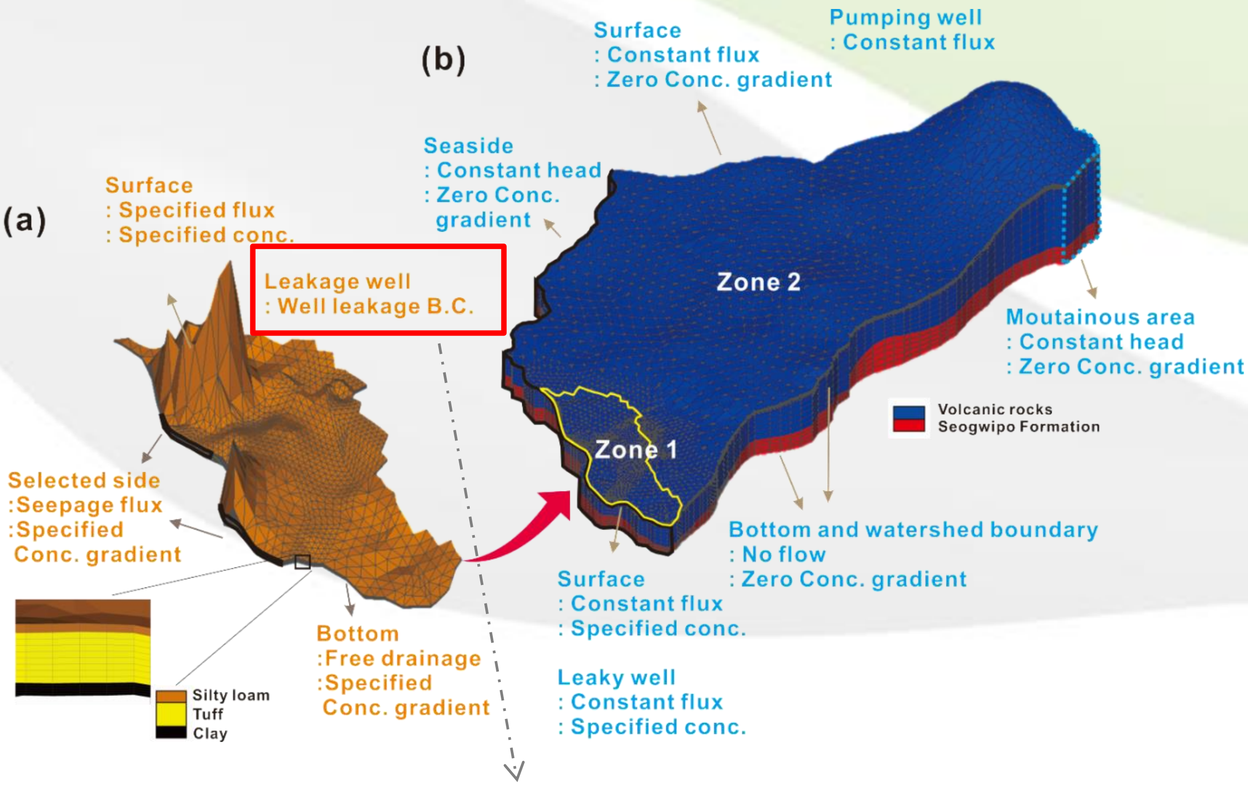


*geologic log data (Jejudo, 2001; 2012)

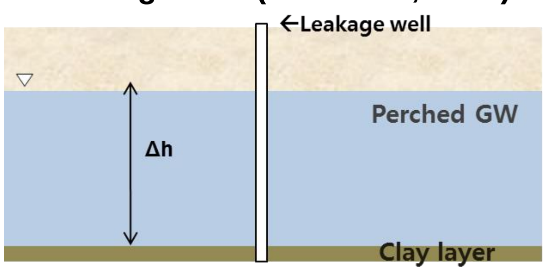
- Model calibration

- Head (Pseudo steady-state simulation), ^3H concentration (transient simulation of 1961~2014)

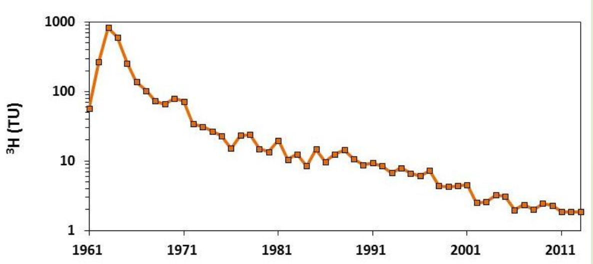
❖ Boundary Conditions



Well leakage B.C. (Koh et al., 2016)

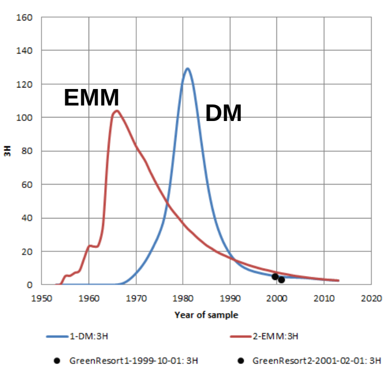


<^{3}H input BC in surface recharge>



^{3}H input history was constructed by Koh et al., (2005)

<Upstream ^{3}H input>



1) EMM
Mean residence time: 10.65 yr

2) DM (DP: 0.01)
Mean residence time: 10.65 yr

▪ **Input parameter**

Hydrostratigraphic units	Calibrated hydraulic conductivity (m/sec) $K_{xx}=K_{yy}$	K_{zz}	Porosity[a]	S_s[b] (m^{-1})	Van Genuchten function parameter[c] S_{wr}	α (m^{-1})	β	Dispersivity (m) a_L	a_T
Silt loam	7.0E-7	7.0E-8	0.45	1.0E-5	0.22	1.87	1.64	30.0	3.0
Tuff	6.6E-7	6.6E-8	0.44	1.0E-5	0.22	1.87	1.64	30.0	3.0
Clay	1.0E-8	1.0E-9	0.42	1.0E-4	0.27	4.54	1.51	0.1	0.01
Volcanic rocks	2.5E-4	7.0E-5	0.35	1.0E-5	-	-	-	50.0	5.0
Seogwipo Formation	1.0E-7	1.0E-8	0.30	1.0E-4	-	-	-	30.0	3.0

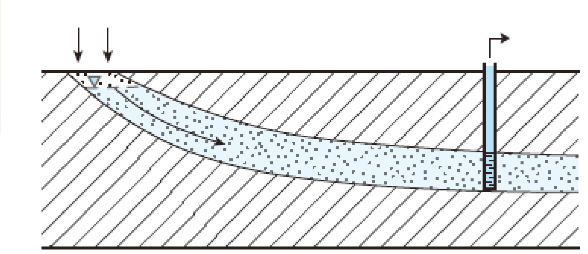
[a]Jejudo; [b] Batu, 1998; [c] Hodnett and Tomasella, 2002

Results: Tracer ages

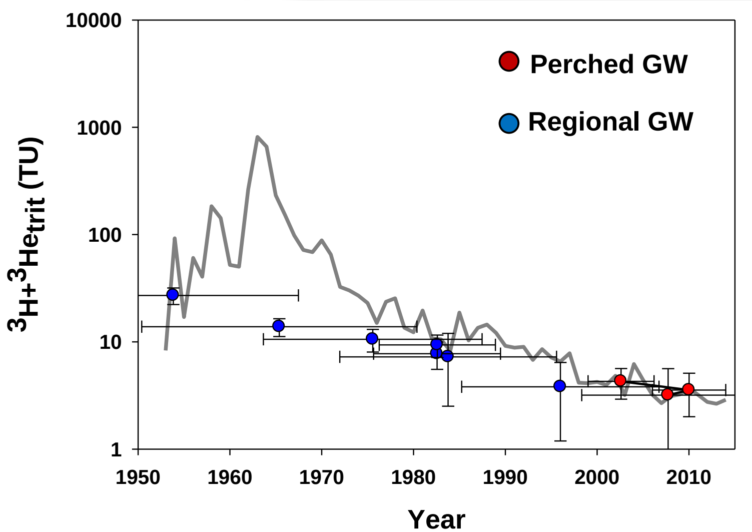
- ^{3}H-^{3}He ages

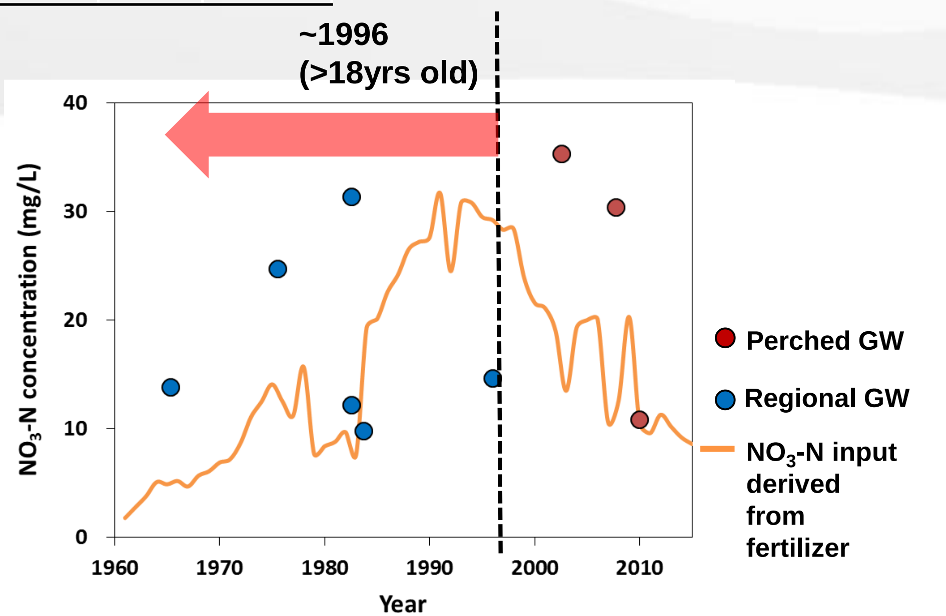
Aquifer type	Well ID	Date	^{3}H (TU)	Ne total (ccSTP/g)	He^{4} (ccSTP/g)	R/Ra	excess air [% Ne]	^{3}He_trit (TU)	^{3}H-^{3}He_age (year)	Recharge year	initial_^{3}H (TU)
Perched GW	M2	2012-06-20	2.4±0.6	1.93E-07	4.47E-08	0.99	6.2	1.8 ±0.7	10.0±3.6	2002.6	4.3
	M3	2012-06-20	3.1±0.8	1.89E-07	4.30E-08	0.94	1.7	0.5 ±0.8	2.6± 4.0	2010.0	3.6
	M5	2014-03-01	2.2±0.8	2.02E-07	4.70E-08	1.02	2.2	1.0 ±1.6	6.6 ±9.4	2007.7	3.2
Regional GW	D-080	2012-06-20	1.0±0.9	2.20E-07	8.45E-08	3.41	16.7	12.8± 1.7	47.2±15.0	1965.4	13.8
	D-190	2013-12-13	1.4±0.9	2.12E-07	8.14E-08	3.25	9.9	2.4 ±1.8	17.9 ±10.7	1996.0	3.8
	D-080	2014-03-01	0.9±0.7	2.47E-07	1.47E-07	4.82	25.1	26.1± 4.0	60.5 ±13.6	1953.8	27.0
	D-088	2014-03-01	1.3±0.5	2.35E-07	1.55E-07	4.81	19.2	5.9 ±4.2	30.5 ±11.8	1983.8	7.2
	D-134	2014-03-01	1.3±0.5	2.48E-07	8.27E-08	2.75	25.9	6.5 ±1.7	31.7 ±6.9	1982.6	7.8
	F-052	2012-06-20	1.7±0.7	2.67E-07	6.74E-08	1.25	39.7	7.6 ±1.5	30.0 ±6.3	1982.6	9.4
	D-170	2013-12-13	1.2±0.9	2.37E-07	5.66E-08	1.10	24.4	9.3 ±1.6	38.3 ±11.9	1975.6	10.5

Piston flow (no mixing)



Jurgens et al., 2012





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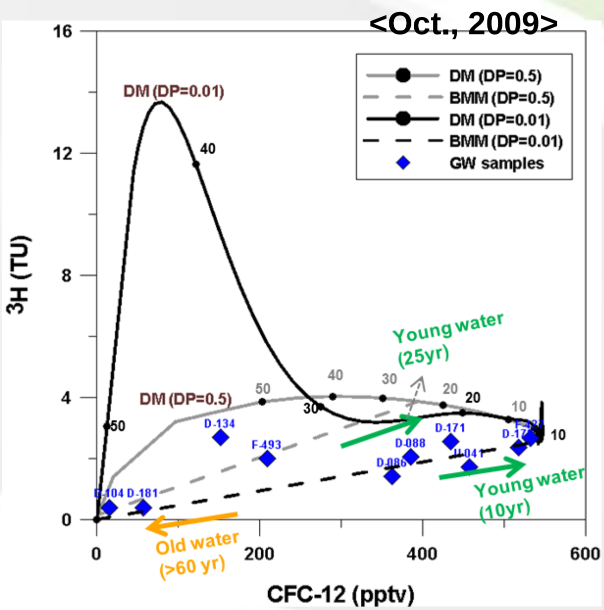
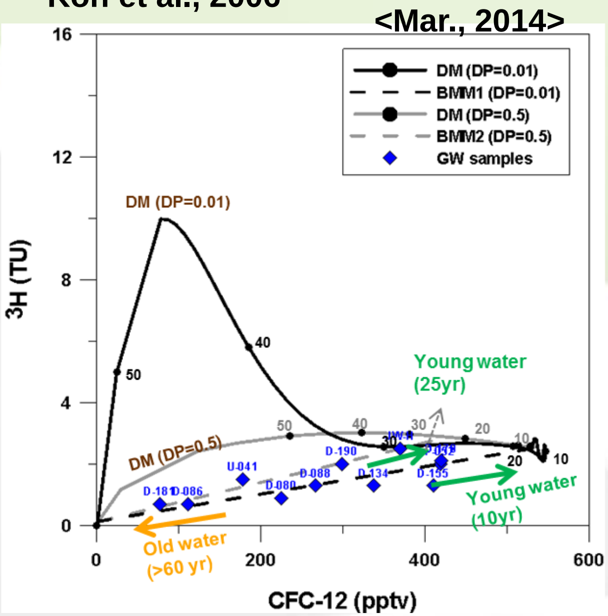
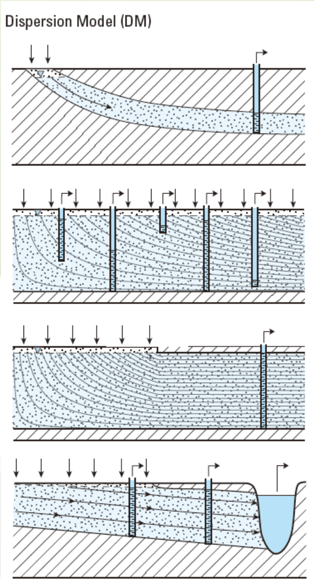
Results: Lumped parameter model

- **Binary mixing model: young (dispersion model)+old water (piston model)**

Koh et al., 2006



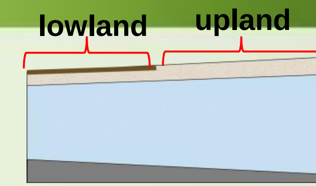




Jurgens et al., 2012

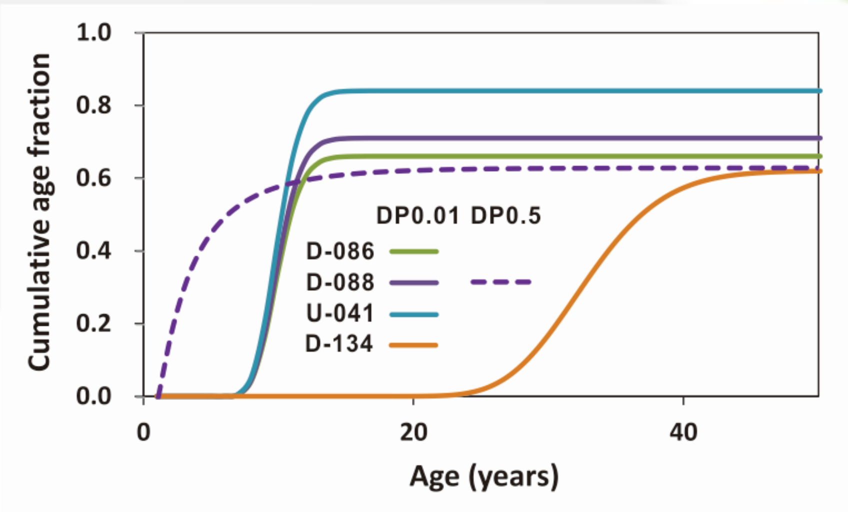
Well ID	Sampling date	^{3}H (TU)	CFC12 (pptv)	NO_3-N (mg/L)	DP 0.01		DP 0.5	
					DM ages	young fraction	DM ages	young fraction
D-134		2.7	151.5	16.90	33	0.62	-	-
D-170		2.4	517.2	15.70	10	0.95	4	0.96
D-171		2.6	434.2	15.50	13	0.81	7	0.82
F-427	Oct., 2009	2.7	531.8	17.60	10	0.97	4	0.98
F-493		2.0	208.9	17.00	27	0.61	25	0.53
D-088		2.0	385.5	20.80	10	0.71	4	0.71
U-041		1.7	457.7	15.40	10	0.84	-	-
F-052		2.0	418.9	31.44	10	0.77	6	0.79
D-134		1.3	337.5	12.16	6	0.62	-	-
D-170		2.1	419.3	23.49	20	0.45	8	0.79
U-041		1.5	178.0	3.84	33	0.35	32	0.33
D-080	Mar., 2014	0.9	224.8	8.89	7	0.41	-	-
D-155		1.3	409.9	23.09	15	0.75	-	-
D-088		1.3	267.0	9.80	20	0.33	10	0.50
D-120		2.5	369.9	12.04	29	0.55	24	0.70
D-190		2.0	298.5	10.40	29	0.50	24	0.56

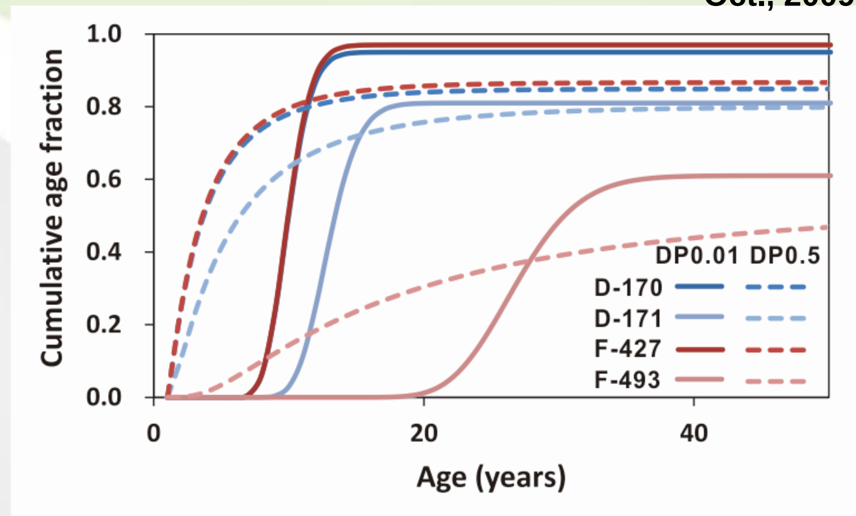
Age fraction of samples: Lumped parameter model

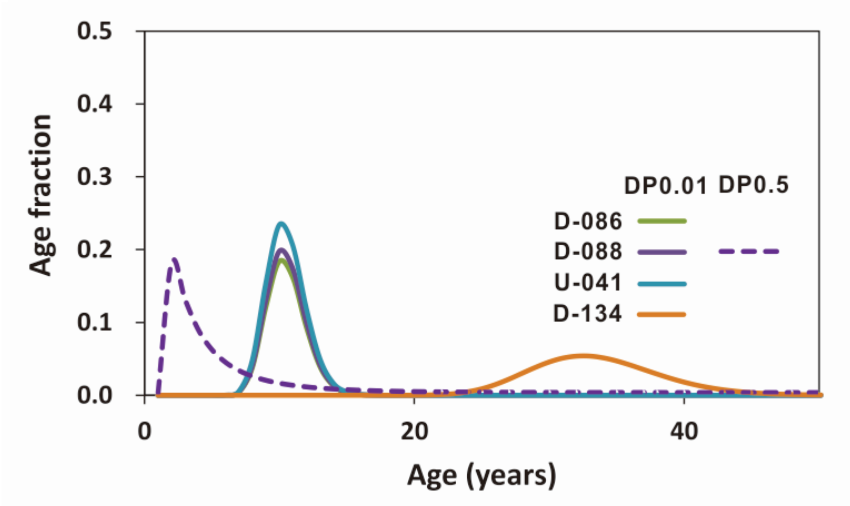


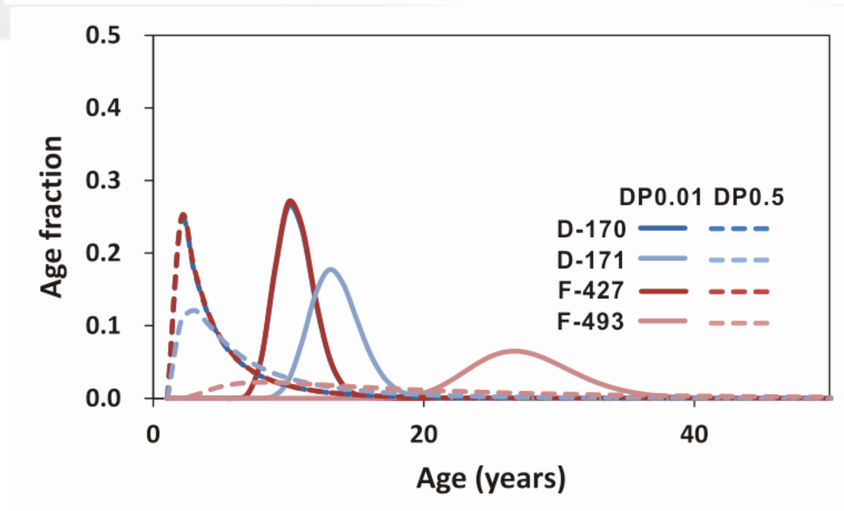
Oct., 2009

- **Lowland well**
- **Upland well**









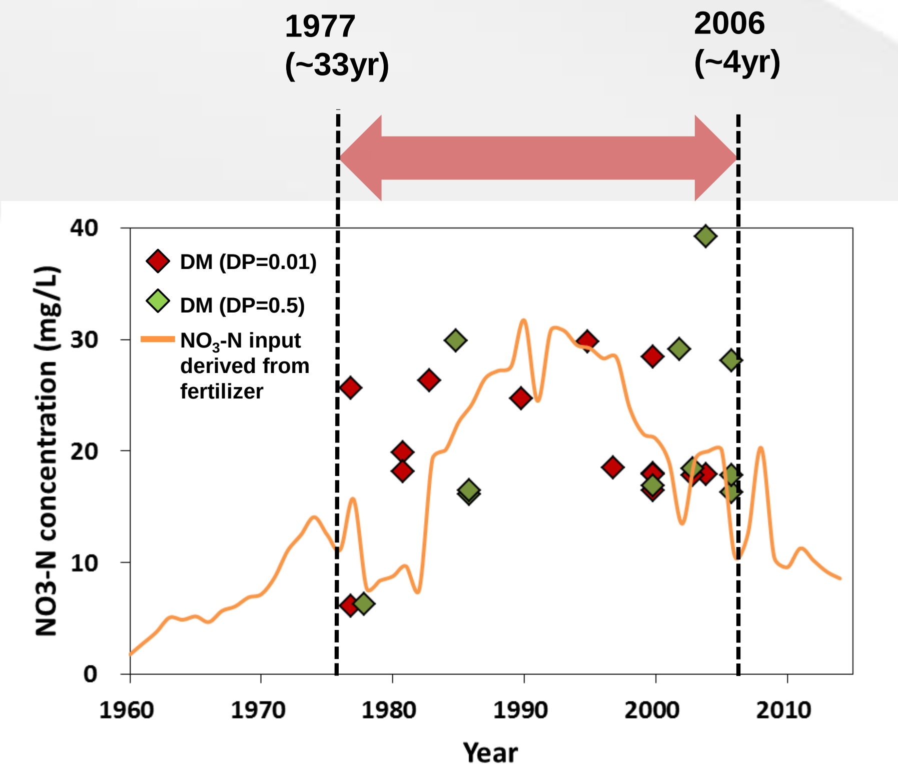
Reconstruction of NO_3-N contamination

- **Estimation of NO_3-N in young water component**

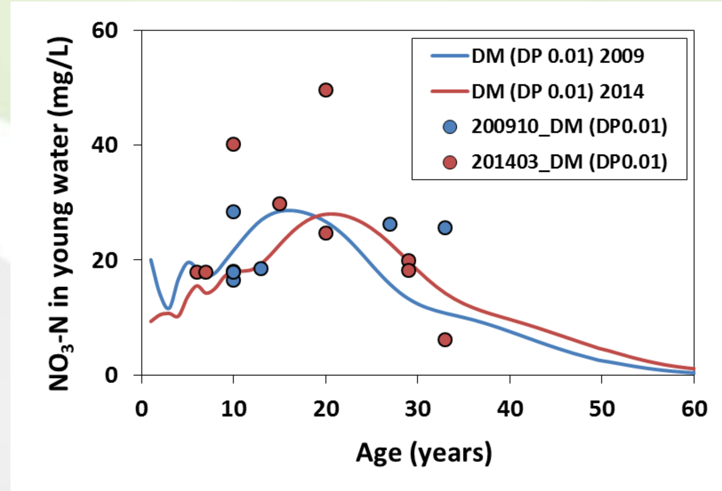
$$NO_3\text{-}N_{sample}=F_{young}*NO_3\text{-}N_{young}+F_{old}*NO_3\text{-}N_{old}$$

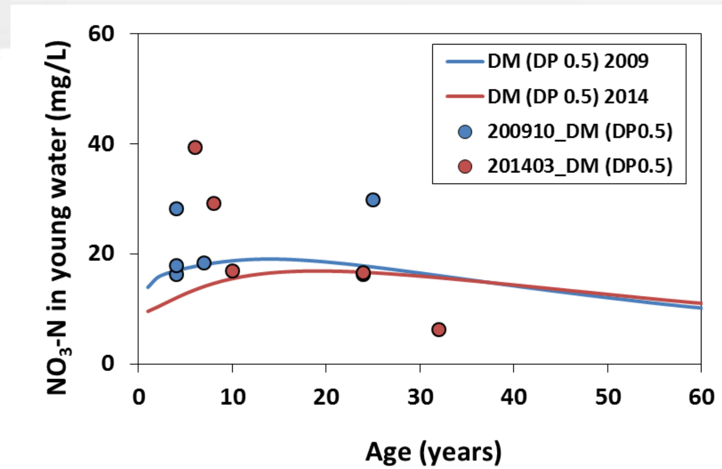
F_{young}: fraction of young water
F_{old}: fraction of old water

↓ 1.6 mg/L averaged for ^3H < 0.5 TU



NO_3-N in young water (dispersion model)



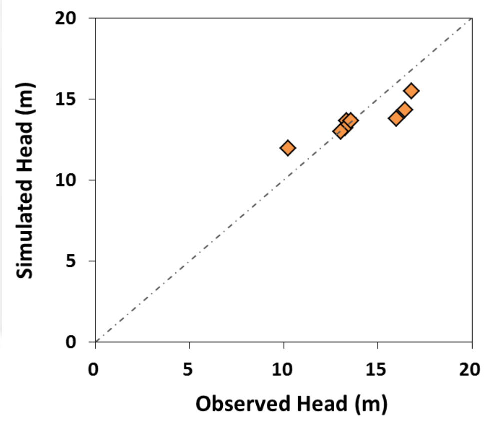


Numerical model results

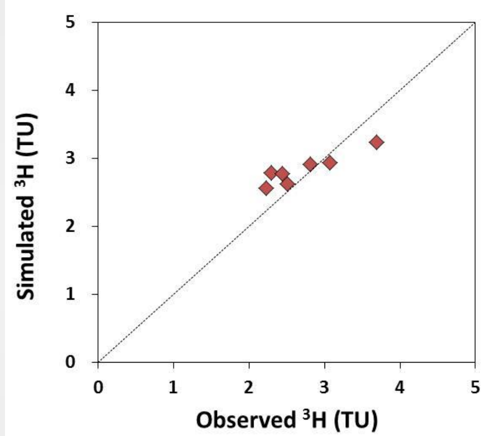
- **Model calibration**

1) Perched GW

Head calibration

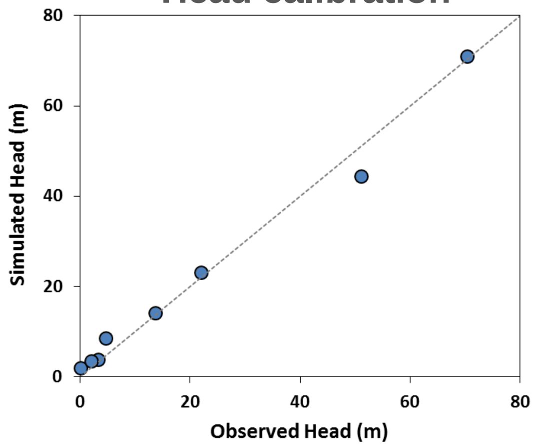


^3H calibration

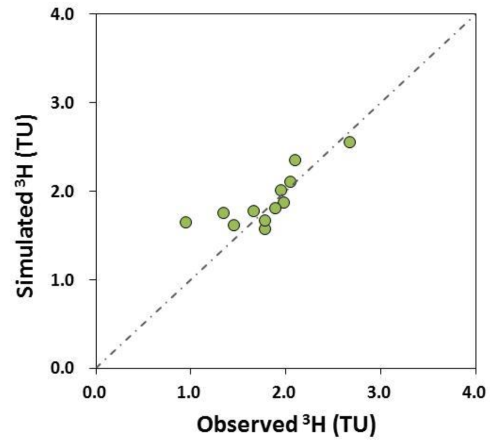


2) Regional GW

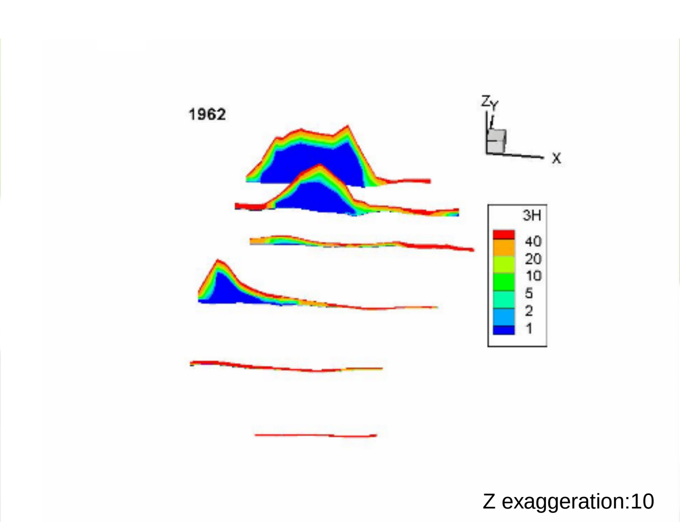
Head calibration

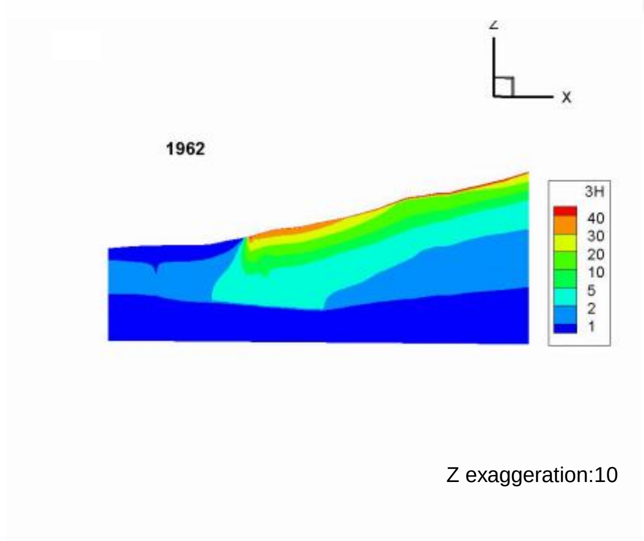


^3H calibration



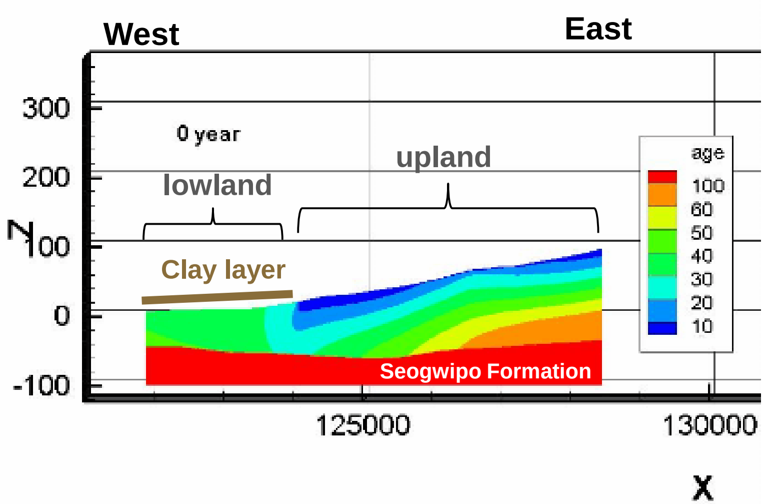
Simulated ^3H distribution



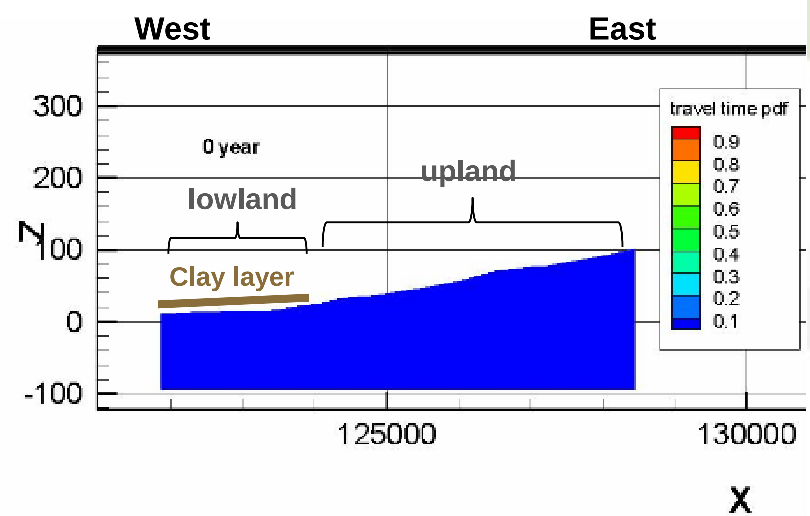


- **Cross-sectional view at the leaky well**

<Mean age>

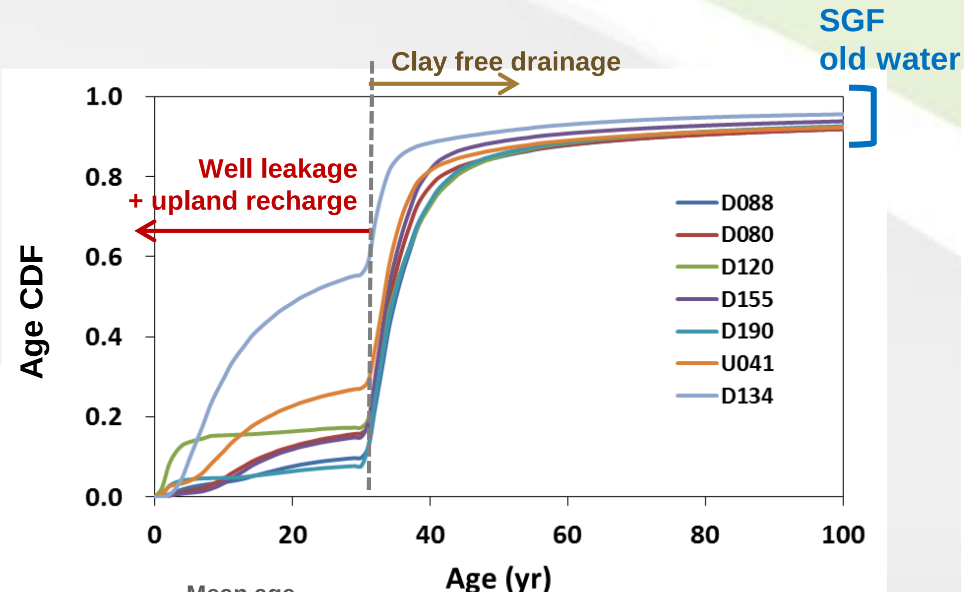


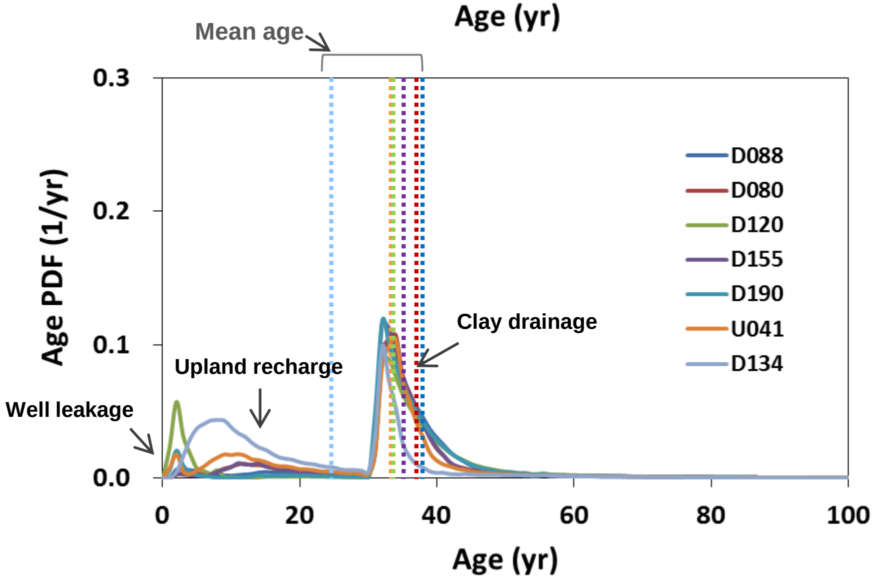
<Age CDF>



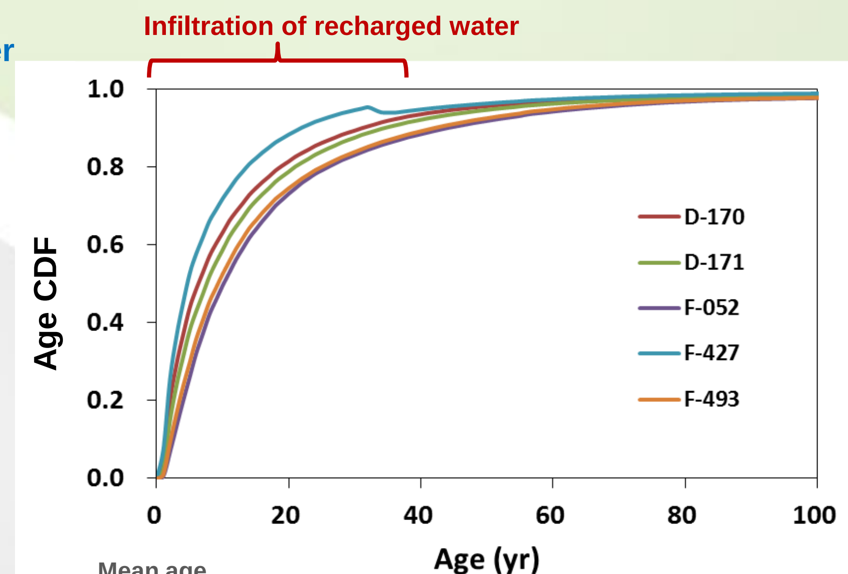
Numerical model results

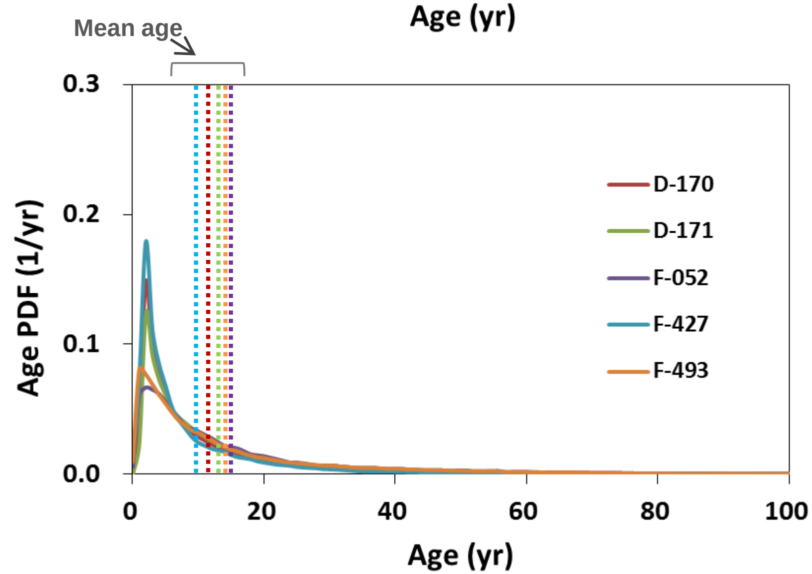
- **Lowland well**



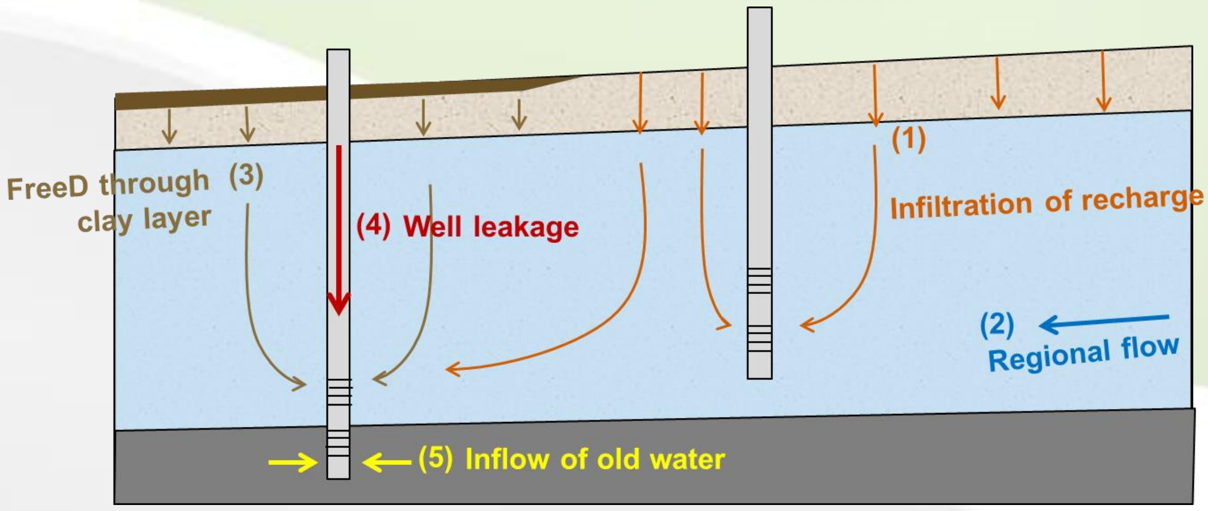


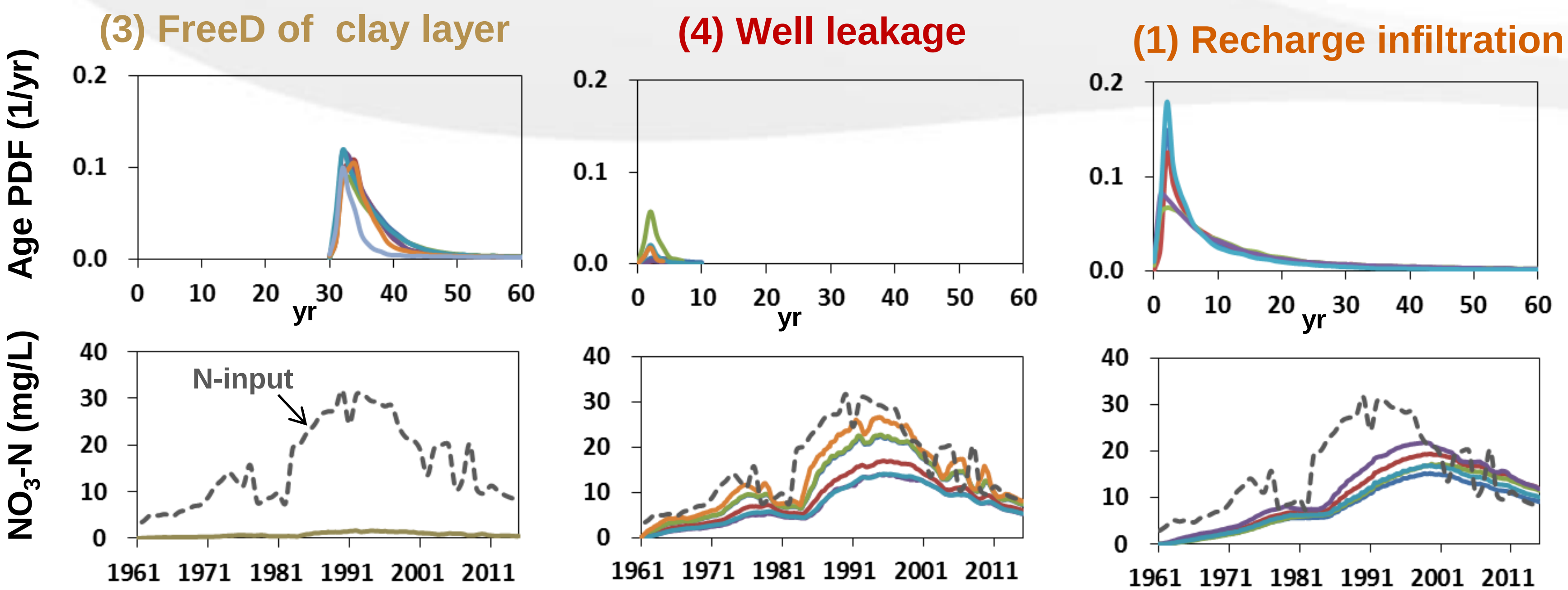
- **Upland well**





NO_3-N transport process with timescale



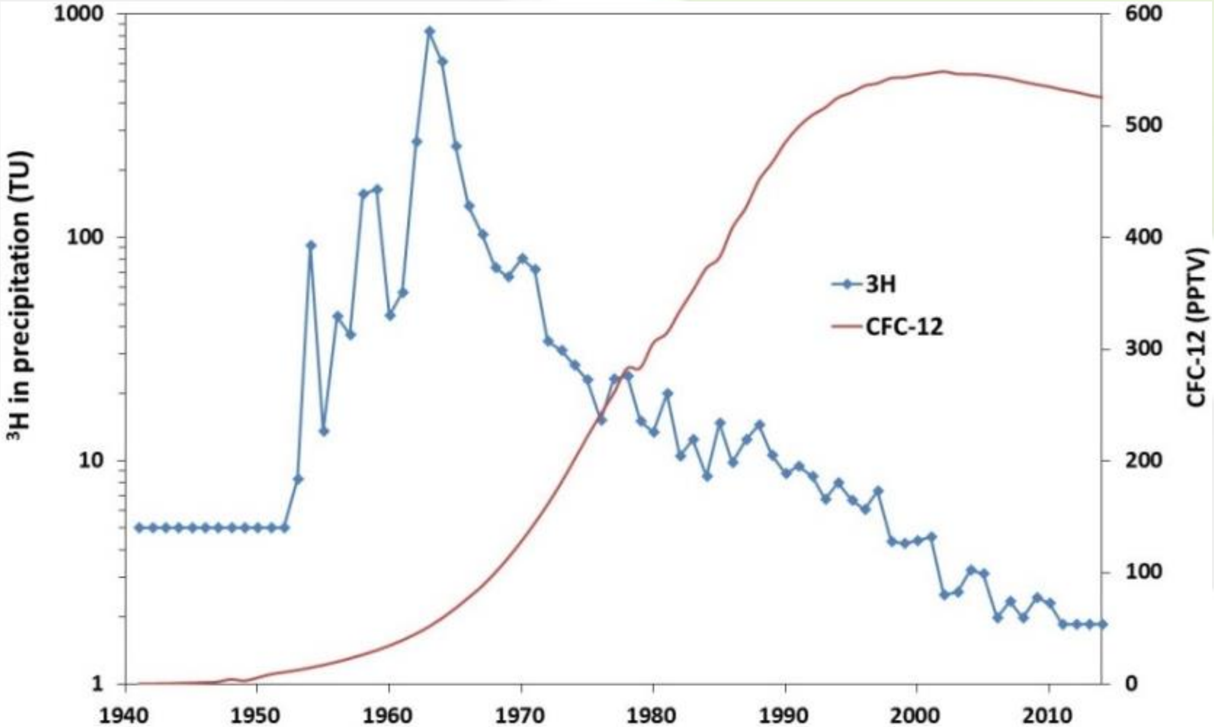


Conclusion

- **Groundwater age can provide information about aquifer's hydrogeologic characteristics.**
- **In the Gosan agricultural area, where has complex hydrogeological settings, interpretation of groundwater age from three estimation methods was utilized to evaluate the nitrate contamination process.**
- **Tracer ages estimated relatively older groundwater ages than the other methods due to no consideration of mixing process.**
- **Lumped parameter model ages could present binary mixing of young and old groundwater. N-input of younger than 30 years would affect the water quality in the regional aquifer.**
- **Numerical model could show the full age distribution and impacts of various age components of waters.**
- **Approaches for evaluating the nitrate contamination process combining with the full age distribution can be applied for establishing groundwater management plans.**


Thank you!

^3H: 재구성한 강우내 농도; CFC-12: 북반구 대기농도



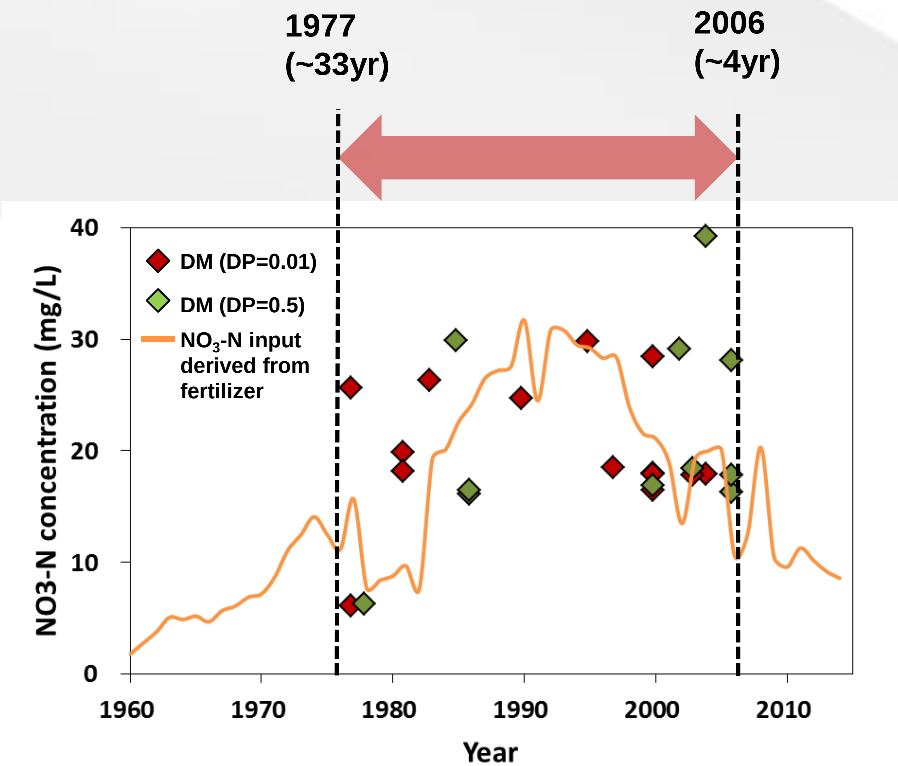
Reconstruction of NO_3-N contamination

- **Estimation of NO_3-N in young water component**

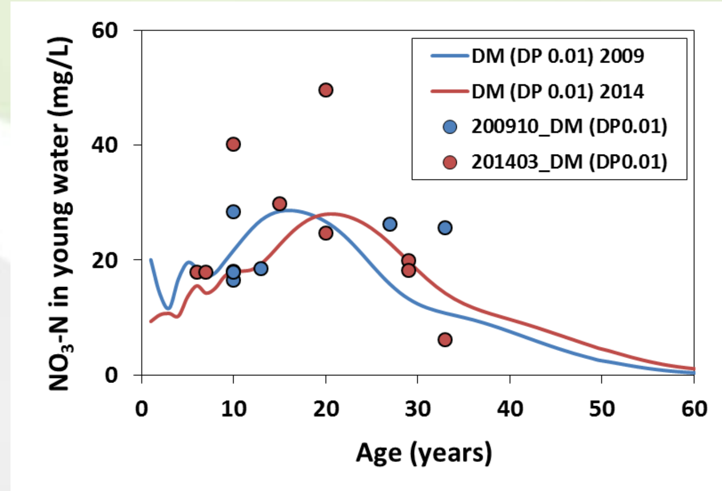
$$NO_3\text{-}N_{sample}=F_{young}*NO_3\text{-}N_{young}+F_{old}*NO_3\text{-}N_{old}$$

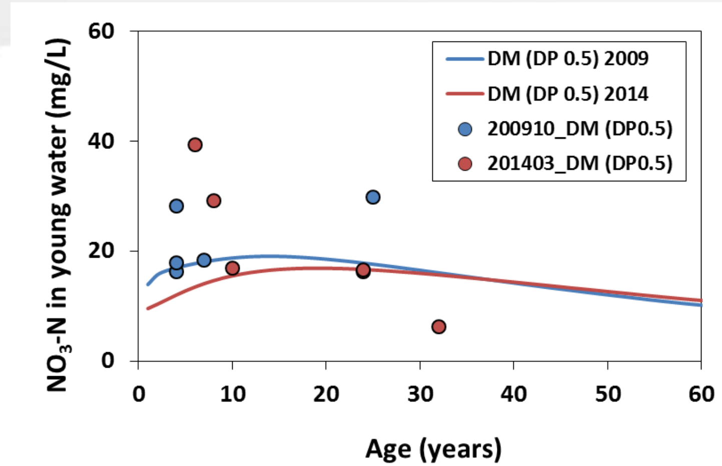
F_{young}: fraction of young water
F_{old}: fraction of old water

1.6 mg/L averaged for ^3H < 0.5 TU

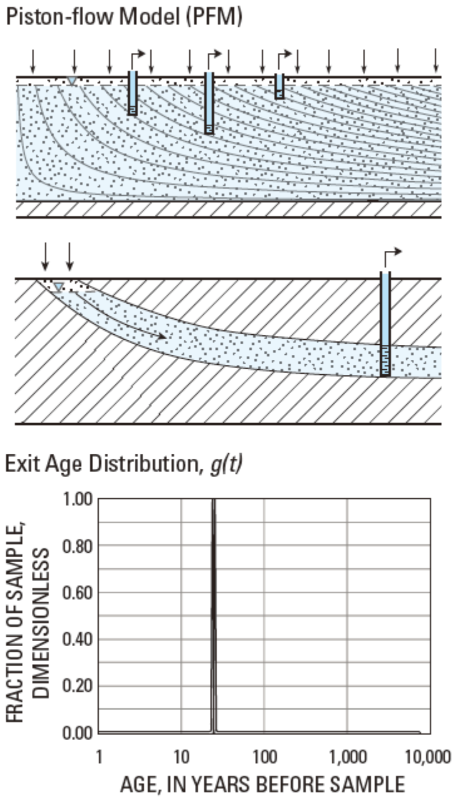


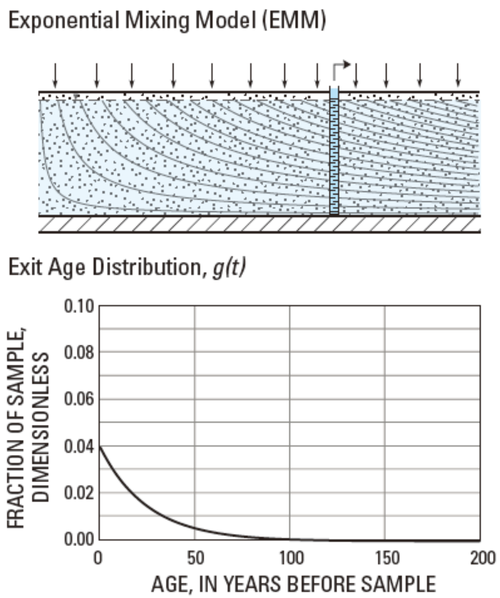
NO_3-N loading in young water

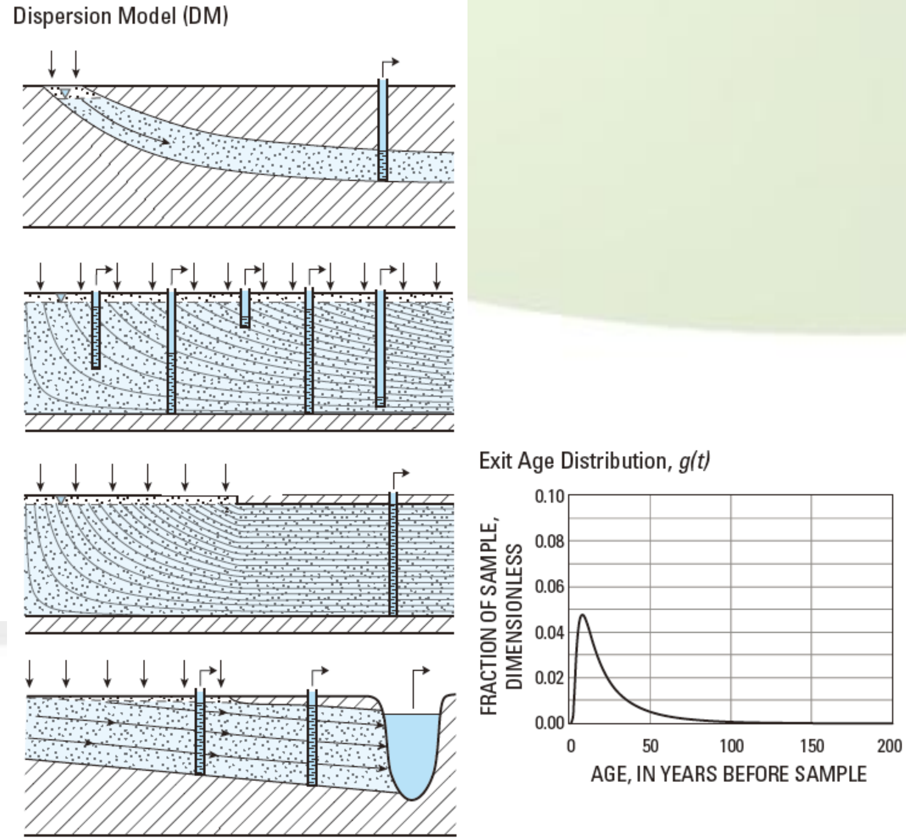




Lumped parameter model







$$PFM_{g(t-t')} = \delta(t - t' - \tau_s)$$

$$EMM_{g(t-t')} = \frac{1}{\tau_s} e^{\frac{(t-t')}{\tau_s}}$$

$$DM_{g(t-t')} = \frac{1}{\tau_s} \frac{1}{\sqrt{4\pi DP \frac{t-t'}{\tau_s}}} e^{\left(-\frac{\left(1-\frac{t-t'}{\tau_s}\right)^2}{4DP\frac{t-t'}{\tau_s}}\right)}$$

t-t': age of water parcel
τ_s: mean age of a sample
δ: dirac delta function

where

$$DP = \text{dispersion parameter} = \frac{\text{Dispersion coefficient}(D)}{vx}$$

V: velocity
X: outlet position

USGS, 2012

^3H-^3He apparent groundwater age

- ^3H decays by β-decay to ^3He with 12.32 yrs of half-life (decay constant, $\lambda=\ln(2)/T_{1/2}=0.0563\ yr^{-1}$)

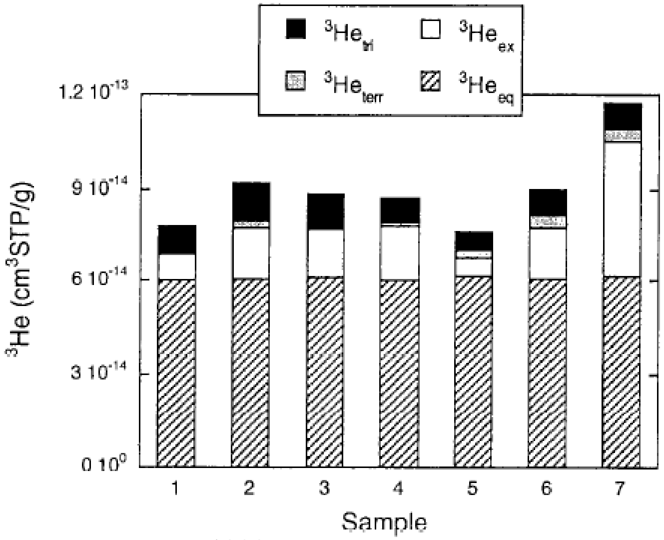
- $^3H/^3He$ age (Schlosser et al., 1989)

$$t = \frac{1}{\lambda}\left(1 + \frac{^3He_{trit}}{^3H}\right)$$

$^3He_{trit}$: tritiogenic ^3He

- $^3He_{tot}={}^3He_{eq}+{}^3He_{exc}+{}^3He_{terr}+{}^3He_{tirt}$

$^3He_{tot}$: total (measured) ^3He
$^3He_{eq}$: ^3He equilibrated with air
$^3He_{exc}$: ^3He equilibrated with excess air (dissolution of entrapped air bubbles near the water table)
$^3He_{terr}$: terrigenic ^3He derived from earth's crust and mantle



P Imboden and Schär, 1999

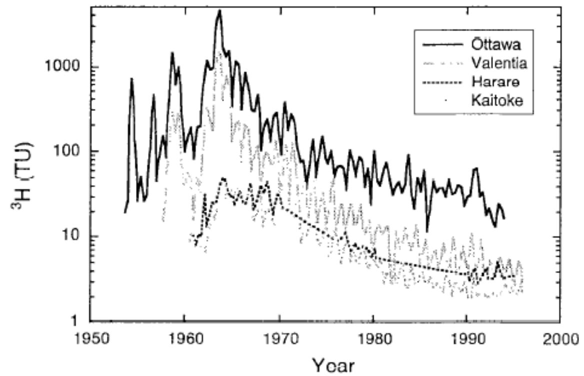


Figure 2.8: Tritium concentration in precipitation since 1950 at four IAEA stations (IAEA/WMO, 1998): Ottawa, Canada (northern hemisphere, continental); Valentia, Ireland (northern hemisphere, marine); Harare, Zimbabwe (southern hemisphere, continental); Kaitoke, New Zealand (southern hemisphere, marine).

Calculation of ^3H-^3He age

- $^3H/^3He$ age (Schlosser et al., 1989)

$$t = \frac{1}{\lambda}\left(1 + \frac{^3He_{trit}}{^3H}\right)$$

$^3He_{trit}$: tritiogenic ^3He

→ ^3H가 붕괴되어 생성되는 $^3He_{trit}$ 값을 구해야 함.

$^4He_{tot} = {^4He_{eq}} + {^4He_{ex}} + {^4He_{terr}}$

$^3He_{tot} = {^3He_{eq}} + {^3He_{ex}} + {^3He_{terr}} + {^3He_{trit}}$

샘플 측정값

$^3He_{ex} = (^3He/^4He)_{air} \times {^4He_{ex}}$ → $^4He_{ex} = (^{20}Ne_{tot} - {^{20}Ne_{eq}}) \times (^4He/^{20}Ne)_{air}$

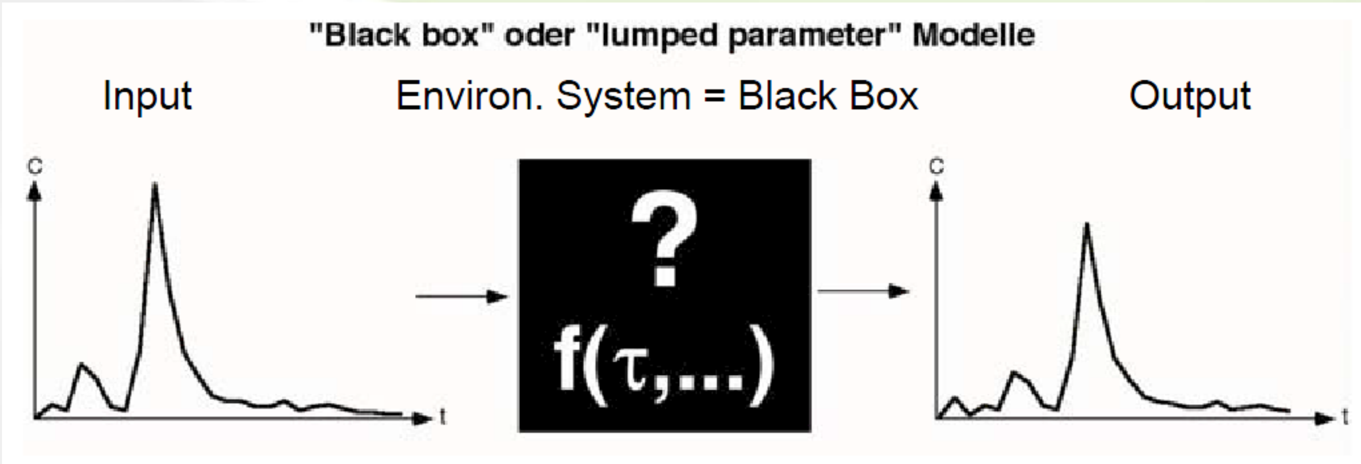
or Excess air model (Noble90)

$^3He_{terr} = {^4He_{terr}} * (^3He/^4He)_{terr}$

↑

$^4He_{terr} = {^4He_{tot}} - {^4He_{eq}} - {^4He_{ex}}$

Lumped parameter model



Decay of radioactive tracer

$$C_{out}(t) = \int_0^\infty C_{in}(t-t')\exp(-\lambda t')\, g(t')\, d$$

Conc. of age tracer

Input conc.

Age distribution functions

t: sampling date
t': date at which a water parcel entered the system
λ: decay constant
t-t': age of water parcel (=τ)

Transit time distribution (TTD)

$$g(t) = C_I(t) / \int_0^\infty C_I(t)\, d$$

$$\int_0^\infty g(t)\, dt = 1$$

$C_I(t)$: the tracer concentration observed at the measuring point

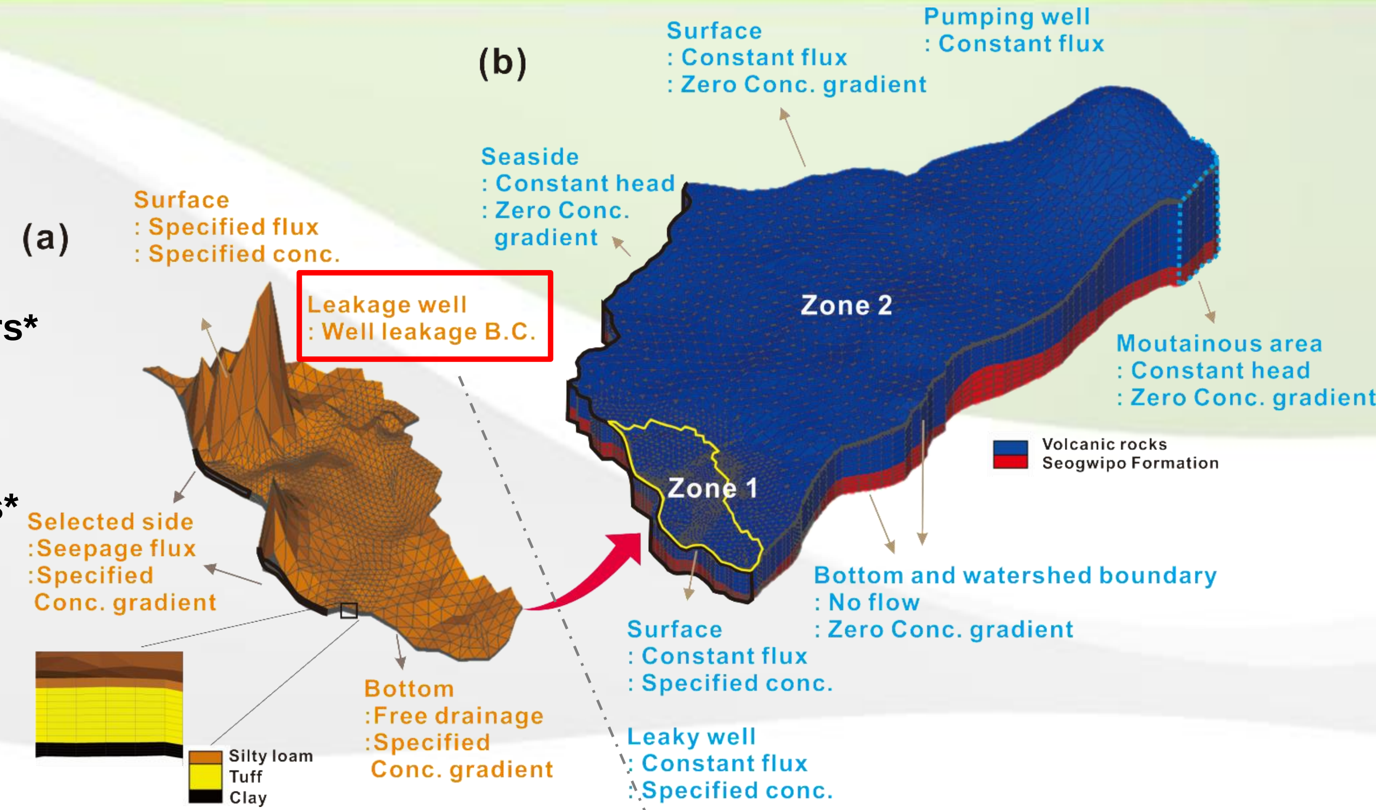
Aeschbach-Hertig, 2011

Model setting

(a) Perched aquifer
- **Total area: 8.22 km²**
- **Three hydrogeological layers***

(b) Regional aquifer
- **Total area: 103.11 km²**
- **Two hydrogeological layers***

*geologic log data (Jejudo, 2001; 2012)



- **Well leakage B.C.**

$$Q_{leakage} = 2\pi \cdot r_{well} \cdot C_{leakage} \cdot \underbrace{(h_{leakage} - Z_{claytop})}_{\Delta h} \qquad h_{leakage} > Z_{clay}$$

$$= \quad 0 \qquad h_{leakage} \leq Z_{clay}$$

$H_{leakage}$: hydraulic head at the leakage node (m)
$Z_{claytop}$: top elevation of clay layer (m)