COMBINING GROUNDWATER QUALITY ANALYSIS AND A NUMERICAL FLOW SIMULATION FOR SPATIALLY ESTABLISHING UTILIZATION STRATEGIES FOR GROUNDWATER AND SURFACE WATER IN THE PINGTUNG PLAIN

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Outline

Limited surface water
Lowest ratio of tap water use (45.8%)
} Over-exploitation groundwater in Pingtung plain

Seawater intrusion, and land subsidence in over the past 5 decades (Ting et al., 1998)
➔ Establish manmade lakes and reservoirs to increase the supply of surface water.

✓ The integrated groundwater quality and quantity are the considered factors in the regional development of water resources.

Groundwater quality

Water with high concentration of Manganese and Iron is used for agriculture and aquaculture
→ Retardation growth or death for plants and fish (Tsai et al., 2006; Liao et al., 2008; Ye et al., 2009)

Arsenic is direct harmful or indirectly harmful to human health through accumulate crops and fish (Huq and Naidu, 2005; Jang et al., 2006)

➔ Needs to be carefully observed.

Groundwater quality

Available surveying a finite amount of field data → Using geostatistics for spatially characterizing the variability and distribution of finite surveyed data.

Indicator Kriging (IK) — Various water using demands

↓

Multivariate indicator Kriging (MVIK) method

↓

Locating suitable groundwater to meet irrigation, aquaculture, and drinking demands (Lee et al. 2008, Jang and Chen. 2009, Jang et al. 2012a, 2012b)

✓ Use for characterizing the spatial uncertainty of variables (hydro-chemical parameters) according to probability estimation.

Groundwater quantity

MODFLOW

Quantifying the changes in groundwater flow and level caused by natural recharge, artificial withdrawal, and specified hydrological events (Rejani et al., 2008; Liu et al., 2010; Mittelstet et al., 2011; Al-Salamah et al., 2011; Jang et al., 2012b)

Applied to predict the effects of recovery on groundwater levels

Objective:

- Analysis of groundwater quality combine with numerical flow simulation to determine the most suitable location for surface water for drinking, irrigation, and aquaculture using purpose in Pingtung Plain.

II MATERIAL AND METHODS

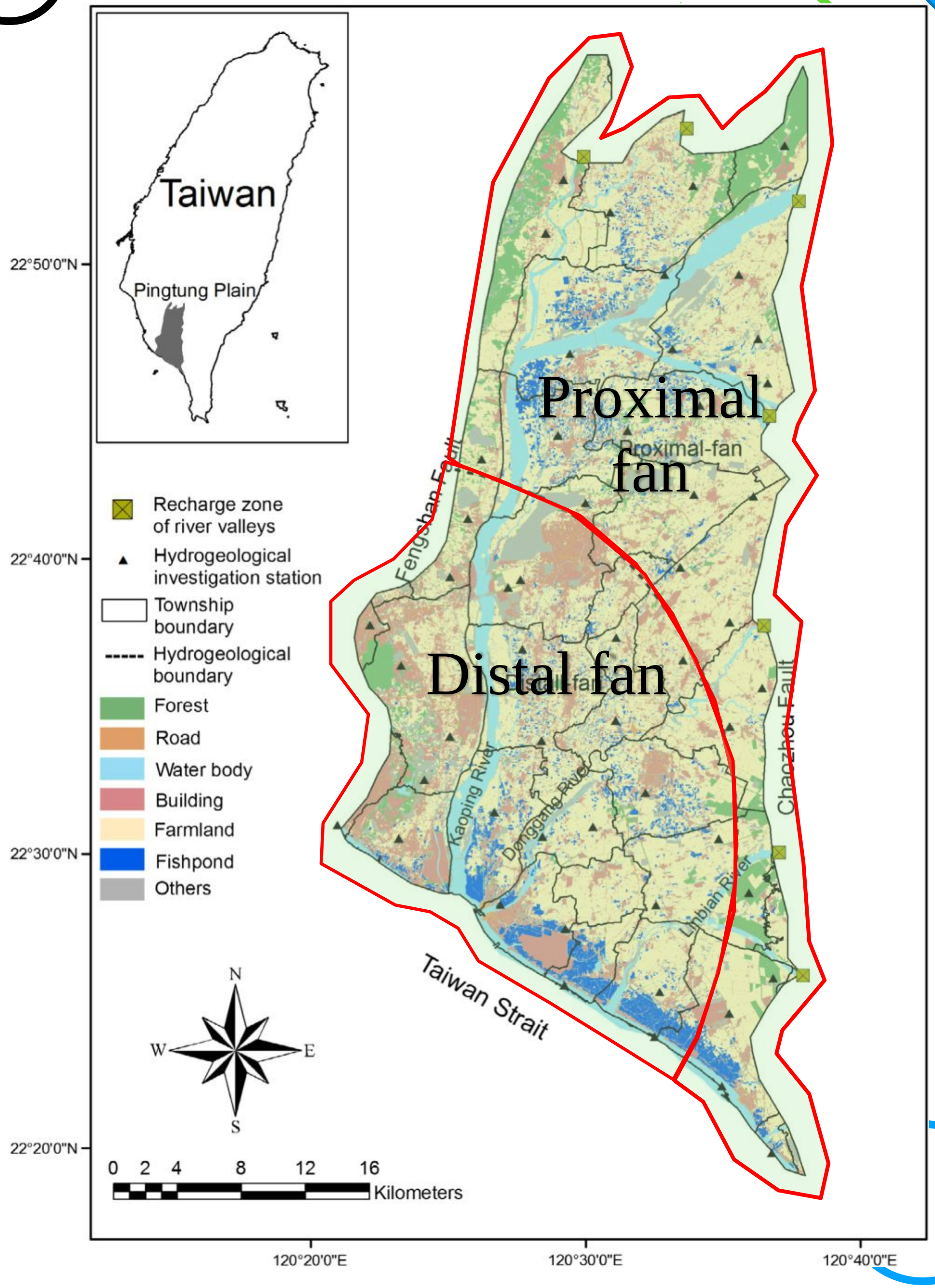
Pingtung plain: 1210 km^2

- Natural boundary
- Rainfall with high annual precipitation (2840mm)
- Unconsolidated Quaternary underlying the plain

Area has rich groundwater resources.

Plain divide
- Proximal fan
- Distal fan

High demand for using water in farmland, fish pond and household result in land subsidence and seawater intrusion.

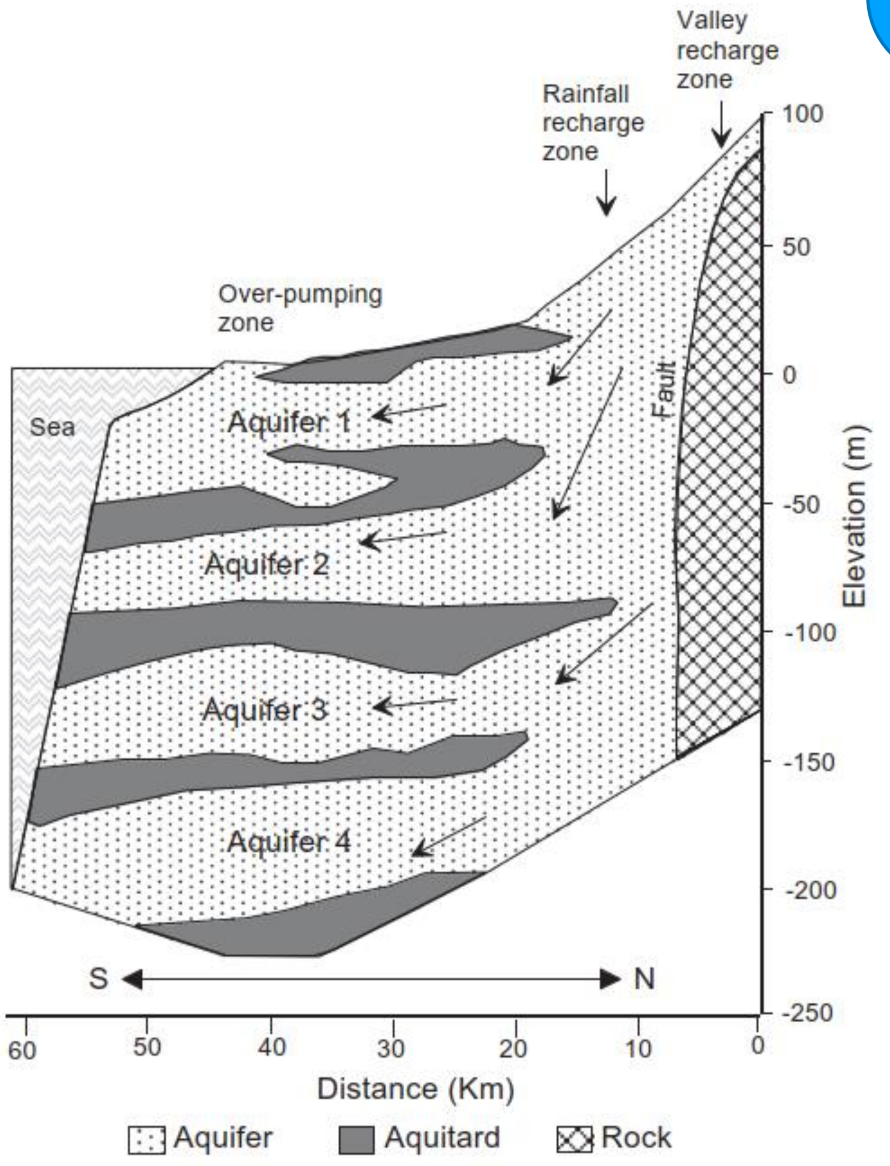


Hydrogeological

The plain sediments in distal-fan can divide into 8 layers

- Aquifer: high permeable coarse sediments, ranging from medium sand to gravel.
- Aquitard: low permeable fine sediments, ranging from clay to fine sand

- Aquitard primarily present in the distal-fan but absent in proximal-fan



A conceptual hydrogeological profile of the Pingtung Plain

Conceptual model

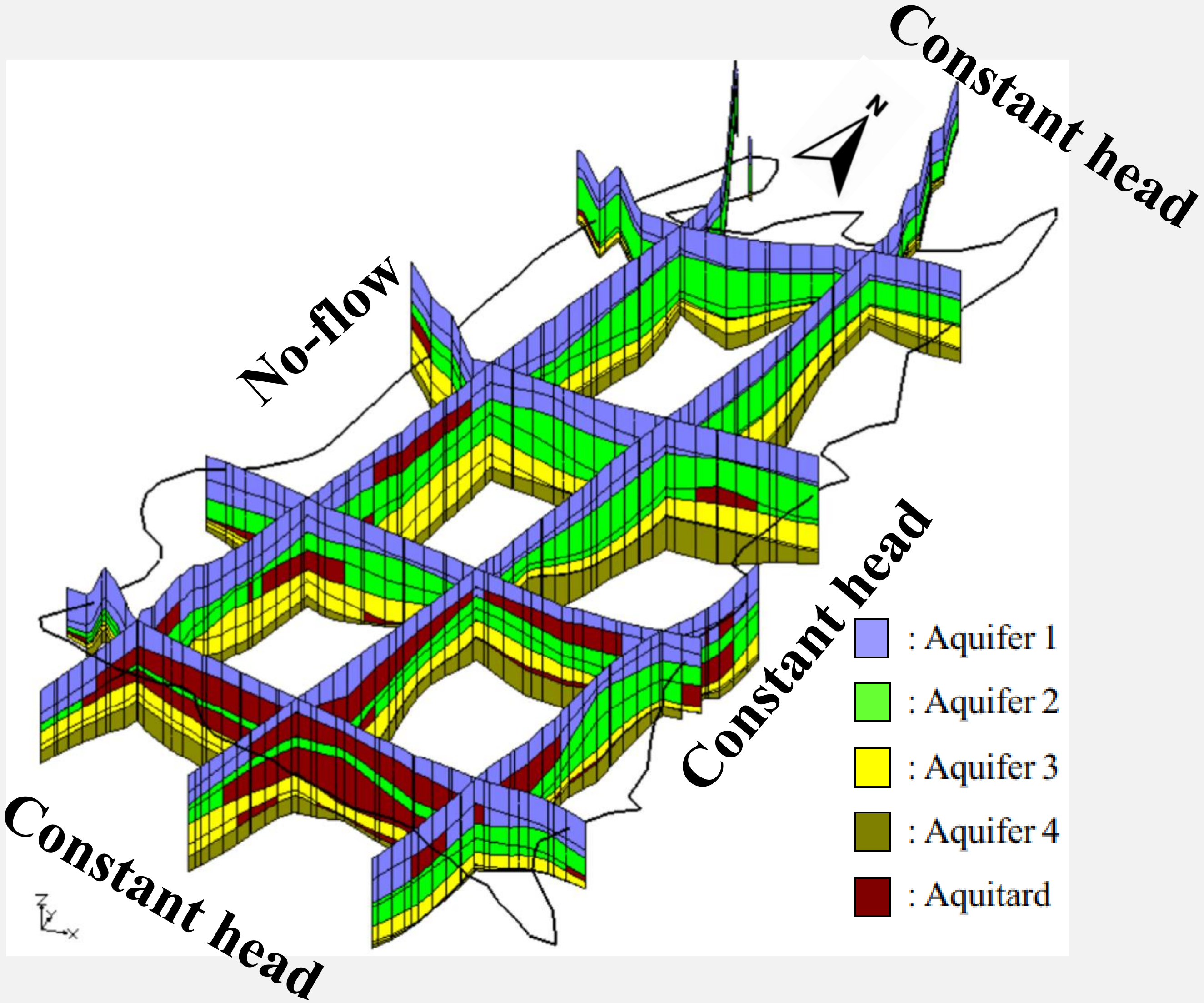
Data input

Calibration

Numerical model of groundwater flow

4 aquifers
4 aquitards

34x72 cells
1000m



Cross sections of the three-dimensional grid of groundwater flow model

Conceptual model

↓

Data input

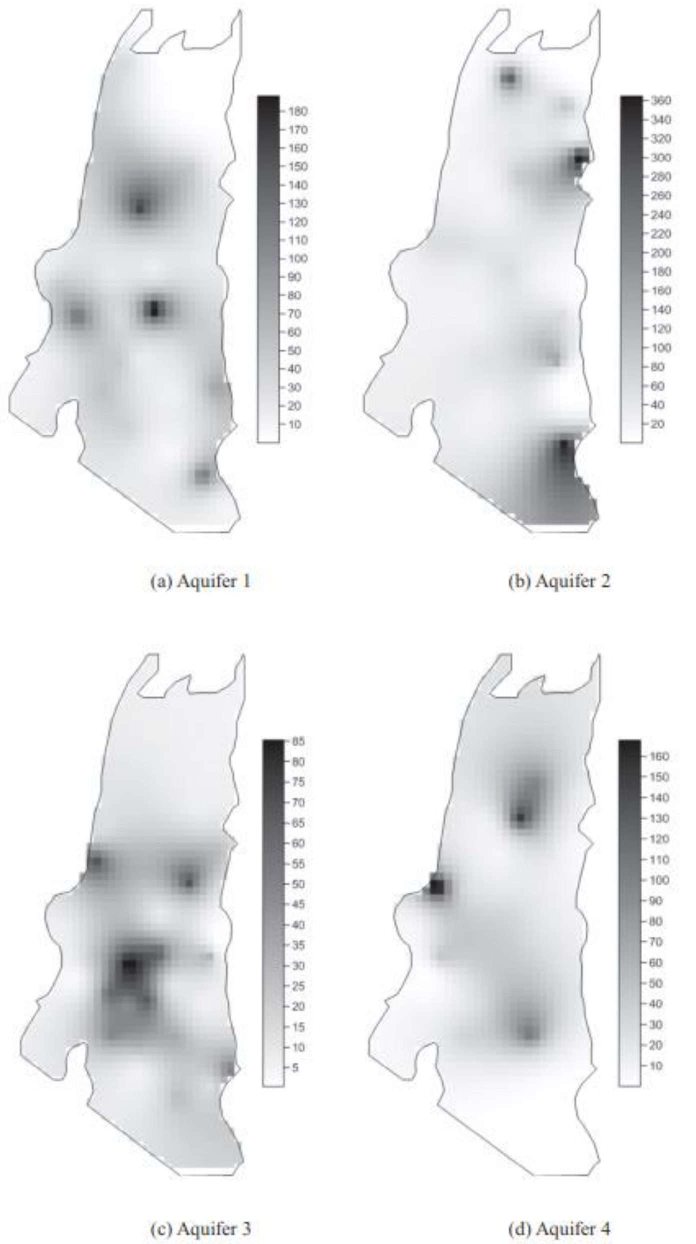
↓

Calibration

Pumping test data (CGS data report, 2002)

- ✓ Hydraulic conductivity
- ✓ Storage coefficient

UCODE: use to inversely determine the recharge rate and pumping rate in townships, aim to minimizing errors between observed and simulated heads



The distribution of hydraulic conductivity use in the model

Conceptual model → Data input → Calibration

Data: monthly groundwater level from monitoring wells from 01/2007-01/2010

Gauge the performance of calibration

- Root Mean Square Error

$$\mathrm{RMSE} = \left[\frac{1}{\mathrm{NW}\cdot\mathrm{SP}}\sum_{t=1}^{SP}\sum_{i=1}^{NW}\left(h_{i,t}^{\mathrm{sim}} - h_{i,t}^{\mathrm{obs}}\right)^2\right]^{0.5}$$

NW: the number of the wells
SP: the simulated period
h^{sim}: the simulated groundwater levels
h^{obs}: observed groundwater levels
t: the duration of the model simulation

- Coefficient of determination between observed and simulated groundwater levels

Hydro-chemical data

- Wells water quality surveyed data from 2009-2012 (Agricultural Engineering Research Center)

31 hydrochemical parameters

- Drinking → Cl^-, SO_4^{2-}, NO_2^- - N, NO_3^- - N, NH_4^+-N, hardness, total dissolved solid (TDS), Fe, Mn, and As
- Irrigation → EC, Cl^-, SO_4^{2-}, total N, Ca^{2+}, Mg^{2+}, Na^+, alkalinity, Fe, Mn, and As
- Aquaculture → NH_4^+-N, Mn, and As.

Result of observation data show a wide distribution of the hydro-chemical parameters those have abnormal distribution or log-normal distribution.

→ Non-parametric geostatistics are suitable for modeling the spatial distributions and uncertainty

Multivariate indicator-based geostatistical approach

Geostatistics provides a variogram of data with a statistical framework to quantify the spatial variability of random variables between two locations.

$$\gamma(h) = \frac{1}{2N(h)} \left\{ \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \right\}$$

Where:

h: the lag
$Z(x_i)$: value of the regional variable of interest at location x_i
$Z(x_i + h)$: value of the regional variable of interest at location $x_i + h$
N(h): the number of pairs of sampling points separated by h

Multivariate indicator-based geostatistical approach

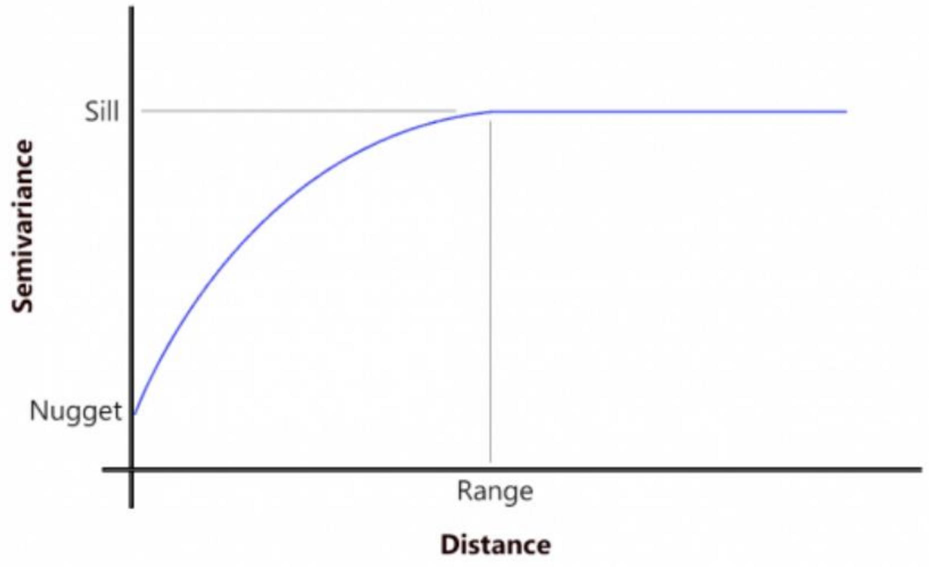
Variograms analysis

Three theorical models

Spherical model: $$\begin{cases} \gamma(\mathbf{h}) = c_0 + c\left[1.5\left(\frac{\mathbf{h}}{a}\right) - 0.5\left(\frac{\mathbf{h}}{a}\right)^3\right], & \mathbf{h} \leqslant a \\ \gamma(\mathbf{h}) = c_0 + c, & \mathbf{h} > a \end{cases};$$

Exponential model: $$\gamma(\mathbf{h}) = c_0 + c\left[1 - \exp\left(-\frac{3\mathbf{h}}{a}\right)\right];$$

Gaussian model: $$\gamma(\mathbf{h}) = c_0 + c\left[1 - \exp\left(-\left(\frac{3\mathbf{h}}{a}\right)^2\right)\right].$$



γ(h): fitted theorical model (the spherical, exponential or Gaussian model)
c_0: the nugget - the value at which the variogram (almost) intercepts the y-axis
c: the sill - the value at which the model first flattens out
a: the range - the distance at which the model first flattens out

→ To fit the spatial variability of random variables in term of hydrochemical data distribution in varies depth of aquifer layers

Multivariate indicator-based geostatistical approach

Variograms analysis

Applied a lag h=5000m to analyze the variograms, then using least squares method to fit the variograms with setting in smallest sum of squares of error.

Purpose standard	Fitted nugget	Sill	Range
Drinking	0–0.07 m	0.045–0.2 m	35,000–40,000 m
Irrigation	0.02–0.15 m	0.077–0.13 m	15,000–40,000m
Aquaculture	0.06–0.135 m	0.03–0.14 m	10,000–35,000 m

✓ The exponential model and spherical model shows the most optimal fitting in the variograms

Indicator kriging (IK) → Multivariate indicator kriging (MVIK)

IK is a nonparametric geostatistical method for characterizing the probability that the attribute value does not exceed a certain threshold

- ✓ Water quality standard have different standard hydrochemical parameters
- ✓ Each hydrochemical parameter have different thresholds for each purpose

→ Multivariate indicator kriging for water quality standards:

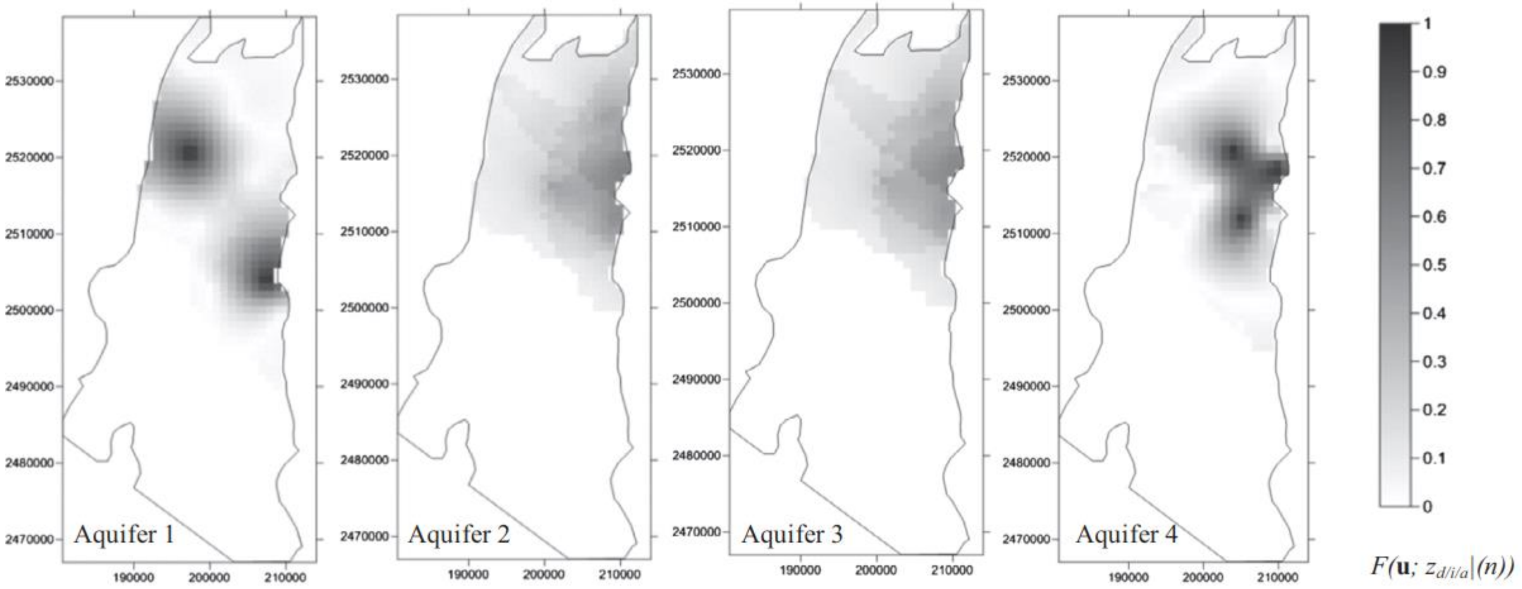
$$I(\mathbf{u}; z_{d/i/a}) = \prod_{j=1}^{m} I_j(\mathbf{u};\ z_k)$$

$z_{d/i/a}$: the water quality standard for drinking, irrigation or aquaculture
m: the number of indicator variables combined for the water quality standard

III RESULTS AND DISCUSSION

1 Spatial variability and probability of the multivariate integration for water using purposes

Result of the estimated probability of multivariate integration variables, average and ranking for drinking purpose



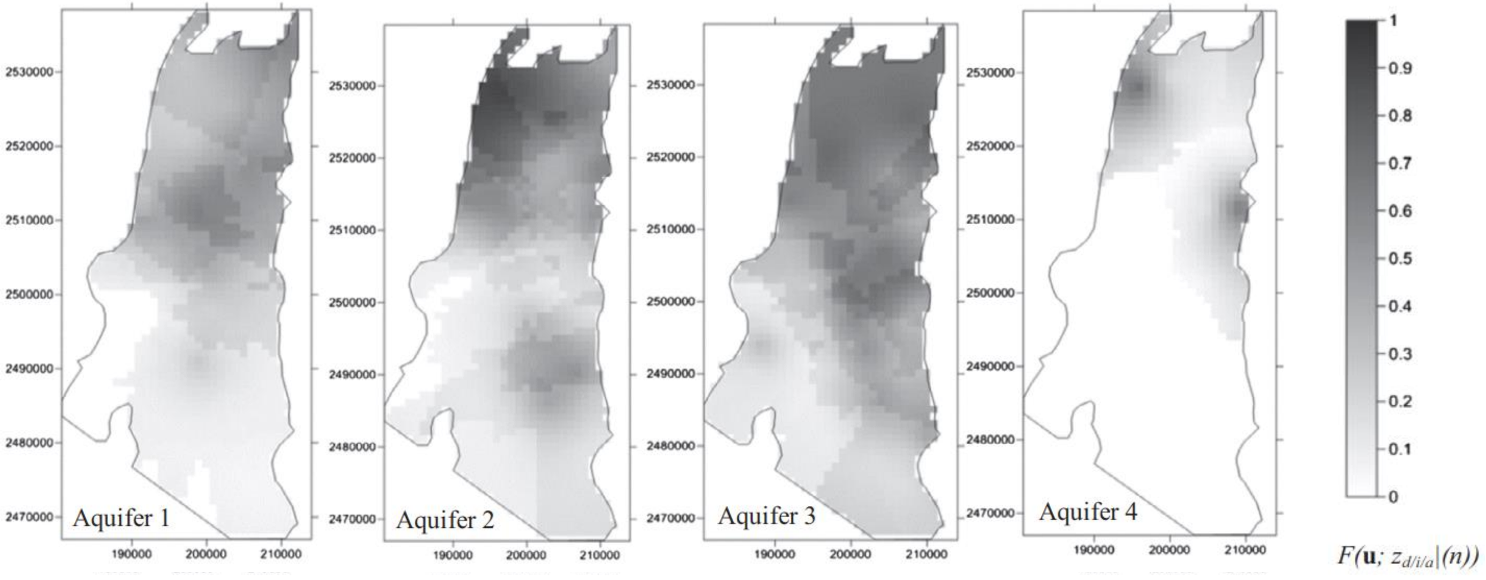
*The greater $F(u; z_{d/i/a|}(n))$ represents the more suitable groundwater quality for drinking

Townships	Drinking Aquifer					
	1	2	3	4	Average	Rank[a]
Qishan (QS)	0.20	0.07	0.09	0.13	0.12	7
Maynong (MN)	0.03	0.14	0.14	0.24	0.14	8
Wanluan (WL)	0.12	0.03	0.03	0.06	0.06	5
Likang (LK)	0.56	0.16	0.17	0.22	0.28	12
Kaoshu (KS)	0.05	0.40	0.39	0.41	0.31	13
Dashu (DS)	0.06	0.04	0.04	0.01	0.04	3
Jiuru (JR)	0.23	0.13	0.13	0.11	0.15	9
Pingtung (PT)	0.03	0.06	0.06	0.06	0.05	4
Yanpu (YP)	0.20	0.40	0.38	0.40	0.34	14
Zhangzhi (ZZ)	0.21	0.26	0.26	0.27	0.25	11
Daliao (DL)	0.00	0.00	0.00	0.00	0.00	1
Wandan (WD)	0.00	0.00	0.00	0.00	0.00	1
Linluo (LL)	0.14	0.04	0.04	0.12	0.08	6
Zhutian (ZT)	0.03	0.00	0.00	0.02	0.01	2
Chiadong (CD)	0.00	0.00	0.00	0.00	0.00	1
Neipu (NP)	0.51	0.15	0.15	0.18	0.25	10
Shinyuan (SY)	0.00	0.00	0.00	0.00	0.00	1
Kanding (KD)	0.00	0.00	0.00	0.00	0.00	1
Chaozhou (CZ)	0.00	0.00	0.00	0.00	0.00	1
Nanzhou (NZ)	0.00	0.00	0.00	0.00	0.00	1
Xinpi (XP)	0.00	0.00	0.00	0.00	0.00	1
Fangliao (FL)	0.00	0.00	0.00	0.00	0.00	1
Linbian (LB)	0.00	0.00	0.00	0.00	0.00	1
Dongkang (DK)	0.00	0.00	0.00	0.00	0.00	1
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	1

- Poorest groundwater quality for drinking purpose ranking: 12 townships

1 Spatial variability and probability of the multivariate integration for water using purposes

Result of the estimated probability of multivariate integration variables, average and ranking for irrigation purpose



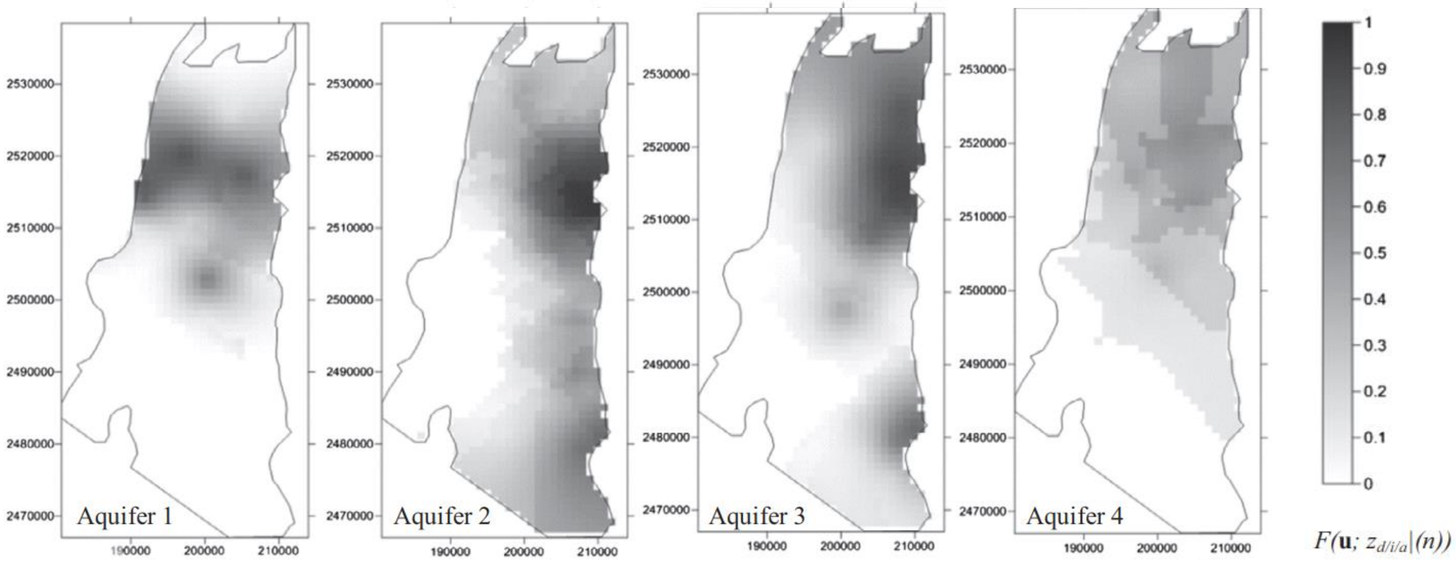
*The greater $F(u; z_{d/i/a|}(n))$ represents the more suitable groundwater quality for irrigation

Townships	Irrigation Aquifer 1	2	3	4	Average	Rank[a]
Qishan (QS)	0.32	0.82	0.62	0.43	0.55	25
Maynong (MN)	0.44	0.65	0.66	0.19	0.49	24
Wanluan (WL)	0.21	0.27	0.46	0.09	0.26	12
Likang (LK)	0.31	0.70	0.67	0.23	0.48	23
Kaoshu (KS)	0.47	0.55	0.65	0.10	0.44	22
Dashu (DS)	0.31	0.37	0.45	0.04	0.29	15
Jiuru (JR)	0.44	0.54	0.58	0.03	0.40	20
Pingtung (PT)	0.42	0.27	0.46	0.02	0.29	16
Yanpu (YP)	0.50	0.44	0.56	0.13	0.41	21
Zhangzhi (ZZ)	0.54	0.35	0.56	0.12	0.40	19
Daliao (DL)	0.04	0.04	0.18	0.00	0.06	2
Wandan (WD)	0.13	0.13	0.30	0.00	0.14	8
Linluo (LL)	0.46	0.20	0.62	0.03	0.33	17
Zhutian (ZT)	0.26	0.24	0.57	0.00	0.27	14
Chiadong (CD)	0.07	0.21	0.23	0.00	0.13	7
Neipu (NP)	0.37	0.23	0.60	0.21	0.35	18
Shinyuan (SY)	0.08	0.10	0.13	0.00	0.08	4
Kanding (KD)	0.18	0.28	0.21	0.00	0.17	9
Chaozhou (CZ)	0.18	0.45	0.43	0.00	0.26	13
Nanzhou (NZ)	0.14	0.29	0.26	0.00	0.17	10
Xinpi (XP)	0.09	0.38	0.41	0.00	0.22	11
Fangliao (FL)	0.05	0.16	0.25	0.00	0.12	6
Linbian (LB)	0.08	0.16	0.13	0.00	0.09	5
Dongkang (DK)	0.08	0.12	0.10	0.00	0.08	3
Linyuan (LY)	0.00	0.03	0.14	0.00	0.04	1

- ➢ Poorest groundwater quality for irrigation purpose ranking: 1 township

1 Spatial variability and probability of the multivariate integration for water using purposes

Result of the estimated probability of multivariate integration variables, average and ranking for aquaculture purpose



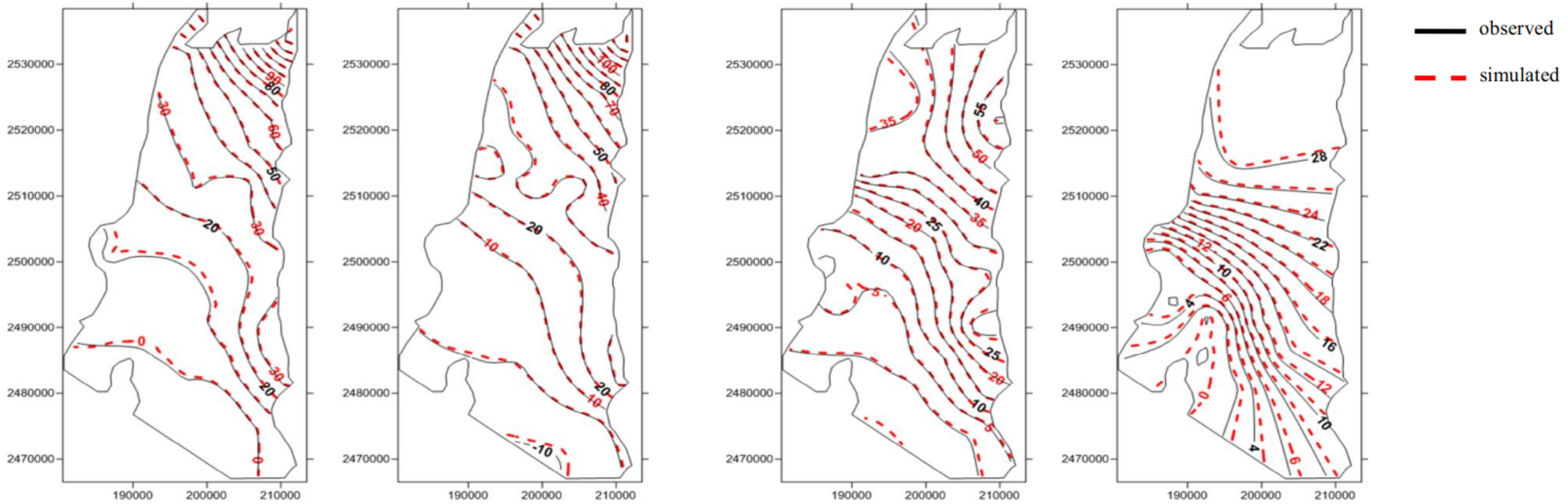
*The greater F(u; $z_{d/i/a|}$(n)) represents the more suitable groundwater quality for aquaculture

Townships	Aquaculture Aquifer 1	2	3	4	Average	Rank[a]
Qishan (QS)	0.33	0.24	0.44	0.24	0.31	17
Maynong (MN)	0.24	0.30	0.54	0.35	0.35	18
Wanluan (WL)	0.11	0.41	0.16	0.11	0.20	13
Likang (LK)	0.50	0.38	0.41	0.51	0.45	22
Kaoshu (KS)	0.39	0.60	0.66	0.61	0.57	24
Dashu (DS)	0.31	0.04	0.08	0.15	0.14	11
Jiuru (JR)	0.51	0.24	0.26	0.51	0.38	21
Pingtung (PT)	0.23	0.15	0.22	0.20	0.20	14
Yanpu (YP)	0.60	0.78	0.63	0.38	0.60	25
Zhangzhi (ZZ)	0.40	0.62	0.54	0.48	0.51	23
Daliao (DL)	0.01	0.00	0.00	0.01	0.00	2
Wandan (WD)	0.08	0.01	0.13	0.20	0.10	8
Linluo (LL)	0.30	0.27	0.36	0.60	0.38	20
Zhutian (ZT)	0.19	0.16	0.24	0.36	0.24	15
Chiadong (CD)	0.00	0.34	0.20	0.00	0.14	10
Neipu (NP)	0.26	0.50	0.45	0.31	0.38	19
Shinyuan (SY)	0.00	0.00	0.01	0.01	0.01	3
Kanding (KD)	0.00	0.07	0.05	0.01	0.03	6
Chaozhou (CZ)	0.03	0.30	0.12	0.08	0.14	9
Nanzhou (NZ)	0.00	0.12	0.00	0.00	0.03	5
Xinpi (XP)	0.00	0.44	0.22	0.08	0.19	12
Fangliao (FL)	0.00	0.58	0.36	0.02	0.24	16
Linbian (LB)	0.00	0.17	0.06	0.00	0.06	7
Dongkang (DK)	0.00	0.06	0.01	0.00	0.02	4
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	1

- Poorest groundwater quality for aquaculture purpose ranking: 1 township

2 Numerical simulation of groundwater flow and level

- ✓ Average RMSE in the calibration process: 0.757 m
- ✓ Coefficient of determination between observed and simulated groundwater levels: 0.998



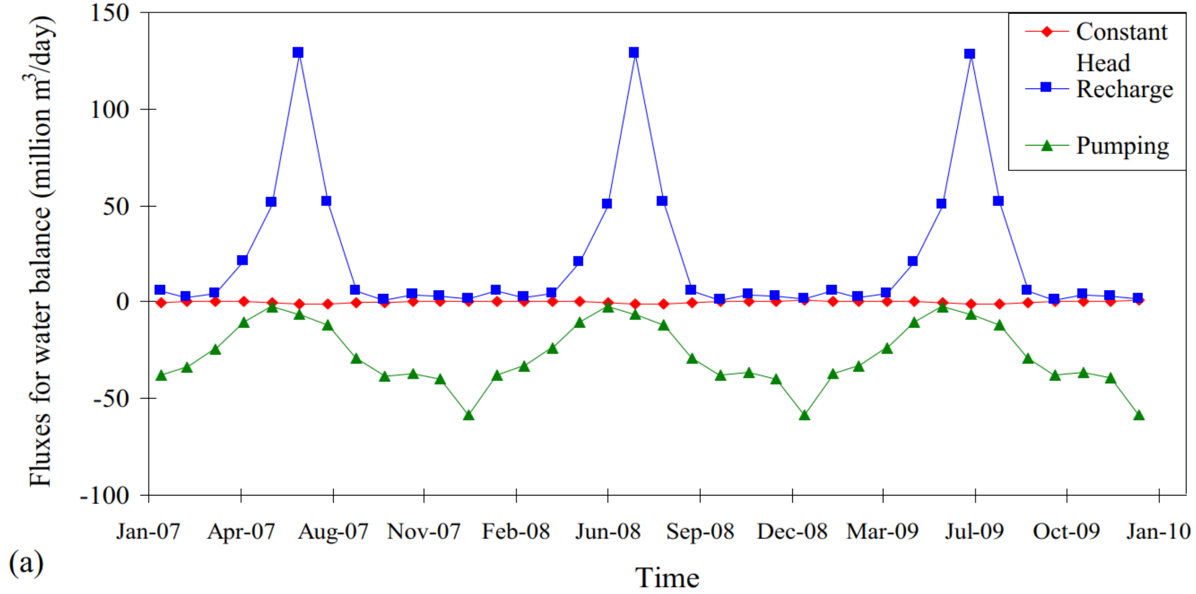
Aquifer 1 Aquifer 2 Aquifer 3 Aquifer 4

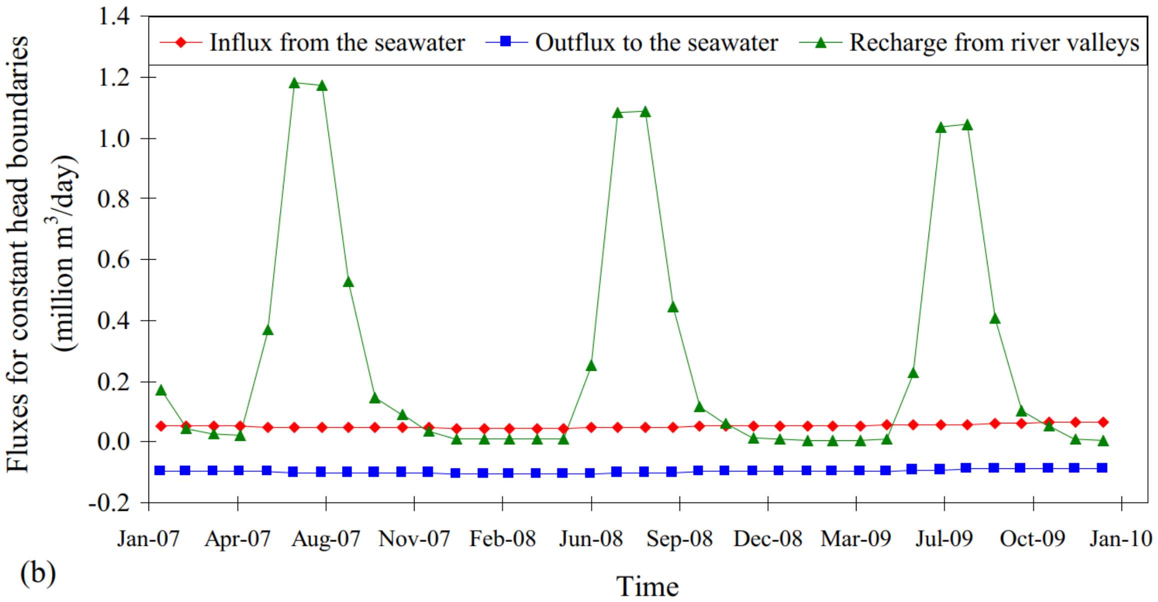
Contoured comparison of observed and simulated groundwater levels in July 2008

➢ The simulated groundwater levels were quite close to the observed levels

2 Numerical simulation of groundwater flow and level

Simulation results for the fluxes in water balance component and fluxes for constant head





- ✓ The simulation result reflect the actual situation of groundwater in this study area

2 Numerical simulation of groundwater flow and level

- Predicted result of the groundwater levels recovery and ranking for each township

The largest recovery groundwater level for agriculture and drinking purposes:

Townships	Agriculture Aquifer						Drinking Aquifer					
	1	2	3	4	Average	Rank[a]	1	2	3	4	Average	Rank[a]
Qishan (QS)	3.34	0.25	0.75	0.13	1.12	21	3.51	0.57	0.75	0.65	1.37	11
Maynong (MN)	3.34	0.17	0.71	3.61	1.96	14	3.51	0.17	0.71	3.61	2.00	10
Wanluan (WL)	3.55	6.51	4.83	2.04	4.23	7	4.43	4.99	4.51	1.35	3.82	5
Likang (LK)	3.21	4.02	0.71	4.84	3.20	11	0.91	3.68	0.71	4.68	2.50	7
Kaoshu (KS)	3.21	4.02	14.33	4.84	6.60	1	0.91	3.68	14.17	4.68	5.86	2
Dashu (DS)	3.65	3.18	0.75	0.95	2.13	13	4.80	2.33	0.75	0.95	2.21	8
Jiuru (JR)	3.34	4.29	7.69	0.09	3.85	8	0.00	0.00	0.00	0.00	0.00	15
Pingtung (PT)	3.34	2.06	0.22	0.12	1.44	19	0.11	2.14	0.20	0.12	0.64	14
Yanpu (YP)	9.07	4.29	7.69	0.09	5.28	5	8.10	3.48	6.52	0.09	4.54	4
Zhangzhi (ZZ)	9.07	7.34	4.30	4.76	6.37	2	8.10	7.23	4.30	4.71	6.08	1
Daliao (DL)	1.99	1.04	0.21	0.21	0.86	22	2.20	1.09	0.21	0.21	0.93	12
Wandan (WD)	3.12	1.89	0.22	0.12	1.34	20	1.05	1.89	0.20	0.12	0.82	13
Linluo (LL)	3.64	2.35	4.30	0.13	2.61	12	0.00	0.00	0.00	0.00	0.00	15
Zhutian (ZT)	3.64	2.35	0.40	0.13	1.63	16	0.00	0.00	0.00	0.00	0.00	15
Chiadong (CD)	0.80	8.47	8.13	2.85	5.07	6	0.00	0.00	0.00	0.00	0.00	15
Neipu (NP)	0.42	0.04	3.43	2.04	1.48	18	3.42	0.04	3.34	1.35	2.04	9
Shinyuan (SY)	3.34	1.45	1.29	0.22	1.58	17	0.00	0.00	0.00	0.00	0.00	15
Kanding (KD)	2.00	1.45	1.64	1.79	1.72	15	0.00	0.00	0.00	0.00	0.00	15
Chaozhou (CZ)	0.66	9.69	2.98	1.79	3.78	9	0.66	9.69	2.98	1.14	3.62	6
Nanzhou (NZ)	3.90	0.37	6.90	3.59	3.69	10	0.00	0.00	0.00	0.00	0.00	15
Xinpi (XP)	1.24	9.69	6.90	3.59	5.36	4	1.24	9.69	6.90	3.59	5.36	3
Fangliao (FL)	2.13	8.47	8.13	2.85	5.40	3	0.00	0.00	0.00	0.00	0.00	15
Linbian (LB)	0.00	0.00	0.00	0.00	0.00	23	0.00	0.00	0.00	0.00	0.00	15
Dongkang (DK)	0.00	0.00	0.00	0.00	0.00	23	0.00	0.00	0.00	0.00	0.00	15
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	23	0.00	0.00	0.00	0.00	0.00	15

[a] The ranks are from high to low levels.

2 Numerical simulation of groundwater flow and level

- Predicted result of the groundwater levels recovery and ranking for each township

  The lowest recovery groundwater level for agriculture purpose

Townships	Agriculture Aquifer					
	1	2	3	4	Average	Rank[a]
Qishan (QS)	3.34	0.25	0.75	0.13	1.12	21
Maynong (MN)	3.34	0.17	0.71	3.61	1.96	14
Wanluan (WL)	3.55	6.51	4.83	2.04	4.23	7
Likang (LK)	3.21	4.02	0.71	4.84	3.20	11
Kaoshu (KS)	3.21	4.02	14.33	4.84	6.60	1
Dashu (DS)	3.65	3.18	0.75	0.95	2.13	13
Jiuru (JR)	3.34	4.29	7.69	0.09	3.85	8
Pingtung (PT)	3.34	2.06	0.22	0.12	1.44	19
Yanpu (YP)	9.07	4.29	7.69	0.09	5.28	5
Zhangzhi (ZZ)	9.07	7.34	4.30	4.76	6.37	2
Daliao (DL)	1.99	1.04	0.21	0.21	0.86	22
Wandan (WD)	3.12	1.89	0.22	0.12	1.34	20
Linluo (LL)	3.64	2.35	4.30	0.13	2.61	12
Zhutian (ZT)	3.64	2.35	0.40	0.13	1.63	16
Chiadong (CD)	0.80	8.47	8.13	2.85	5.07	6
Neipu (NP)	0.42	0.04	3.43	2.04	1.48	18
Shinyuan (SY)	3.34	1.45	1.29	0.22	1.58	17
Kanding (KD)	2.00	1.45	1.64	1.79	1.72	15
Chaozhou (CZ)	0.66	9.69	2.98	1.79	3.78	9
Nanzhou (NZ)	3.90	0.37	6.90	3.59	3.69	10
Xinpi (XP)	1.24	9.69	6.90	3.59	5.36	4
Fangliao (FL)	2.13	8.47	8.13	2.85	5.40	3
Linbian (LB)	0.00	0.00	0.00	0.00	0.00	23
Dongkang (DK)	0.00	0.00	0.00	0.00	0.00	23
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	23

[a] The ranks are from high to low levels.

2 Numerical simulation of groundwater flow and level

- Predicted result of the groundwater levels recovery and ranking for each township

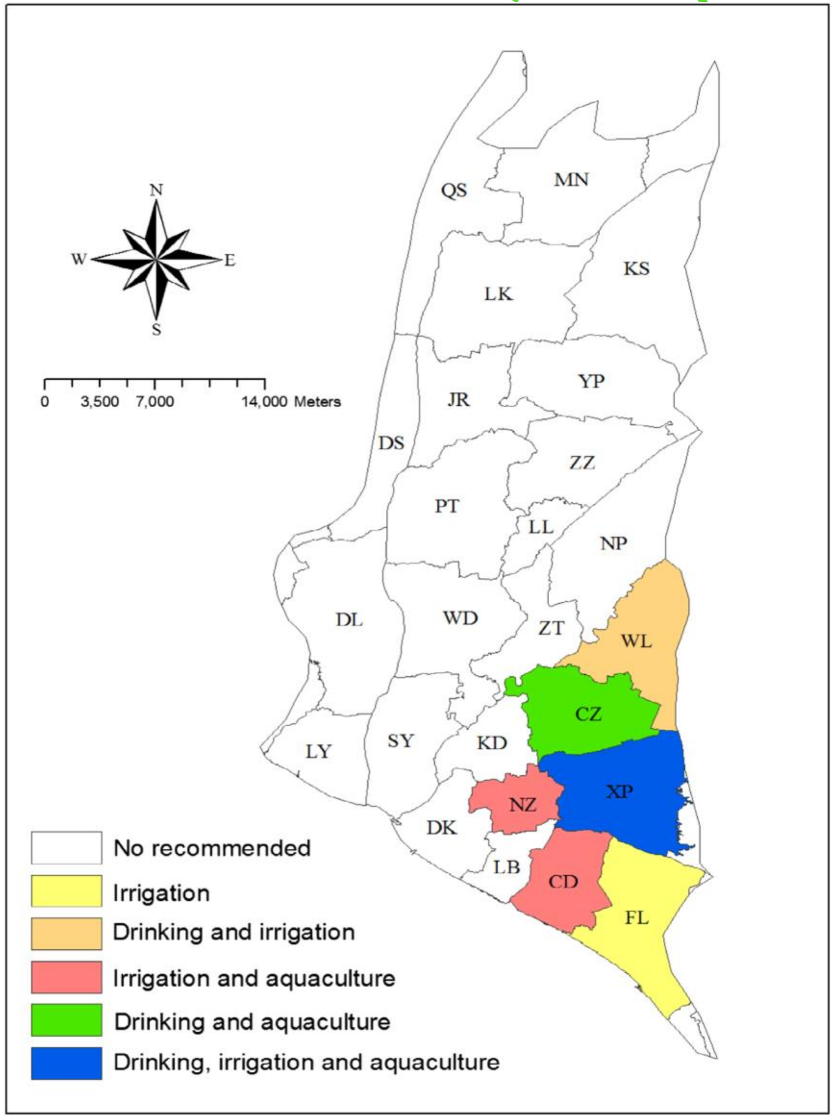
The lowest recovery groundwater level for drinking purpose:

Townships	Drinking Aquifer					
	1	2	3	4	Average	Rank[a]
Qishan (QS)	3.51	0.57	0.75	0.65	1.37	11
Maynong (MN)	3.51	0.17	0.71	3.61	2.00	10
Wanluan (WL)	4.43	4.99	4.51	1.35	3.82	5
Likang (LK)	0.91	3.68	0.71	4.68	2.50	7
Kaoshu (KS)	0.91	3.68	14.17	4.68	5.86	2
Dashu (DS)	4.80	2.33	0.75	0.95	2.21	8
Jiuru (JR)	0.00	0.00	0.00	0.00	0.00	15
Pingtung (PT)	0.11	2.14	0.20	0.12	0.64	14
Yanpu (YP)	8.10	3.48	6.52	0.09	4.54	4
Zhangzhi (ZZ)	8.10	7.23	4.30	4.71	6.08	1
Daliao (DL)	2.20	1.09	0.21	0.21	0.93	12
Wandan (WD)	1.05	1.89	0.20	0.12	0.82	13
Linluo (LL)	0.00	0.00	0.00	0.00	0.00	15
Zhutian (ZT)	0.00	0.00	0.00	0.00	0.00	15
Chiadong (CD)	0.00	0.00	0.00	0.00	0.00	15
Neipu (NP)	3.42	0.04	3.34	1.35	2.04	9
Shinyuan (SY)	0.00	0.00	0.00	0.00	0.00	15
Kanding (KD)	0.00	0.00	0.00	0.00	0.00	15
Chaozhou (CZ)	0.66	9.69	2.98	1.14	3.62	6
Nanzhou (NZ)	0.00	0.00	0.00	0.00	0.00	15
Xinpi (XP)	1.24	9.69	6.90	3.59	5.36	3
Fangliao (FL)	0.00	0.00	0.00	0.00	0.00	15
Linbian (LB)	0.00	0.00	0.00	0.00	0.00	15
Dongkang (DK)	0.00	0.00	0.00	0.00	0.00	15
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	15

[a] The ranks are from high to low levels.

3 Assessment combining groundwater quality and quantity

Townships	Drinking	Irrigation	Aquaculture	Demands of water resources
Qishan (QS)	18	46	38	–
Maynong (MN)	18	38	32	–
Wanluan (WL)	10	19	20	Drinking and irrigation
Likang (LK)	19	34	33	–
Kaoshu (KS)	15	23	25	–
Dashu (DS)	11	28	24	–
Jiuru (JR)	24	28	29	–
Pingtung (PT)	18	35	33	–
Yanpu (YP)	18	26	30	–
Zhangzhi (ZZ)	12	21	25	–
Daliao (DL)	13	24	24	–
Wandan (WD)	14	28	28	–
Linluo (LL)	21	29	32	–
Zhutian (ZT)	17	30	31	–
Chiadong (CD)	16	13	16	Irrigation and aquaculture
Neipu (NP)	19	36	37	–
Shinyuan (SY)	16	21	20	–
Kanding (KD)	16	24	21	–
Chaozhou (CZ)	7	22	18	Drinking and aquaculture
Nanzhou (NZ)	16	20	15	Irrigation and aquaculture
Xinpi (XP)	4	15	16	Drinking, irrigation and aquaculture
Fangliao (FL)	16	9	19	Irrigation
Linbian (LB)	16	28	30	–
Dongkang (DK)	16	26	27	–
Linyuan (LY)	16	24	24	–



✓ Results in six southeastern townships with poor groundwater quality and fast recovery effects are the most suitable for locating surface water.

- This study determined six townships have poorest groundwater quality and high recovery in quantity, surface water could be used instead of groundwater after the construction of man-made lakes or reservoirs.
- The combination is useful for planning the regional development of water resources
  - ✓ Using MVIK for analysing the spatial variability of groundwater quality
  - ✓ Using MODFLOW to simulate numerical model of groundwater flow then detemine the response of groundwater quantity for each water usage purpose.
- This study can provide Taiwan government detailed information on how to sustainably use and conserve groundwater in overexploited areas.

THANK YOU
FOR YOUR ATTENTION

Q & A

FUTURE WORK

Data collection (CGS)

Groundwater level

Borehole data
(44 wells)

SET UP STUDY DOMAIN - THMC

Simplify rock material → Set hydrogeologic unit

Hydraulic conductivity

Porosity

Combine

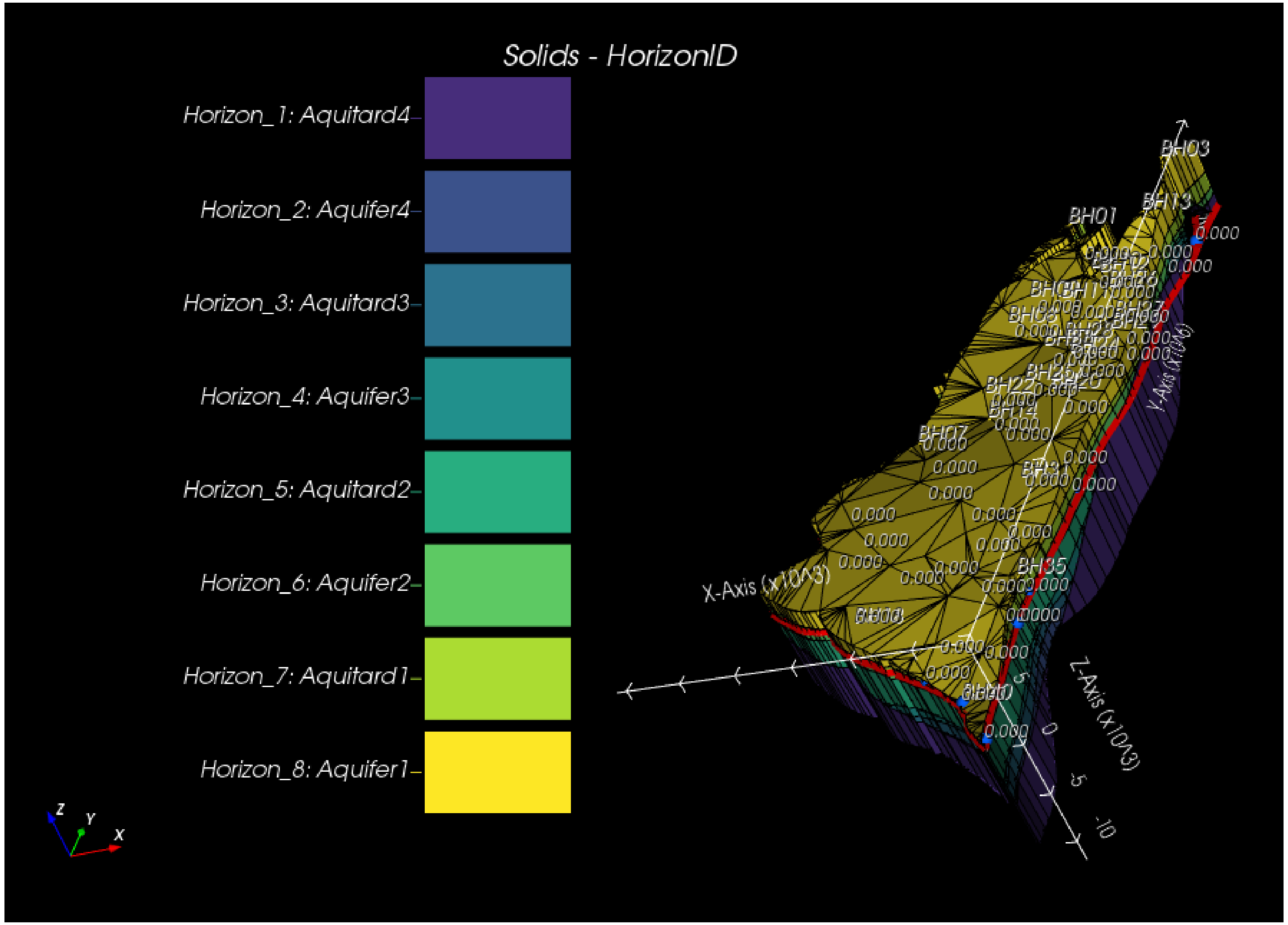
Simplify according thickness and set material ID

8 layers
- 4 aquifer layers
- 4 aquitard layers

Set and simplify according layer range limit

FUTURE WORK

Primarily simplified data test result for building study area domain



- The limited range of layers have not in expect
- Density in the middle too larger

1 Spatial variability and probability of the multivariate integration for water using purposes

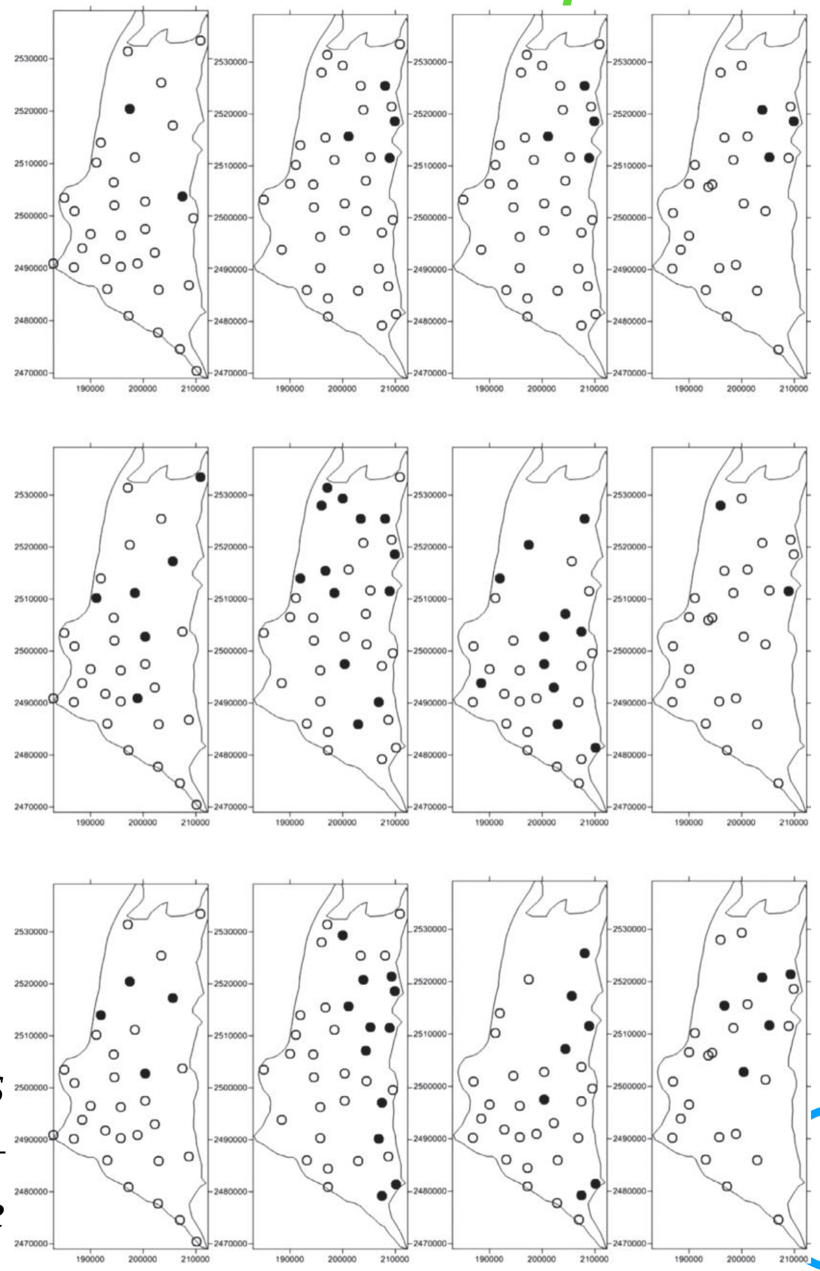
Statistics concerning hydro-chemical parameters in groundwater, and the water quality standards of drinking, irrigation, and aquaculture in Taiwan.

Statistical data	EC (μS/cm 25 °C)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	NH_4^+-N (mg/L)	Total N[a] (mg/L)	Hardness[b] (mg/L)	TDS (mg/L)	SAR $(meq/L)^{0.5}$	RSC (meq/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)
Water quality standards for drinking (D), irrigation (I) and aquaculture (A)[c]	I: 750	D: 250 I: 175	D: 250 I: 200	D: 0.1	D: 10	D: 0.1 A: 0.3	I: 3	D: 300	D: 500	I : 6	I: 2.5	D: 0.3 I: 5	D: 0.05 I: 0.2 A: 0.05	D: 0.01 I: 0.05 A: 0.05
Minimum	148	3.2	2.1	ND	ND	ND	0.12	58.0	120	0.12	−105	ND	ND	ND
Maximum	50,078	17,981	2377	0.36	10.1	45.4	45.8	7256	35,505	47.6	8.10	18.7	11.0	0.35
Average	3530	1163	148	0.01	1.17	2.14	3.35	592	2520	3.78	−6.68	1.20	0.40	0.02
Standard deviation	9893	3788	402	0.04	1.76	6.5	6.45	1263	7190	9.03	22.1	2.32	1.10	0.04
Number of wells with water exceeding the standard for drinking water	–	17	9	2	1	79	–	32	30	–	–	74	93	29
Number of wells with water exceeding the irrigation water	29	17	15	–	–	–	29	–	–	16	11	5	56	11
Number of wells with water exceeding the aquaculture water	–	–	–	–	–	48	–	–	–	–	–	–	93	11

[a] Total N: the sum of NO_3^--N, NO_2^--N and NH_4^+-N.
[b] Expressed by $CaCO_3$.

1

According to surveyed data, most of water quality in the wells exceed water quality standard at varied aquifer depths in the distal-fan.



Observation data on groundwater quality parameters meeting (d) or exceeding (s) water quality standards for (a–d) drinking, (e–h) irrigation and (i–l) aquaculture

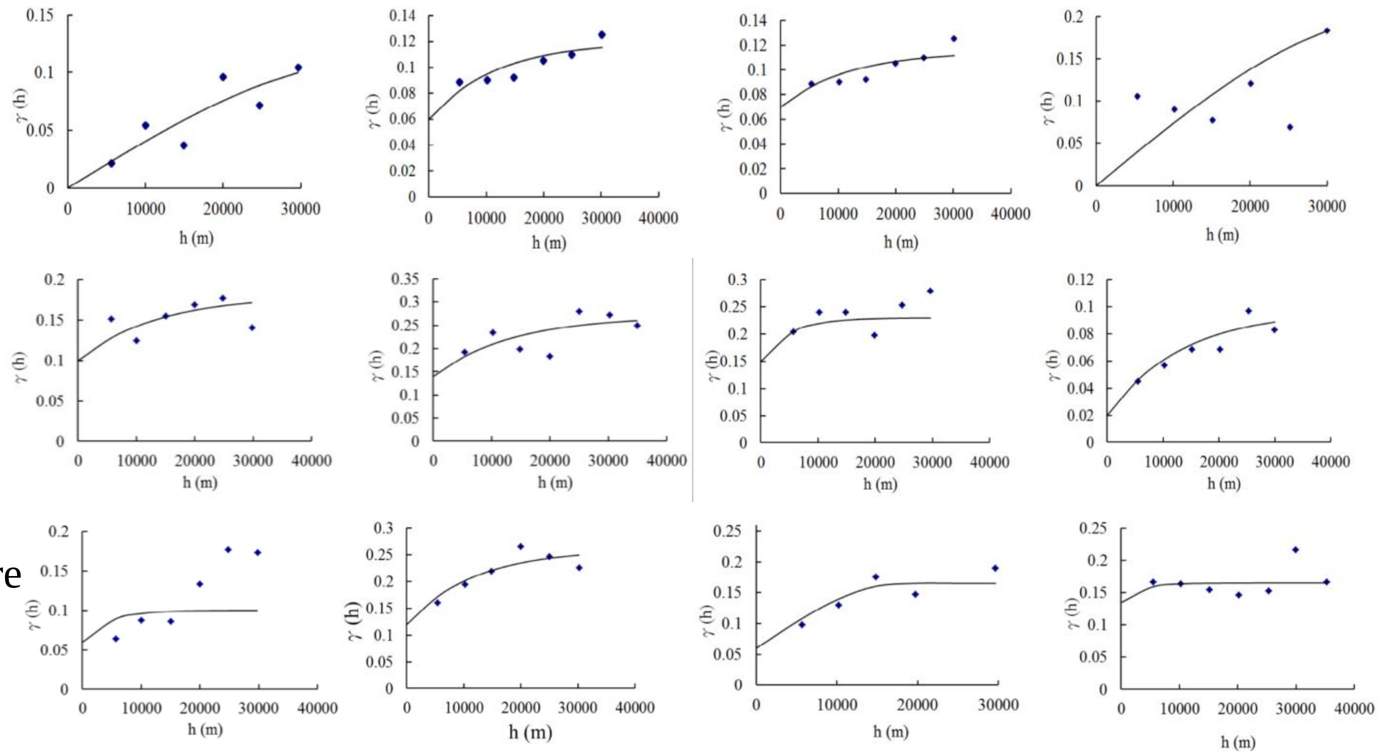
1 Spatial variability and probability of the multivariate integration for water using purposes

Applied theorical model to fit variograms result

Drinking

Irrigation

Aquaculture



Aquifer 1 Aquifer 2 Aquifer 3 Aquifer 4

Purpose standard	Fitted nugget	Sill	Range
Drinking	0–0.07	0.045–0.2	35,000–40,000
Irrigation	0.02–0.15	0.077–0.13	15,000–40,000
Aquaculture	0.06–0.135	0.03–0.14	10,000–35,000

2 Numerical simulation of groundwater flow and level

Groundwater right amounts ($\times 10^{-3}$ m/day) for townships used in the numerical model of groundwater flow according to groundwater rights published by the Taiwan WRA.

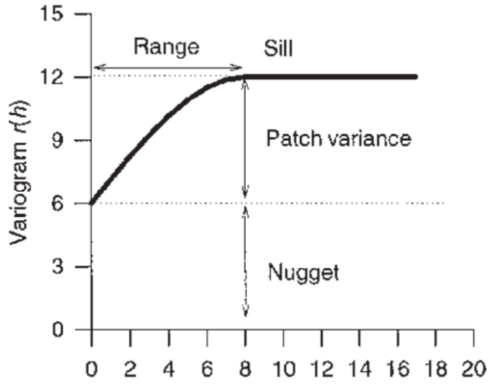
Townships	Agriculture Aquifer				Drinking Aquifer			
	1	2	3	4	1	2	3	4
Qishan (QS)	1.25	93.74	59.81	93.74	2.36	4.69	3.55	5.94
Maynong (MN)	1.25	1.51	2.49	1.51	2.36	28.72	20.87	17.70
Wanluan (WL)	6.12	6.12	6.12	2.68	12.04	12.04	12.04	32.73
Likang (LK)	4.41	4.35	2.49	4.35	1.19	11.71	20.87	11.71
Kaoshu (KS)	4.41	4.35	4.38	4.35	1.19	11.71	14.36	11.71
Dashu (DS)	9.25	9.25	59.81	9.25	1.85	18.54	3.55	18.54
Jiuru (JR)	4.58	9.07	9.07	9.07	0.00	0.00	0.00	0.00
Pingtung (PT)	4.58	1.47	2.33	2.33	96.58	1.67	72.15	86.12
Yanpu (YP)	6.41	9.07	9.07	9.07	18.36	2.13	2.13	2.13
Zhangzhi (ZZ)	6.41	3.16	5.88	3.16	18.36	33.90	25.43	33.90
Daliao (DL)	39.01	29.10	39.01	29.10	72.15	53.83	72.15	53.83
Wandan (WD)	3.25	3.25	2.33	2.33	0.02	0.02	72.15	86.12
Linluo (LL)	6.12	6.12	5.88	6.12	0.00	0.00	0.00	0.00
Zhutian (ZT)	6.12	6.12	1.74	6.12	0.00	0.00	0.00	0.00
Chiadong (CD)	1.31	1.90	2.34	1.90	0.00	0.00	0.00	0.00
Neipu (NP)	46.12	2.58	4.61	2.68	0.05	0.05	0.05	32.73
Shinyuan (SY)	2.30	2.58	2.30	1.37	0.00	0.00	0.00	0.00
Kanding (KD)	1.60	56.98	1.60	88.96	0.00	0.00	0.00	0.00
Chaozhou (CZ)	11.11	20.18	40.36	88.96	11.11	20.18	40.36	23.96
Nanzhou (NZ)	4.75	9.61	66.25	66.25	0.00	0.00	0.00	0.00
Xinpi (XP)	4.75	20.18	66.25	66.25	3.42	20.18	4.77	4.77
Fangliao (FL)	2.66	1.90	2.34	1.90	0.00	0.00	0.00	0.00
Linbian (LB)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dongkang (DK)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Linyuan (LY)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

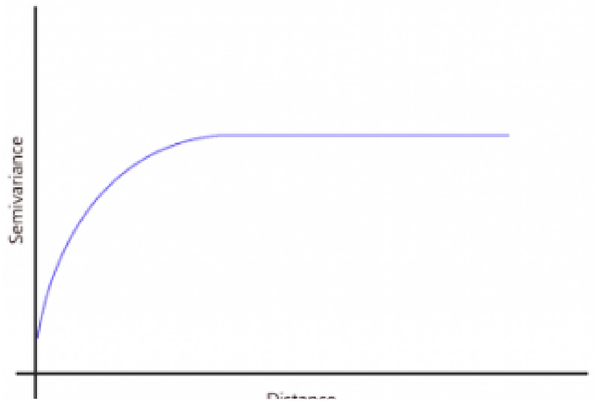
VARIOGRAM (SEMIVARIANCE) (FUNCTION)

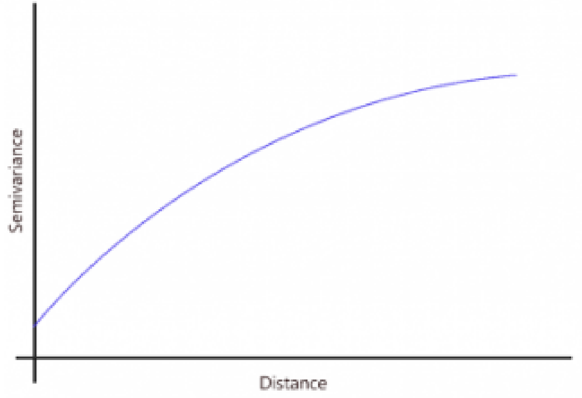
- Purpose: describing the spatial or the temporal correlation of observations in geostatistic.
- Can be used
- - To fit a model of the temporal/spatial correlation of the observed phenomenon.
- - Further used to define the weights of the kriging function

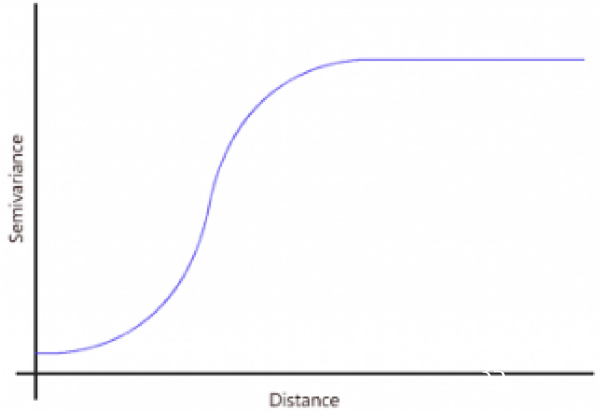
Definition and different of 3 type of variogram

1. spherical model is one of the most common models we use in variogram modeling. It is a modified quadratic equation where spatial dependence flattens out as the sill and range
2. exponential model resembles the spherical model in that spatial variability reaches the sill gradually. The relationship between two sample points decays gradually, while at a distance of infinite spatial dependence dissipates
3. Gaussian function uses a normal probability distribution curve. This type of model is useful where phenomena are similar at short distances because of its progressive rise up the y-axis.









SILL: The value at which the model first flattens out.
RANGE: The distance at which the model first flattens out.
NUGGET: The value at which the semi-variogram (almost) intercepts the y-value.