Application of Managed Aquifer Recharge (MAR)
(有效管理的) 含水層人工補給之應用

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Outline

1. Basics of MAR
2. MAR in Chinese mainland
3. MAR in Yuen Long South Hong Kong
4. Conclusions

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***Managed* aquifer recharge**

MAR: Purposeful recharge of water to aquifers (through injection wells, infiltration basins & galleries**) for subsequent recovery for environmental benefit** (Dillon et al 2009)

Unintentional/ unmanaged:

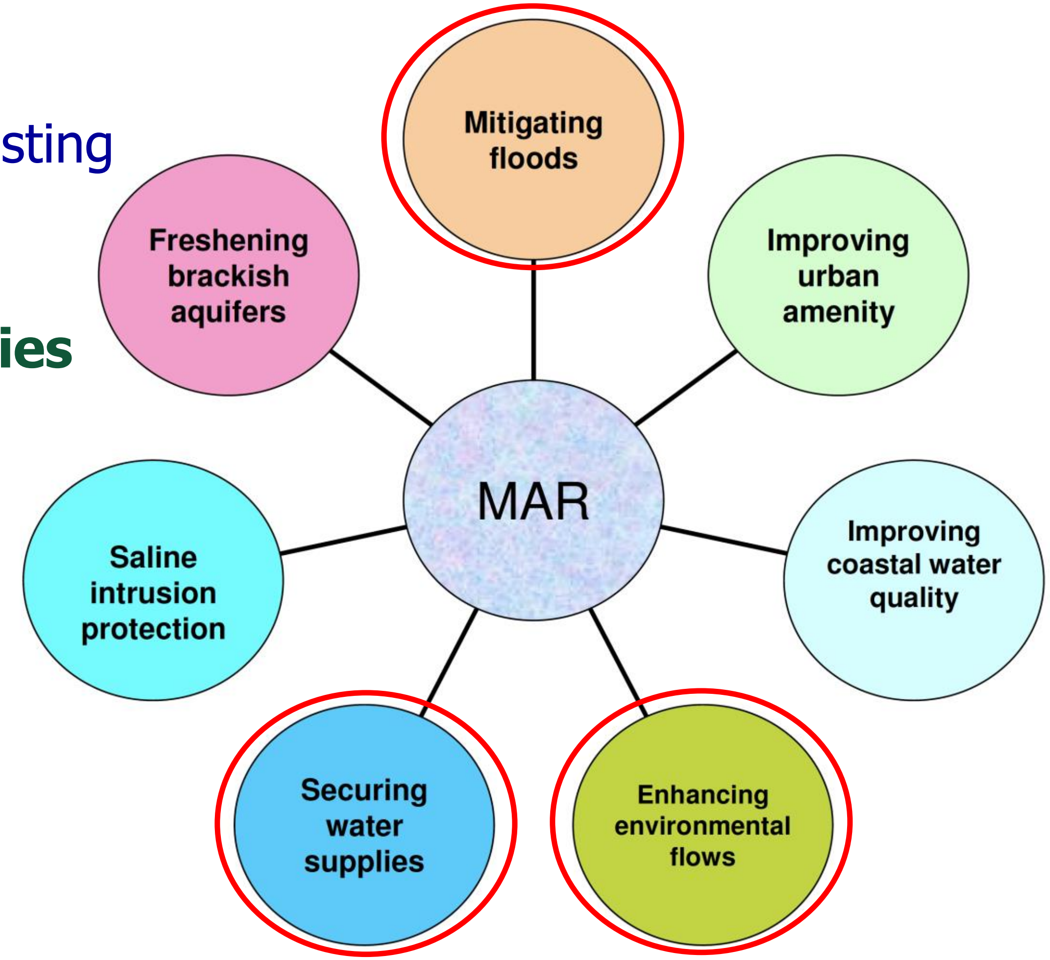
- Leaks from water mains

  25% drinking water leaks underground in HK
- Stormwater drainage wells, sumps etc, usually for disposal of unwanted water **without thought of reuse**

Common reasons for using MAR

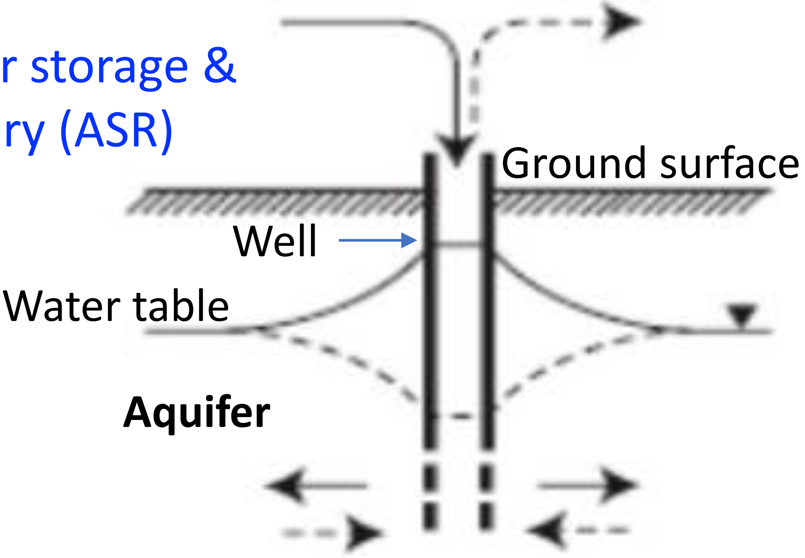
MAR increase storage capacity to cope with the runoff variability exacerbated by climate change, assist in harvesting abundant water in urban areas currently unused. More specifically:

- **Store water to secure and enhance water supplies**
- **Enable reuse of waste or storm water**
- Improve groundwater quality
- Prevent salt water intrusion into coastal aquifers
- Manage land subsidence
- **Environmental flows** and groundwater-dependent ecosystems to improve local amenity, land value and biodiversity.

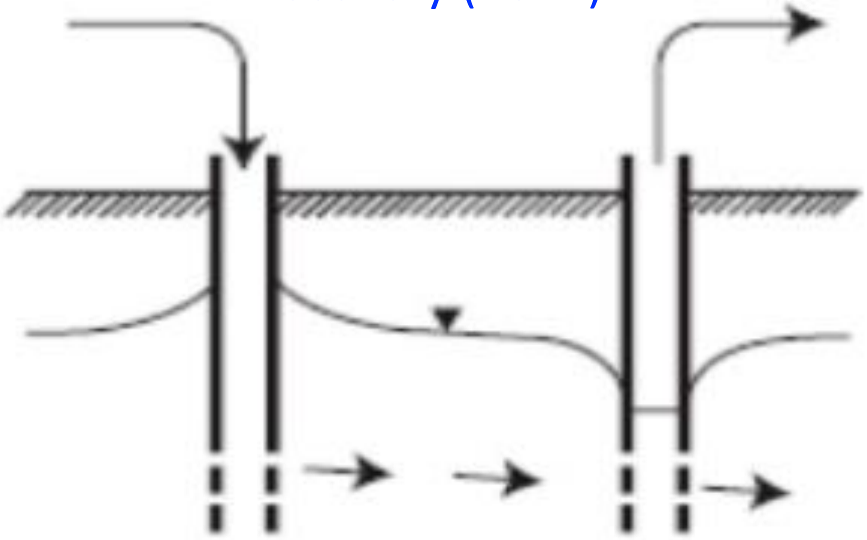


Some types of MAR

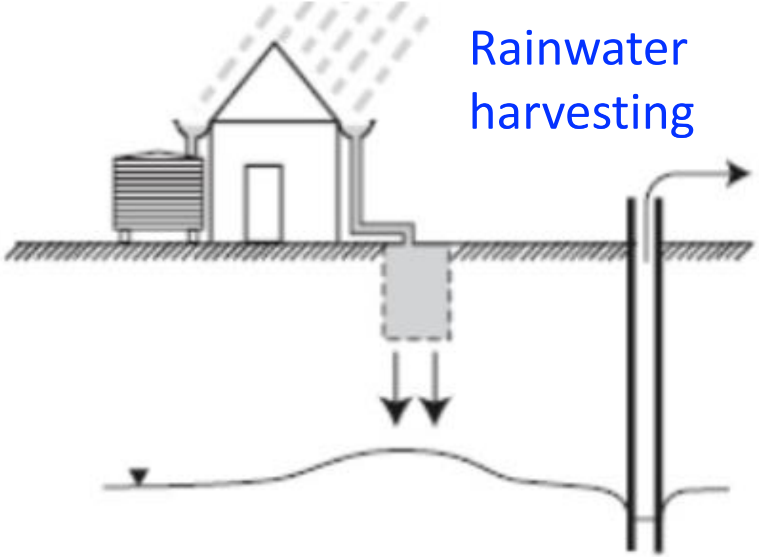
Aquifer storage & recovery (ASR)



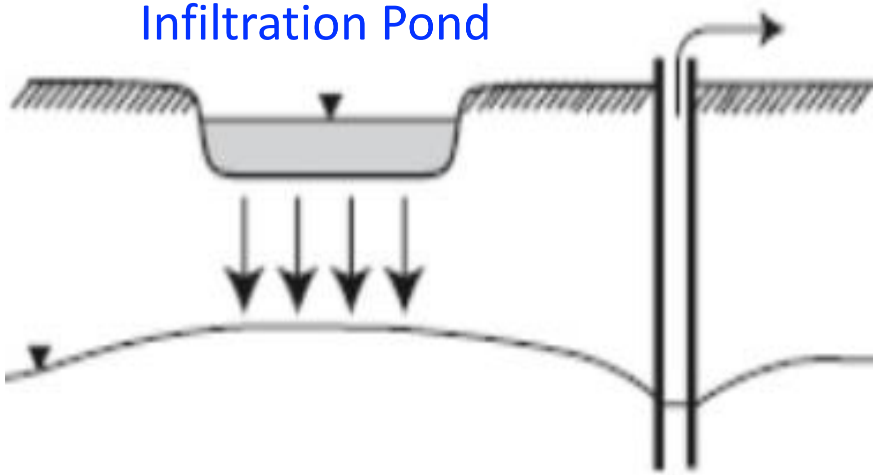
Aquifer storage, transfer & recovery (ASTR)

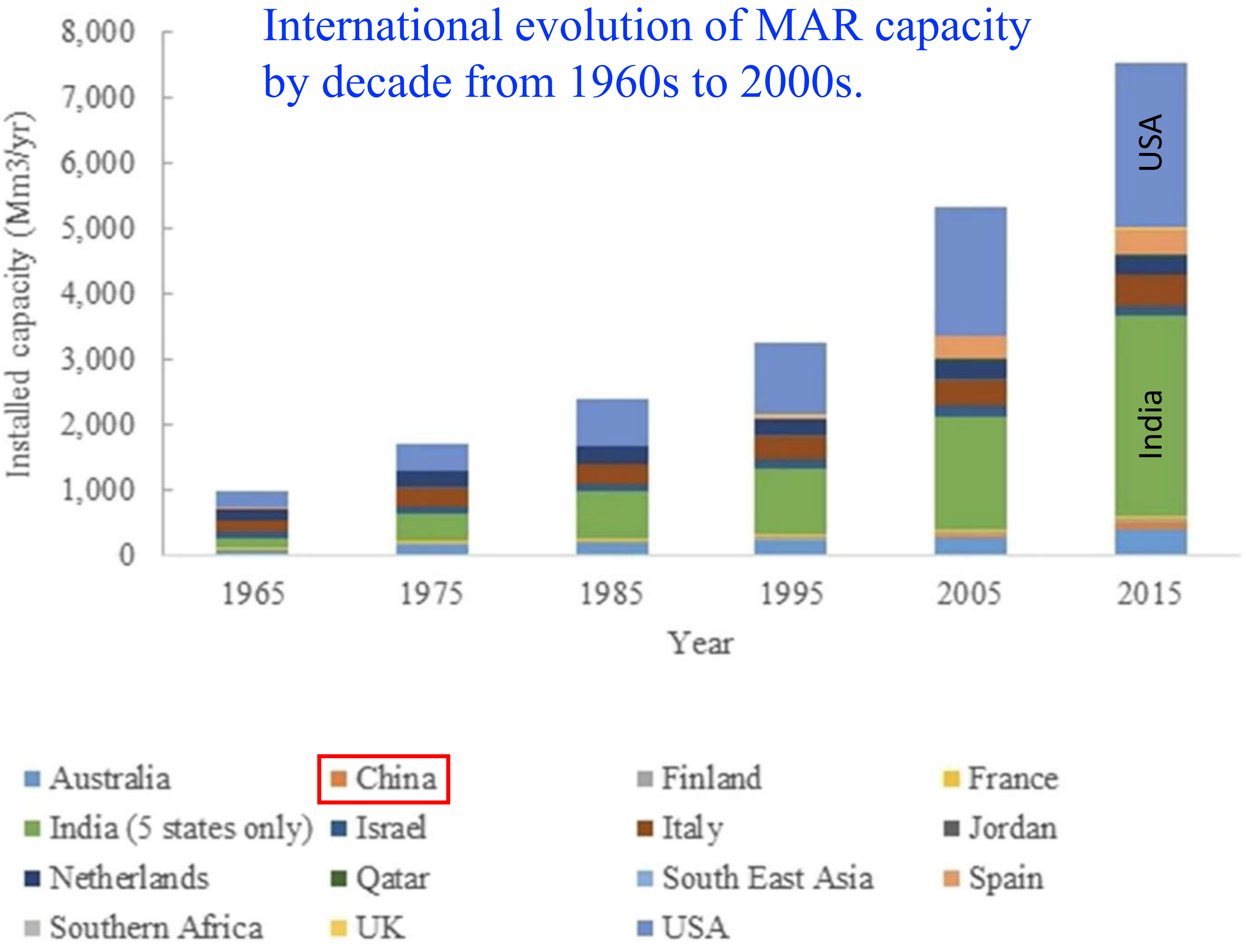


Rainwater harvesting



Infiltration Pond




International evolution of MAR capacity by decade from 1960s to 2000s.

MAR has become a common practice in the world

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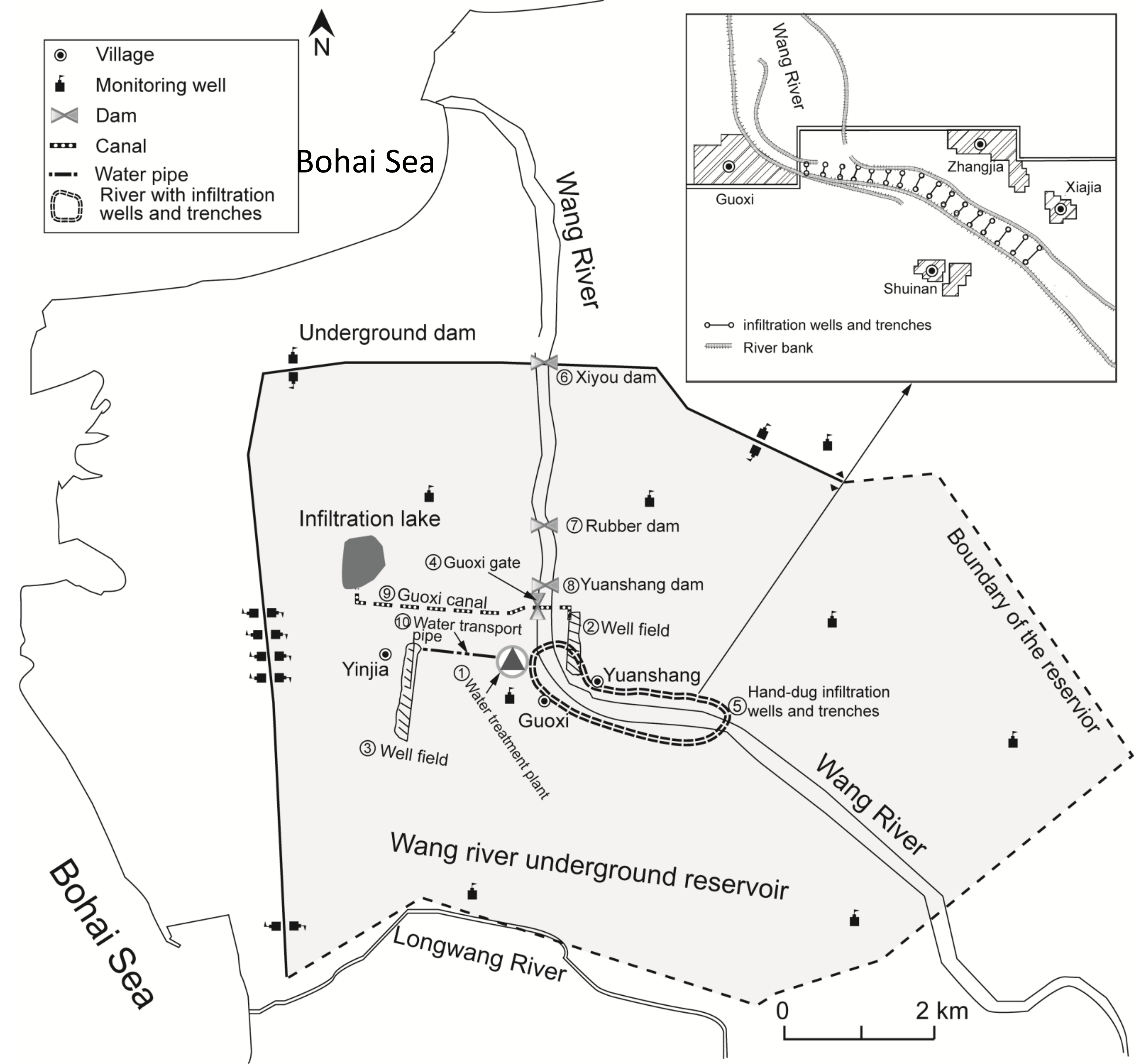
MAR in Wang River Delta, Shangdong, China (1970-2000)



Various facilities

- River dams to stop seawater intrusion in river and raise river water level to enhance infiltration
- An infiltration lake for rain to recharge shallow aquifer
- Infiltration wells & trenches to enhance infiltration of river water
- Underground dams to stop seawater intrusion & create an underground reservoir

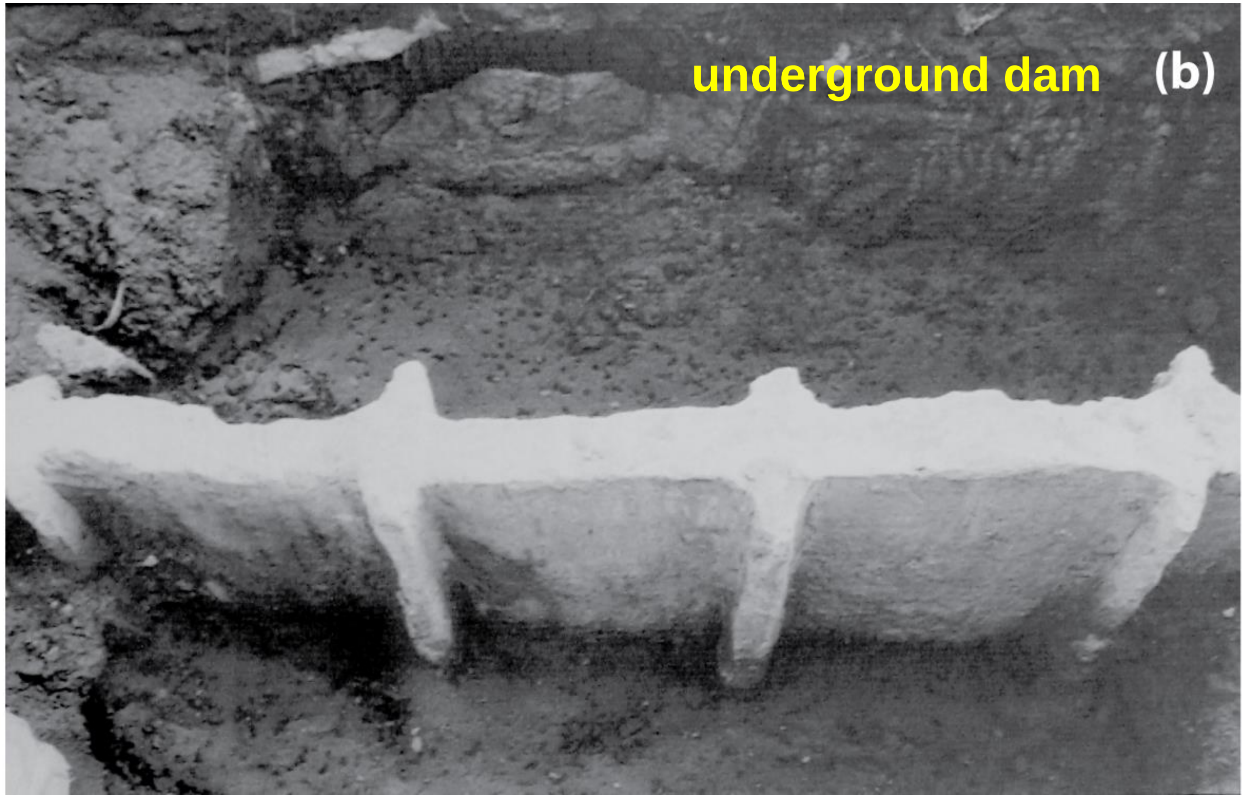
Results

- Water levels rose up to 8 m
- 32 million m^3 of water artificially recharged, 13 million m^3 pumped out for irrigation
- water reached potable quality.

(Jiao and Post, 2019, Coastal Hydrogeology)

Some MAR facilities in Wang River Delta, Shangdong, China

(a) Drilled infiltration well of ~ 20 m deep at river bed. The well is capped with a slotted concrete cover and sits in a catch pit which has not yet been filled with coarse materials



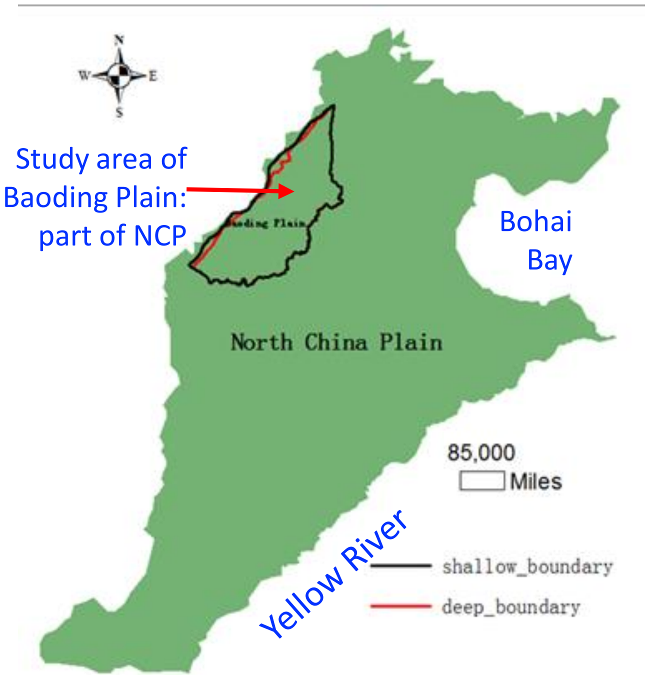
(b) Section of underground dam, which was excavated at this site to demonstrate dam quality

(Jiao and Post, 2019, Coastal Hydrogeology)

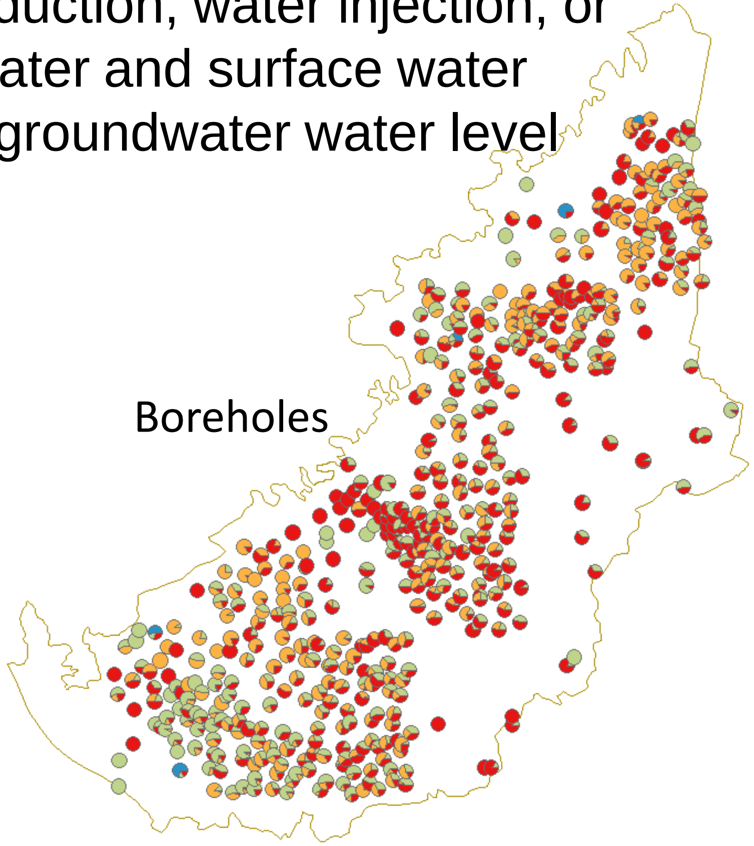
MAR in the Baoding Plain, China: Opportunities to Restore Overexploited Aquifers

Miss Wensi Guo
Joint PhD student between
HKU and SUSTech

- North China Plain (NCP): Largest groundwater cone of depression in the world
- Water from South to North Water Diversion (SNWD) Project to NCP
- Objective: How pumping reduction, water injection, or conjunctive use of groundwater and surface water can lead to recovery of the groundwater water level

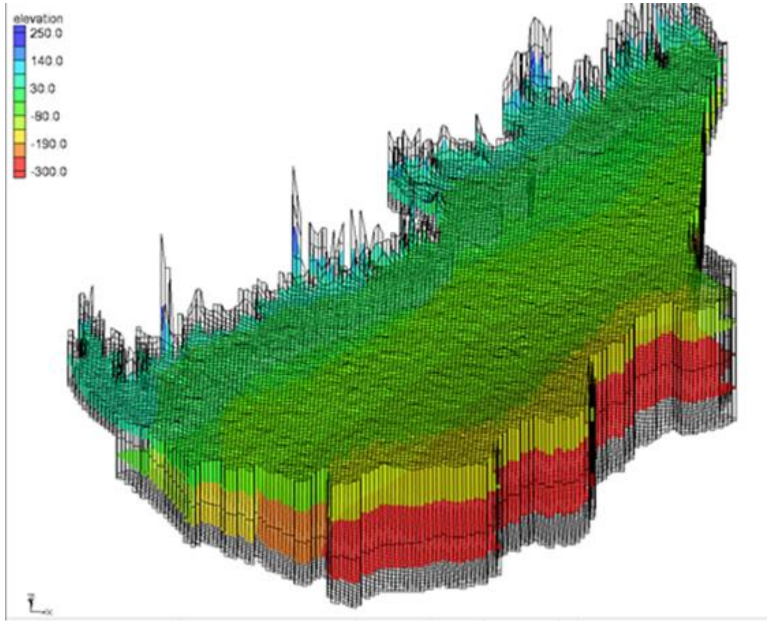


Study area of Baoding Plain: part of NCP



Boreholes

A multilayer, heterogeneous and anisotropic groundwater flow model

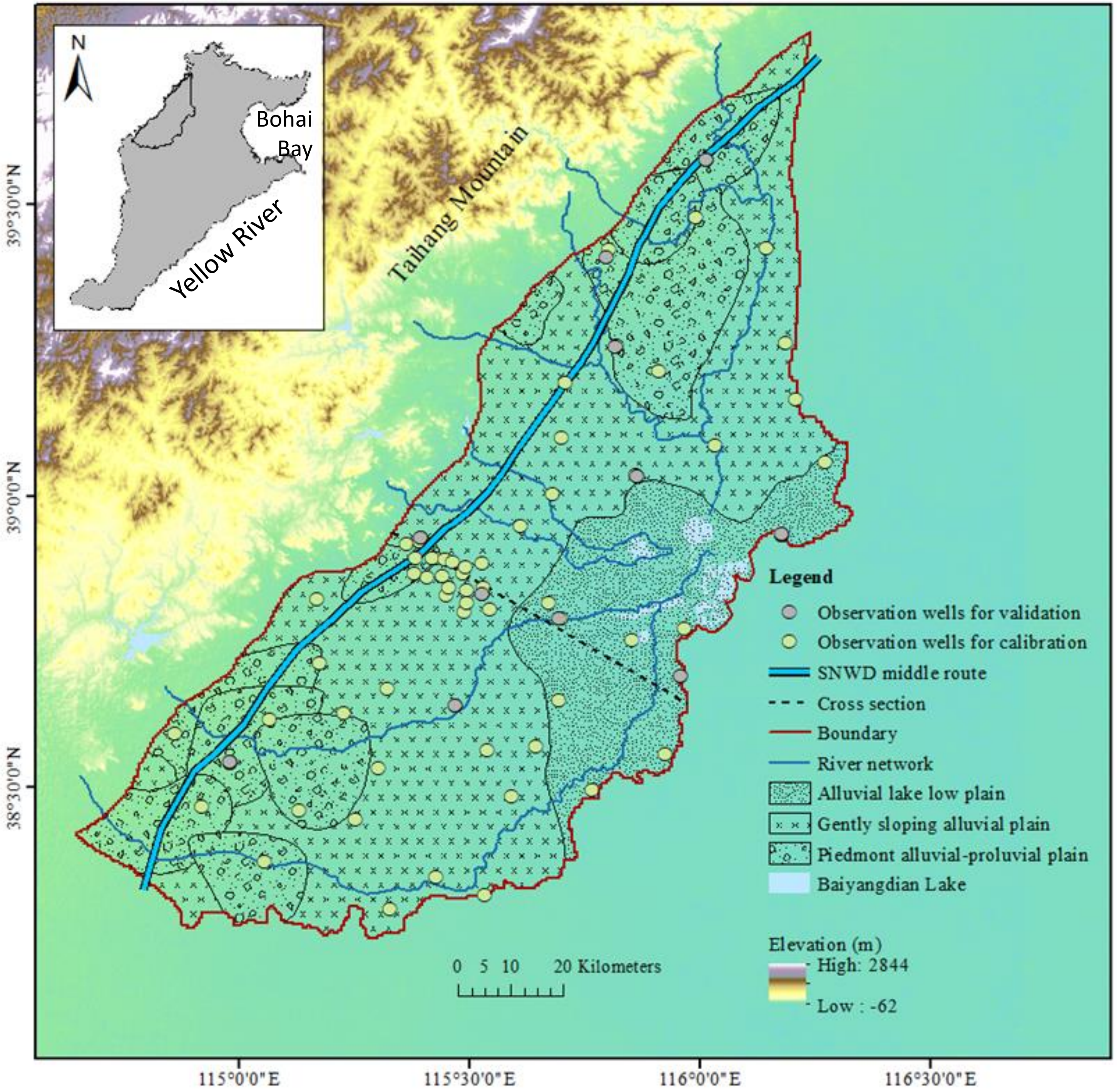


MAR in Baoding Plain

Models used:

- Geostatistical model (TProGS) for 3D geological structure
- Integrated surface water groundwater model (MIKE SHE) to study flow
- Multi-objective optimization model for optimization of MAR

- **Water source for MAR:**
  Reservoirs, rainfall, & water from SNWD central route
- **Recharge area for MAR:**
  Highly permeable geology adjacent to the mountain



Conclusions of MAR studies in in Baoding Plain

- Groundwater deficit reached **15.5 ± 6.7 km^3** by 2015
- **Had groundwater not been pumped** between 2000 and 2016, the storage deficit would be less, at **2.7 km^3**
- Of the three MAR scenarios, **infiltration basins** lose ~80% water to evaporation, **in-channel with MAR infrastructure** and **recharge well** are comparable
- **It would take > 50 yrs to compensate for the groundwater deficit caused by pumping** between 2000 and 2016

	2000-2016 GWS recovered (km^3)	2016-2020 GWS recovered	Time Required for MAR (Years)
Recharge Well	4.5	TBD	55
Infiltration Basin	0.8	TBD	310
In-Channel	3.2	TBD	78
Irrig. Red.	2.3	TBD	107
No Pumping	12.8	TBD	20

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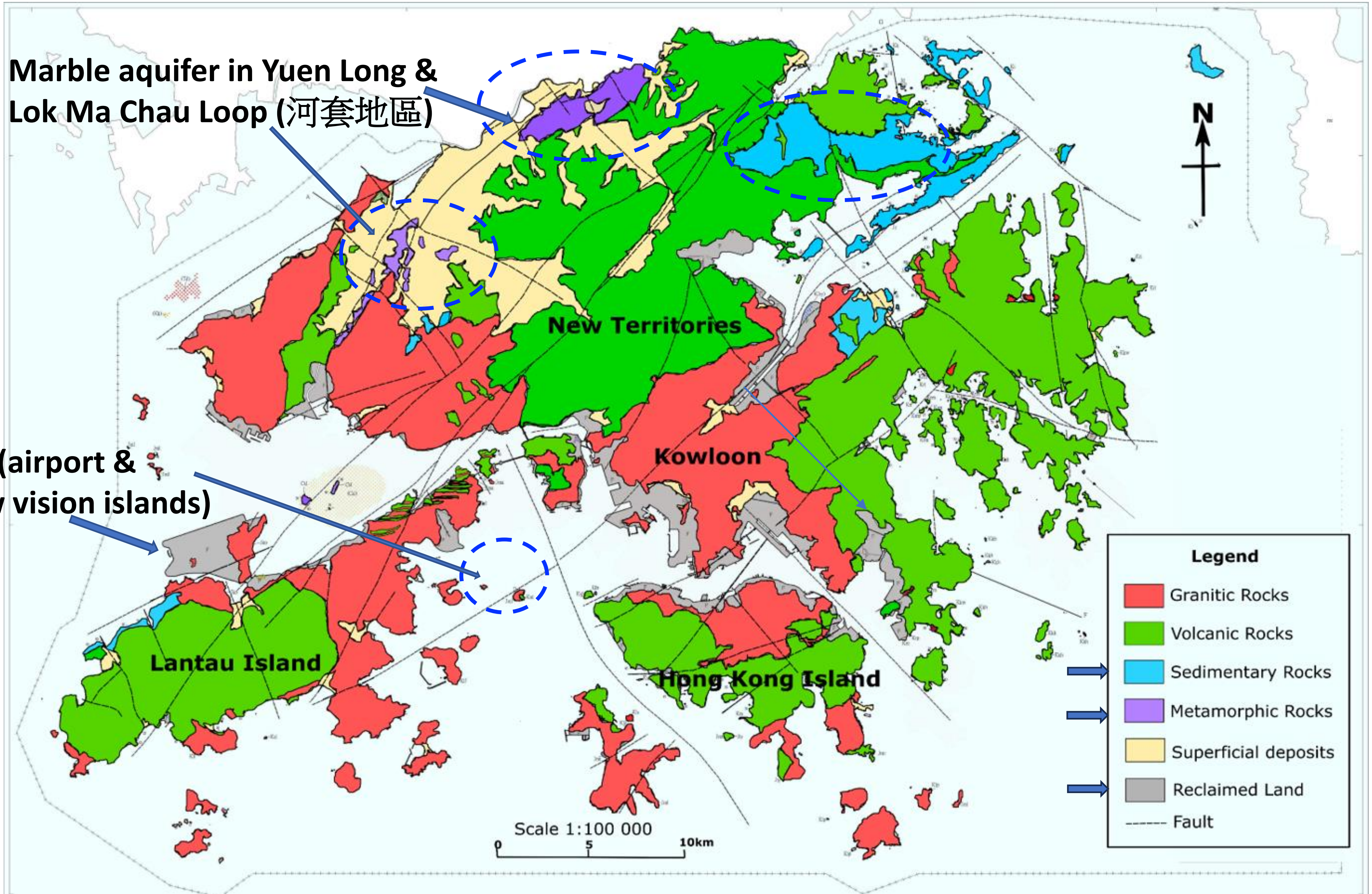
Project (2021):

Managed Aquifer Recharge Study in Yuen Long South – Stage I: Groundwater flow modelling

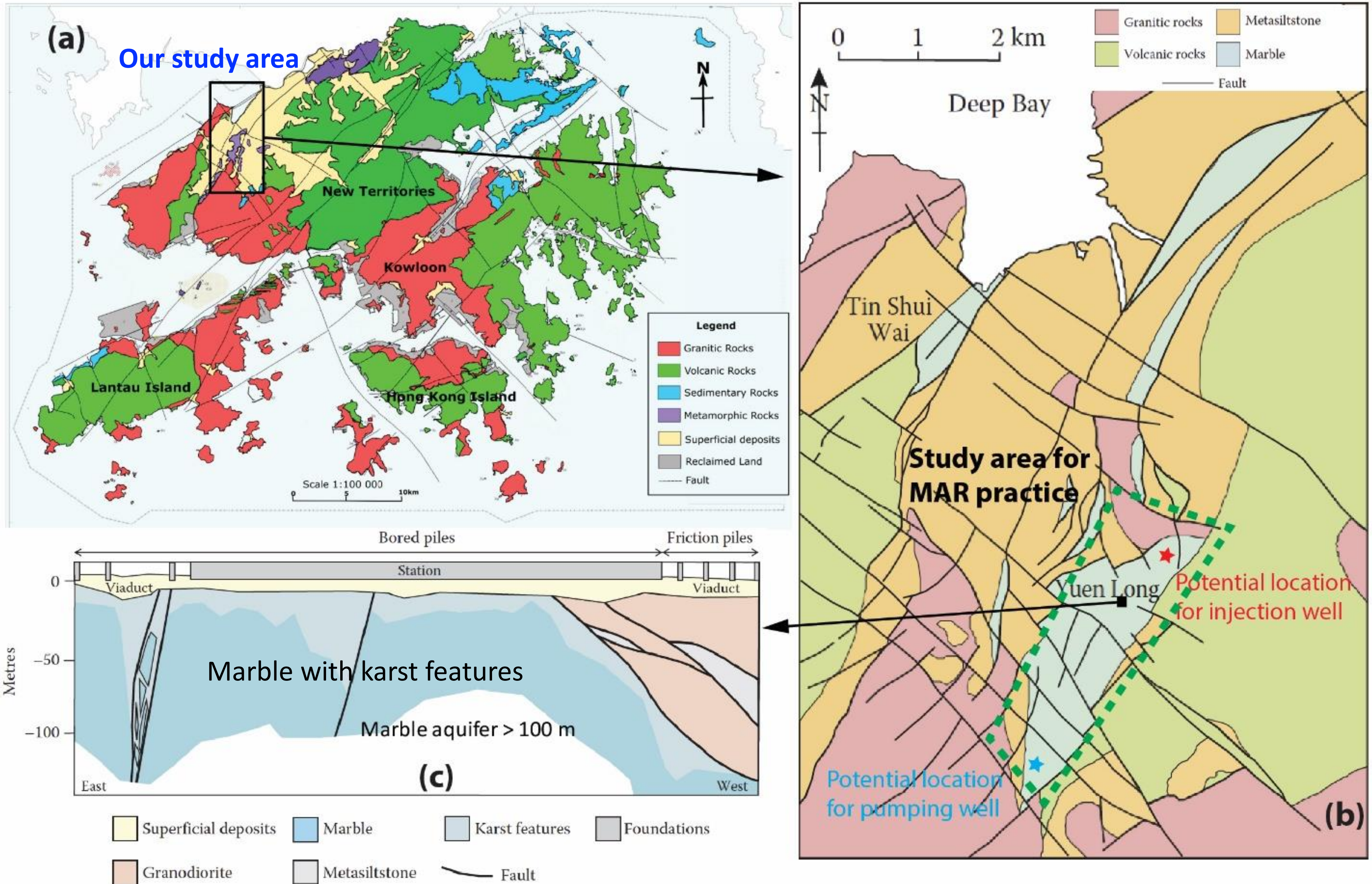
for Binnies Hong Kong Limited as part of “River Revitalisation and Flood Resilience Planning in Yuen Long South – Feasibility Study” supported by DSD, HK

Best aquifers in HK (high permeability and storativity)



Marble aquifer in Yuen Long & Lok Ma Chau Loop (河套地區)

Reclaimed areas (airport & Lantau tomorrow vision islands)



Our study area

Study area for MAR practice

Potential location for injection well

Potential location for pumping well

Marble with karst features

Marble aquifer > 100 m

Background

Opportunities in Yuen Long South

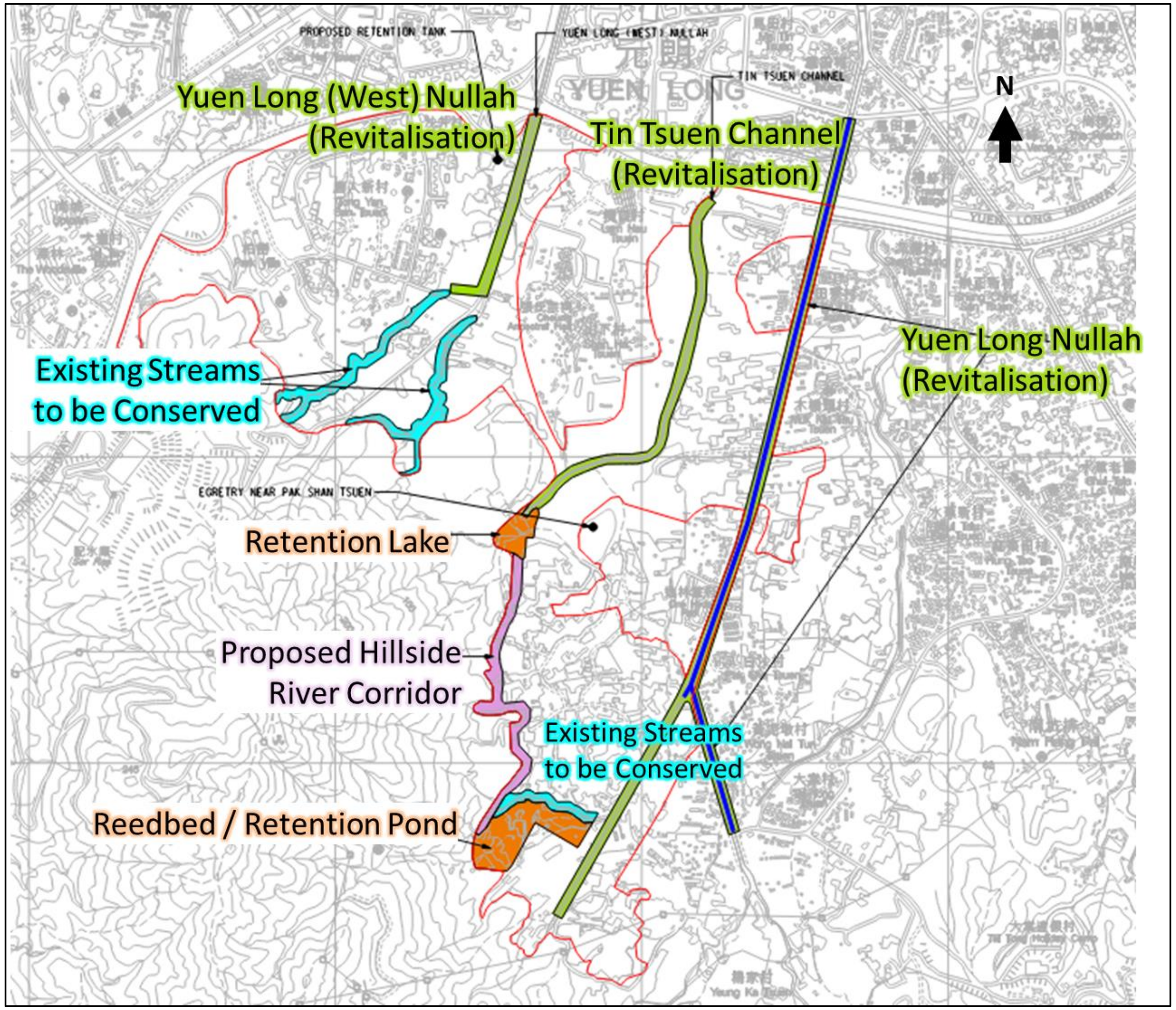
- Existence of marble zone
- ~100 ha of brownfield sites will be **re-developed**
- **Two planned flood retention ponds/lakes**

Initial Idea of MAR at Yuen Long:

- Can recharge the collected stormwater in proposed flood attenuation facilities to marble aquifer for **flood storage** & subsequent **recovery/re-use**?

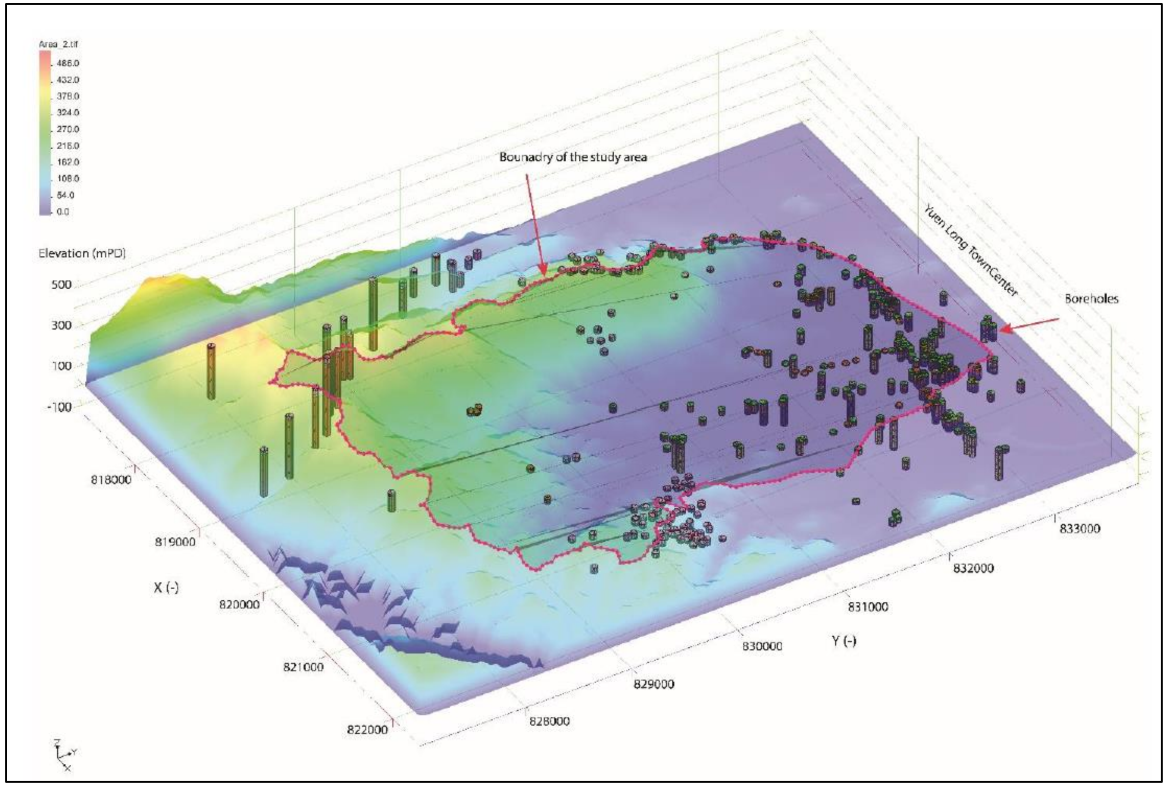
Objectives:

- Investigate whether MAR can be applied in Yuen Long South to support the flood control/resilience
- Establish a numerical model to simulate the MAR system and to preliminary explore different application methods of MAR



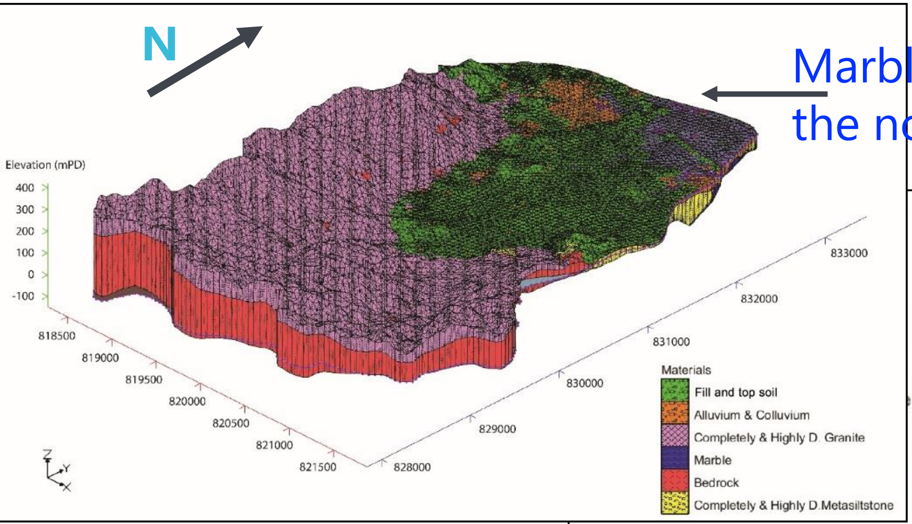
Data Collection for MAR Study

Data type	Quantity & Source
Ground investigation (GI) reports	142 from CEDD
Geological maps	1 from CEDD
Digital elevation model (DEM) data	1 from CEDD
Land use map	1 from PlanD
Borehole logging data	540 from CEDD
Hydraulic conductivity data	46 from CEDD
Groundwater level data	179 from CEDD
Rainfall data	2016-2020 (yearly, monthly, and daily) from HKO

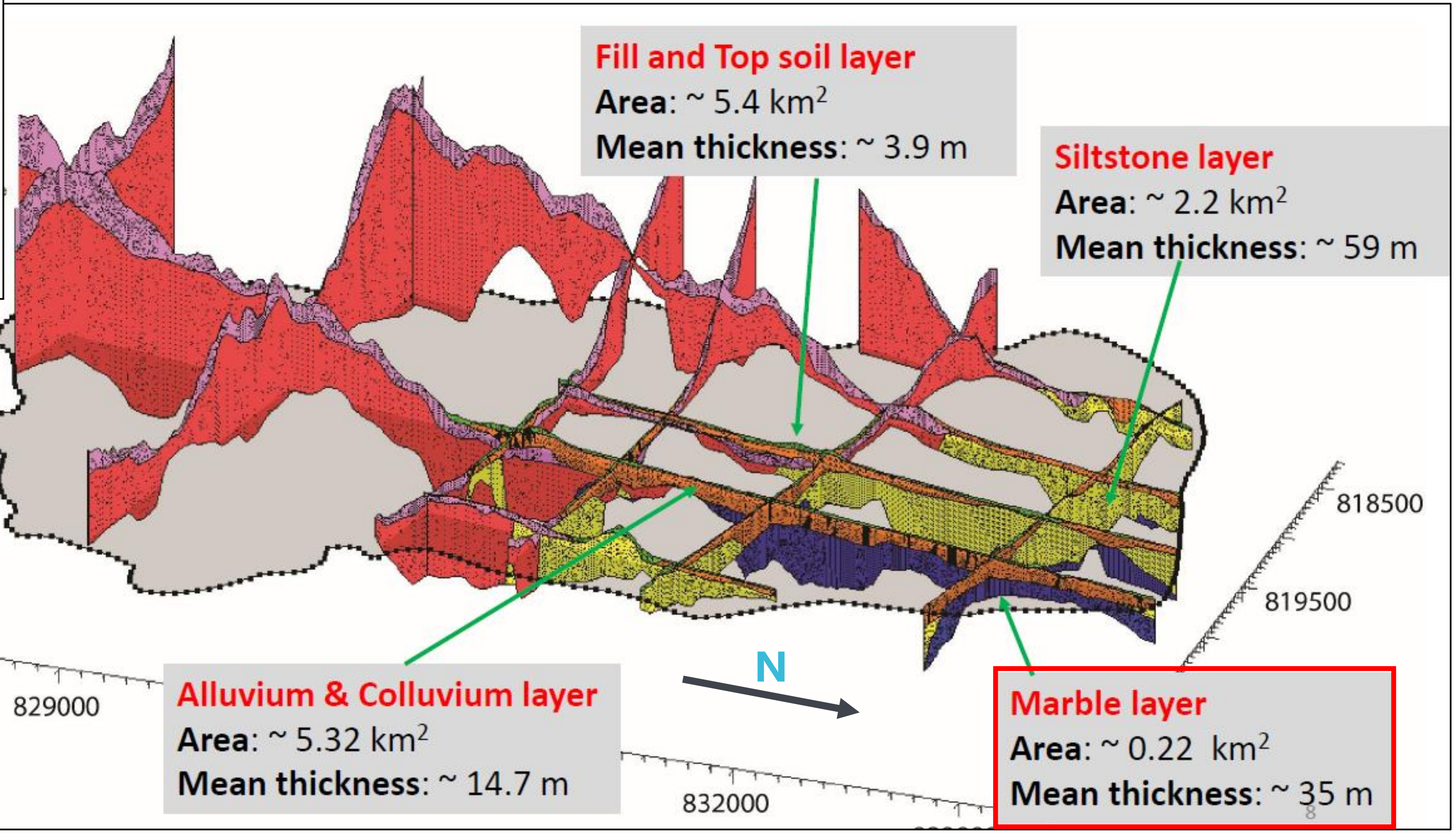


Borehole Distribution

3D Hydrogeological Stratigraphical Model



Marble is mainly located at the northeast corner



Fill and Top soil layer
Area: ~ 5.4 km^2
Mean thickness: ~ 3.9 m

Siltstone layer
Area: ~ 2.2 km^2
Mean thickness: ~ 59 m

Alluvium & Colluvium layer
Area: ~ 5.32 km^2
Mean thickness: ~ 14.7 m

Marble layer
Area: ~ 0.22 km^2
Mean thickness: ~ 35 m

Mterials in the model are simplified into <u>6 types</u>:
(1) fill & top soil;
(2) alluvium & colluvium;
(3) metasiltstone;
(4) marble;
(5) completely to highly decomposed granite;
(6) fresh granite bedrock

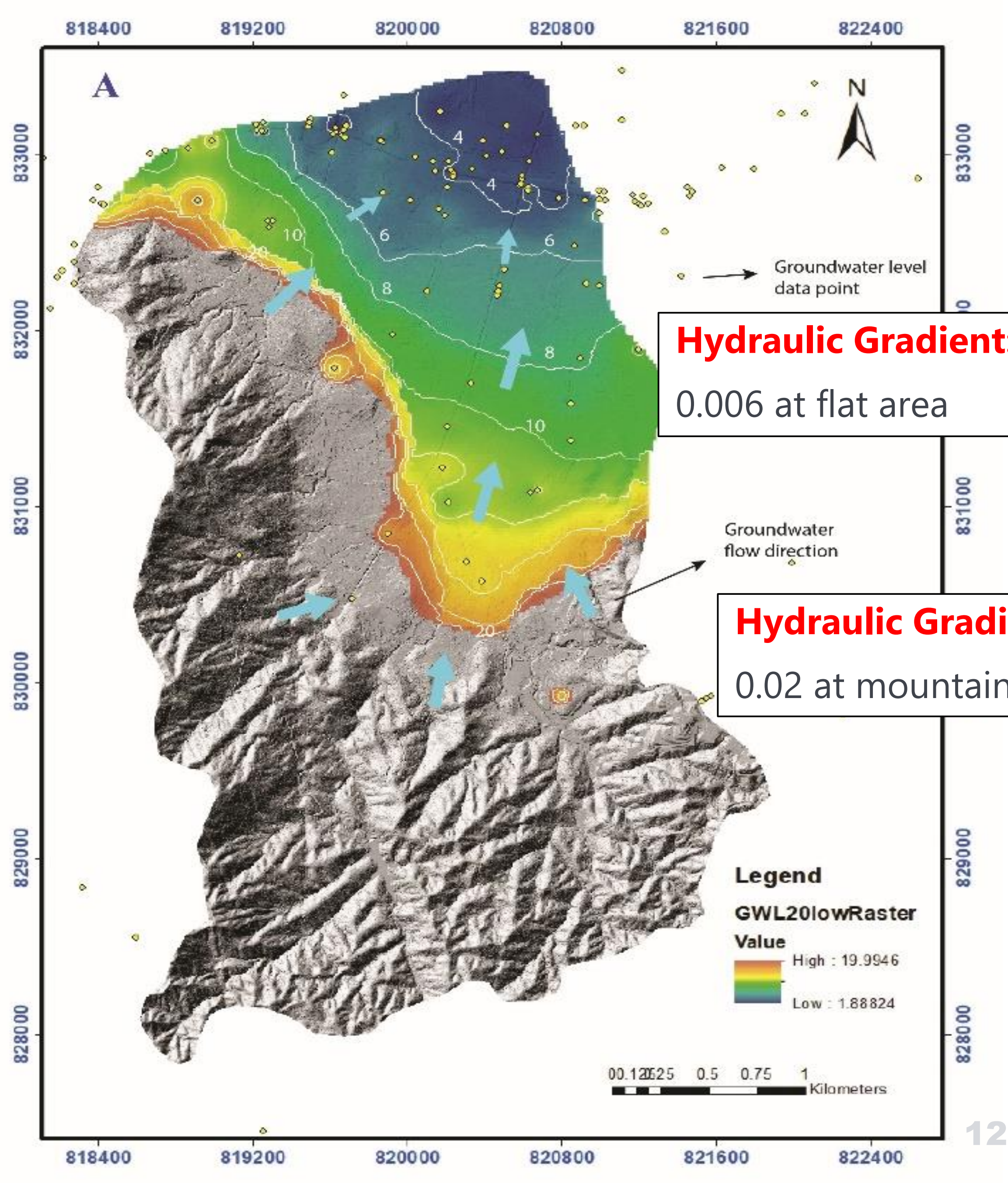
Groundwater Flow

Overall Flow Direction:

- Mountain front to Yuen Long Town Center (toward North)

Natural Recharge:

- Rainfall infiltration mainly at the mountain front and open space at the flat area



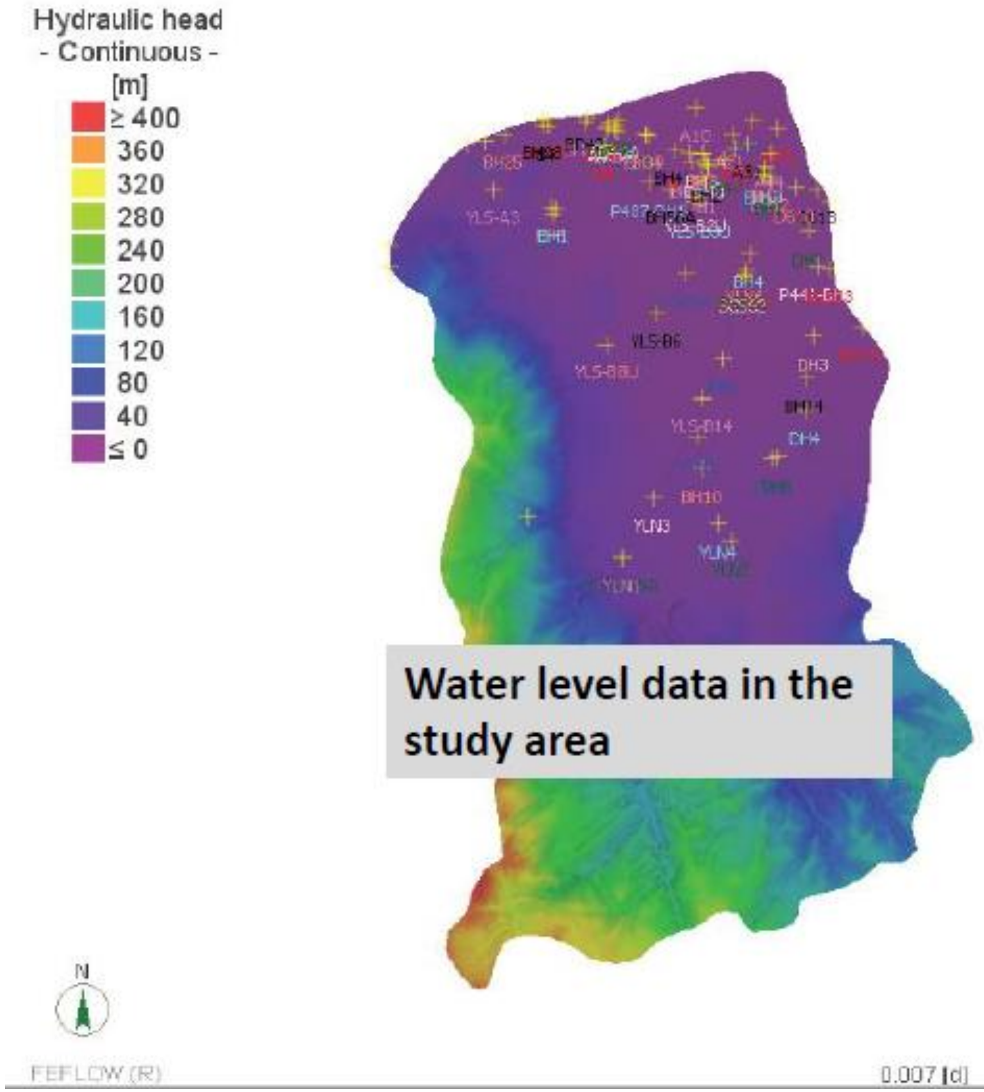
Hydraulic Gradient:

0.006 at flat area

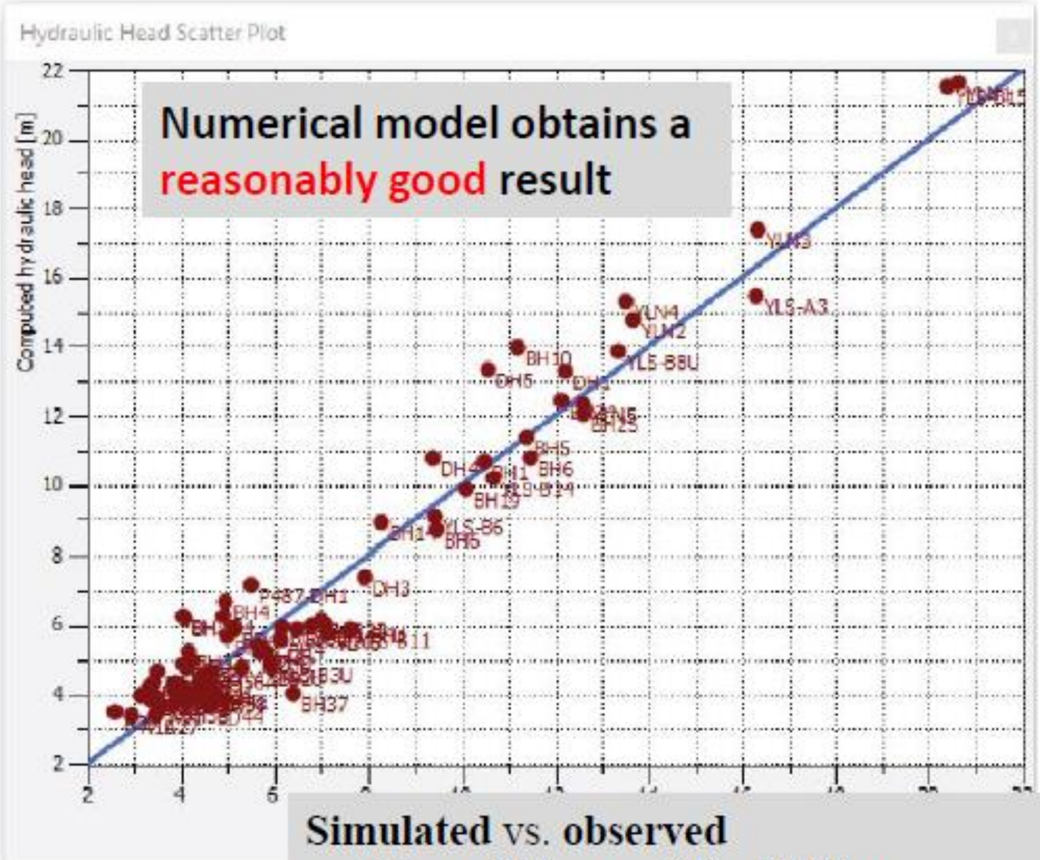
Hydraulic Gradient:

0.02 at mountain front

Model Calibration Results



Water level data in the study area



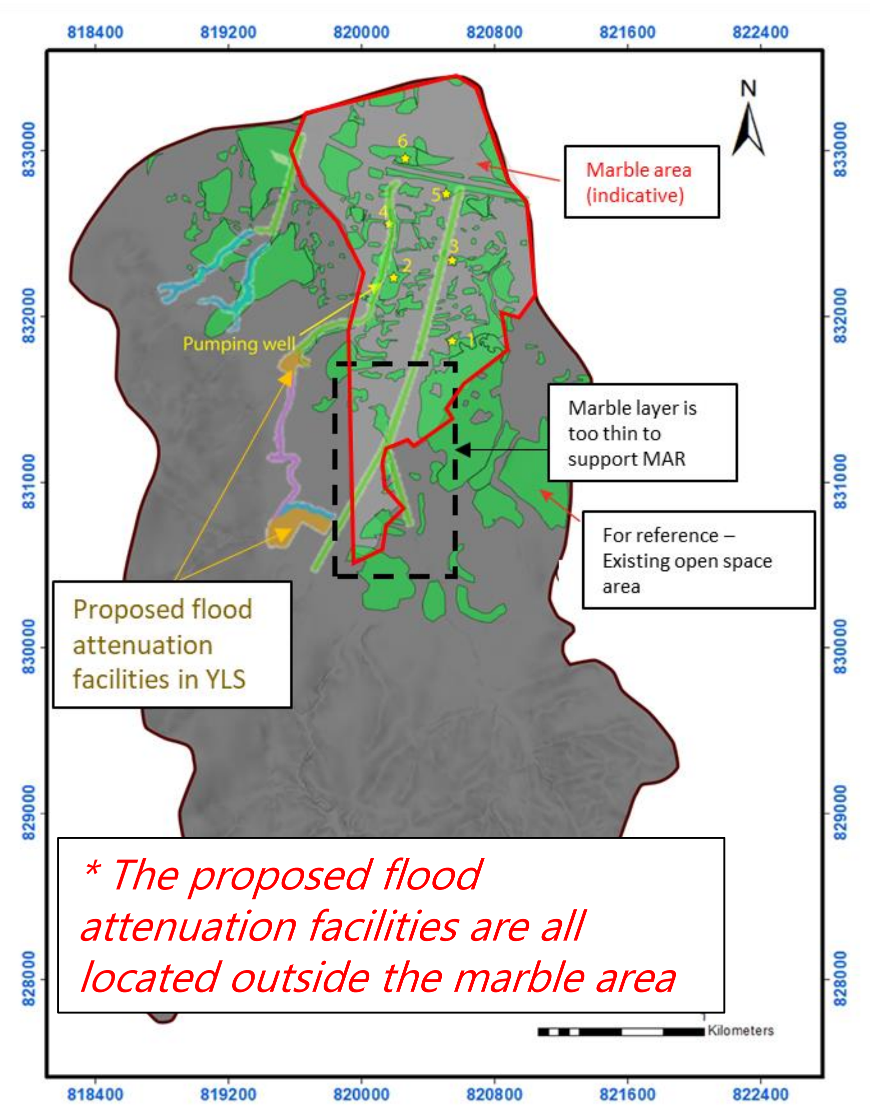
Numerical model obtains a reasonably good result

Simulated vs. **observed**

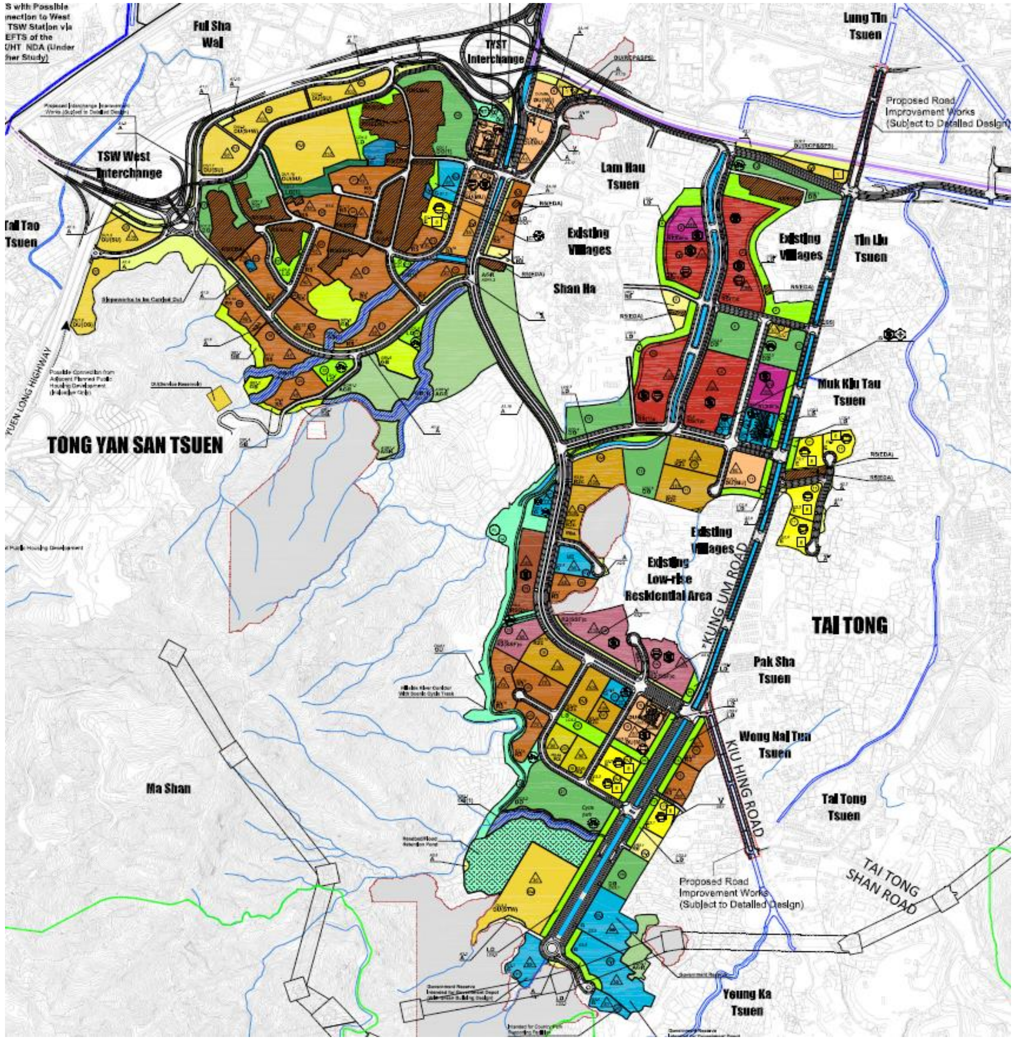
- Mean difference (Ē) of 0.78 m
- Root mean square error (RMS) of 0.99
- standard deviation (σ) of 0.99

Simulation of Different MAR Scenarios

Proposed Testing Well Locations



** The proposed flood attenuation facilities are all located outside the marble area*



Simulation of Different MAR Scenarios

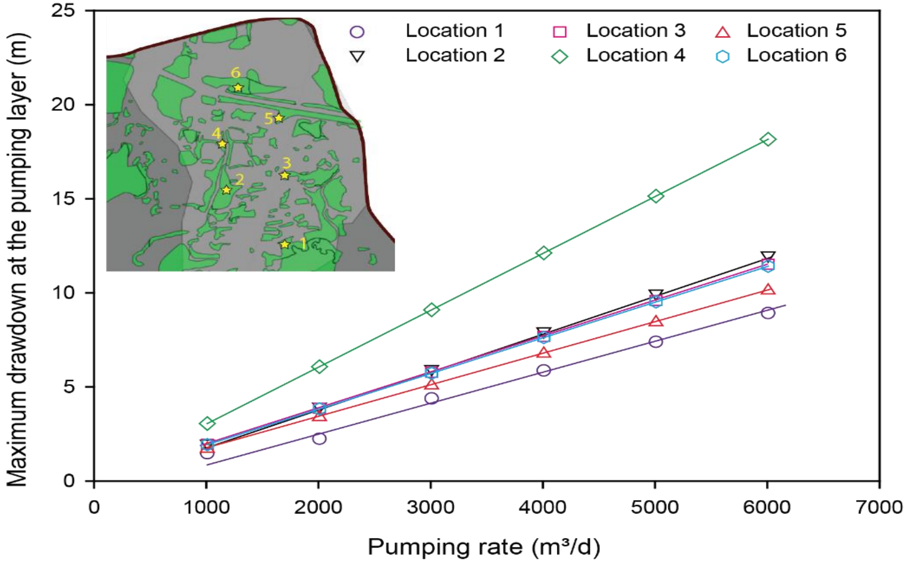
Scenario 1 (Pumping rate vs. drawdown)

- Pumping rate controls the maximum drawdown
- Higher pumping rate ➔ higher drawdown

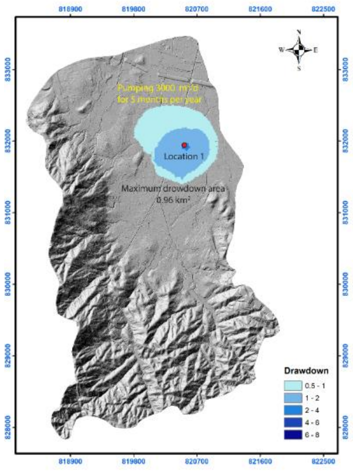
Scenario 2 (Single-well vs. paired-well pumping)

- Increase no. of pumping wells ➔ reduce the maximum drawdown, slightly increases the area of depression cone
- **Paired-well scheme is better**

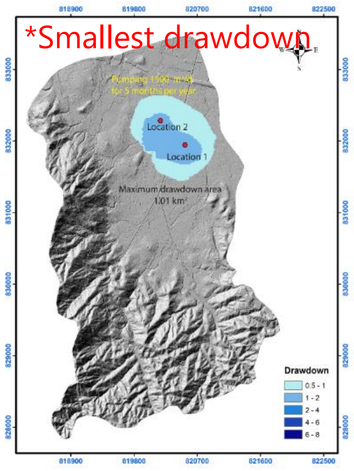
Case 1 (Single well)	Case 2 (Paired well)	Case 3 (Paired well)
• Pumping rate: 3000 m^3/d for 5 months • 7-month recovery	• Pumping rate: 1500 m^3/d **in both wells** for 5 months • 7-month recovery	• Pumping rate: 3000 m^3/d in 1st well for 2.5 months, then switch to 2nd well • 9.5-month recovery



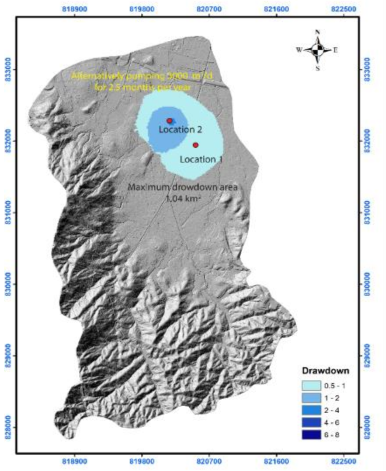
Case 1



Case 2


*Smallest drawdown

Case 3

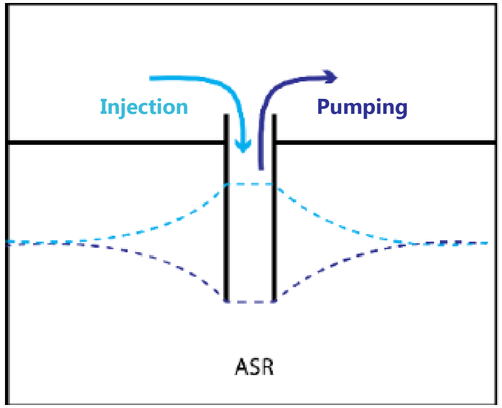


Simulation of Different MAR Scenarios

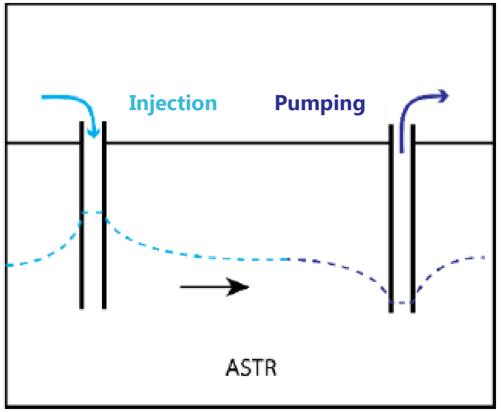
Scenario 3 (Different methods: ASR vs ASTR vs Pond infiltration)

- Reduction of injection rate ➔ decrease in water level rise
- Paired-well injection increases the water mound area
- Recharge at upstream effectively reduces the depression cone size
- Recharge during the dry season ➔ smaller depression cone
- **ASR**: much less water level increase during injection
- **ASTR**: smaller area of the depression cone; much higher water level rise
- **Infiltration Pond**: large area of water level increase; larger land area required

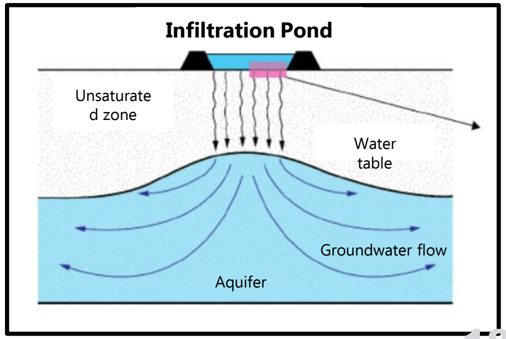
➢ **ASTR is preliminary recommended in terms of smallest area with water level change**



Aquifer Storage Recovery (**ASR**: pumping and injection in the same well)



Aquifer Storage and Transfer recovery (**ASTR**: pumping and injection in different wells)



Infiltration Pond

Simulation of Different MAR Scenarios

Settlement considerations

- Pumping rate of 3000 m^3/day is preliminarily recommended

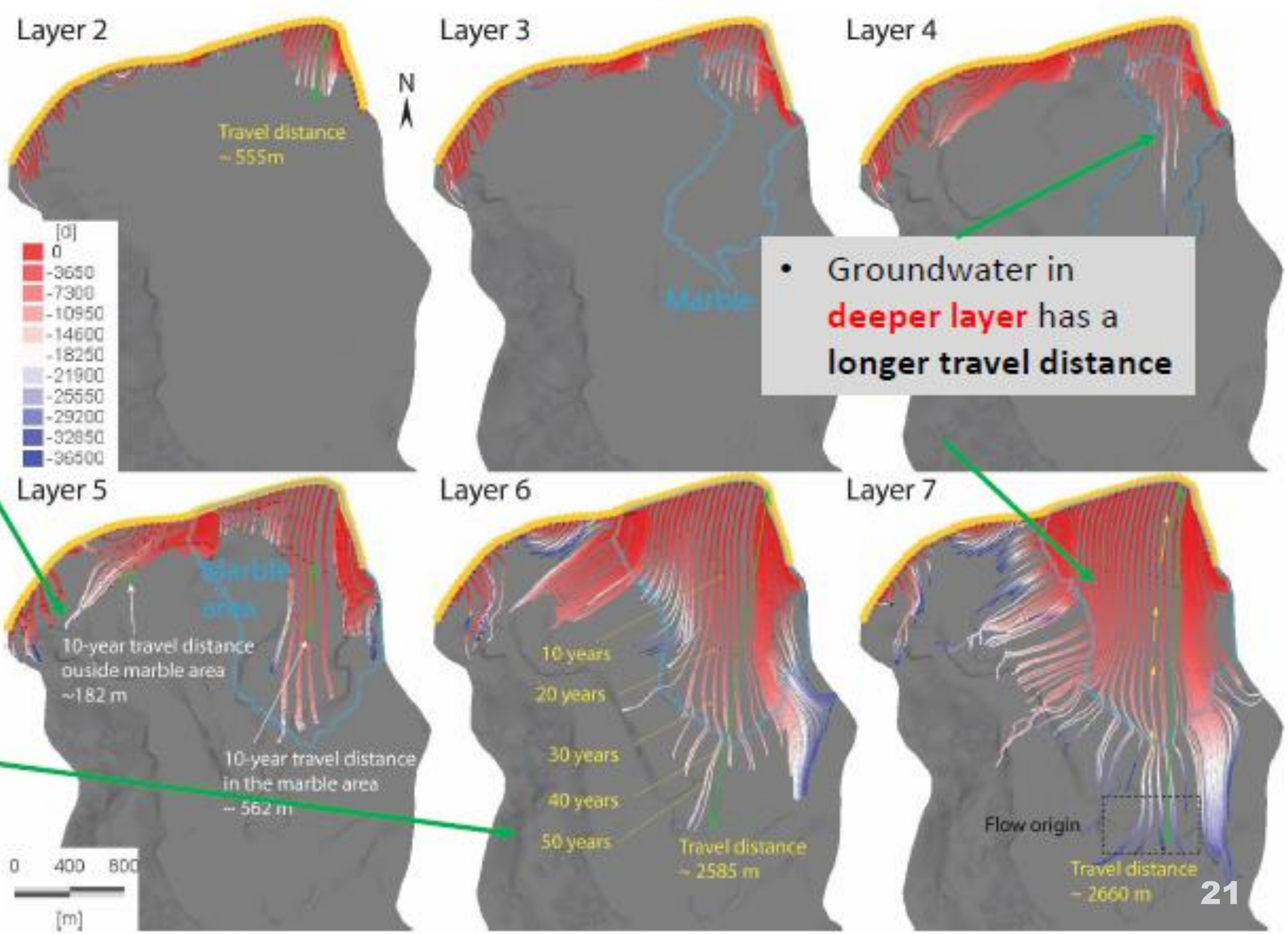
- For preliminary reference, from Mainland experience (Suzhou, China), the largest settlement of clay-rich sediments is about 40 mm at the center of the depression cone when the pumping rate is 3000 m^3/day

- Marble should be more resistant than the clay-rich sediments in Suzhou and hence the resulted settlement should be lesser

Regional Flow System and Travel Time

Comparison of Travel Distance in Different Layers

- From MAR practice in California, USA using treated sewage as water source, the groundwater residence time in aquifer is **1 year** and travel distance is **610m**, before pumping out for re-use



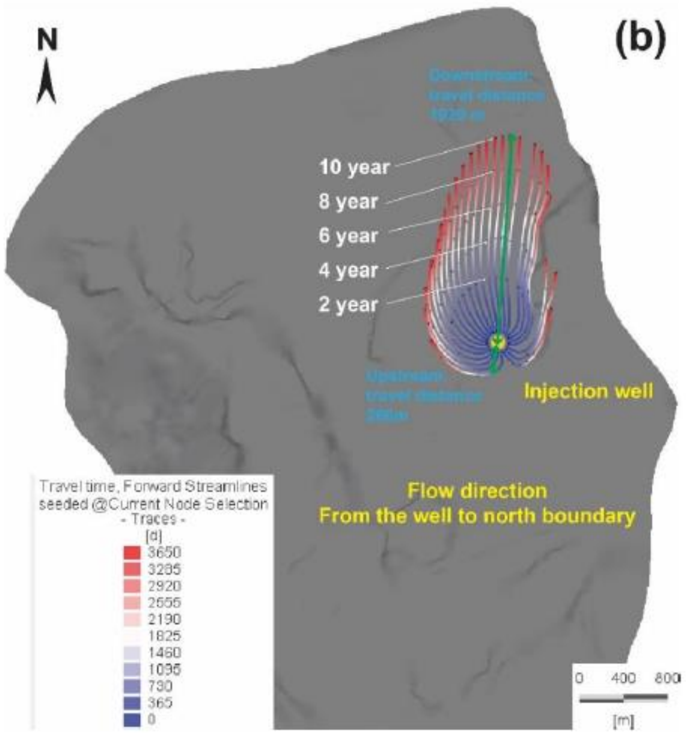
- Groundwater in the **marble area** has a **longer travel distance**

- Groundwater in **deeper layer** has a **longer travel distance**

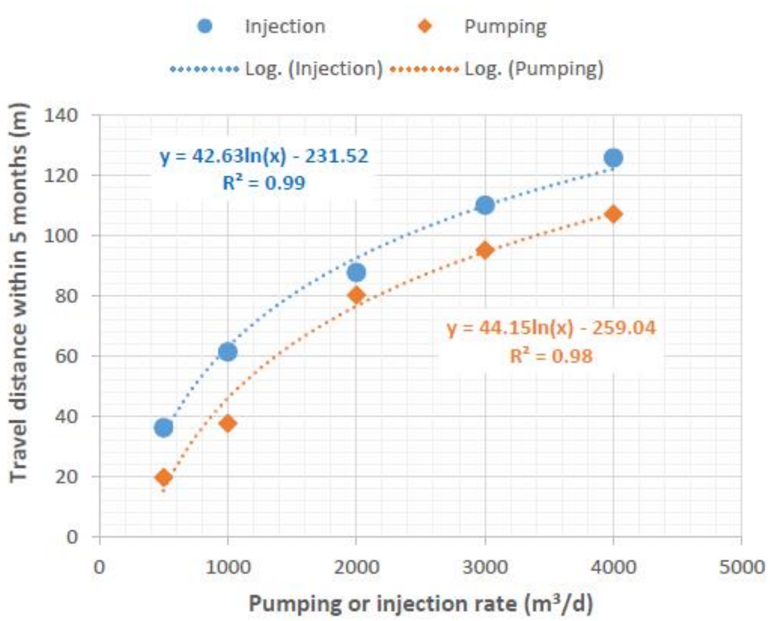
- **Travel distance** is about **2585 m** and the **travel time** is about **50 years** in layer 6

Regional Flow System and Travel Time

Comparison of Travel Time & Distance around Pumping/Injection Well



Travel distance vs. pumping/injection rate



- **Pumping** influences groundwater at upstream more than downstream, **Injection** influences groundwater at downstream more than upstream
- Travel distance **increases** with pumping or injection rate
- From model simulation, the two-years travel distance of underground water in marble is around 200 to 300m
- The travel distance, though less than the travel distance experience in California, USA (~610m), may still be acceptable since rainwater is used as a water source

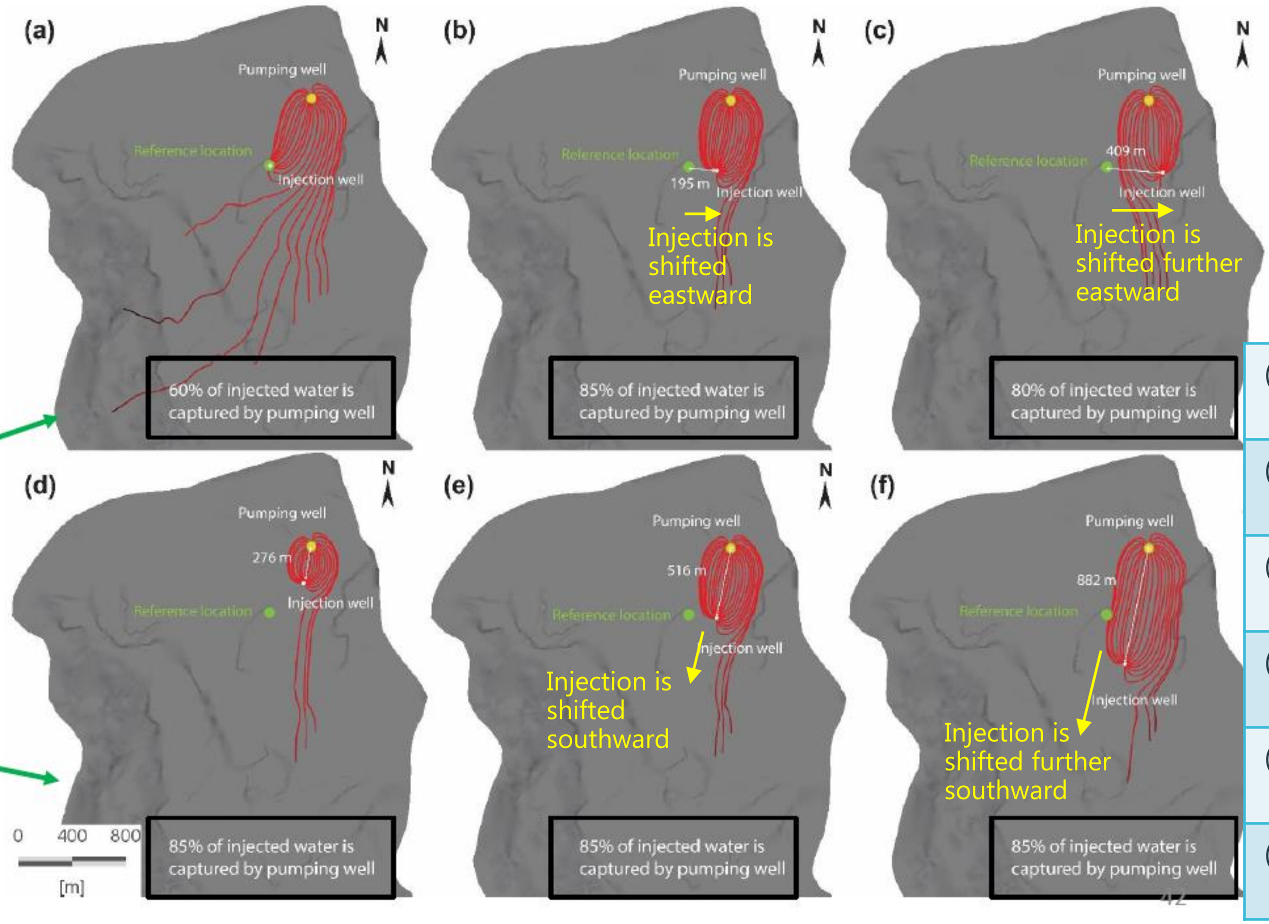
Regional Flow System and Travel Time

Recovery efficiency of different MAR method

- The **recovery efficiency** of ASTR and pond infiltration ranges from **60% to 85%.**

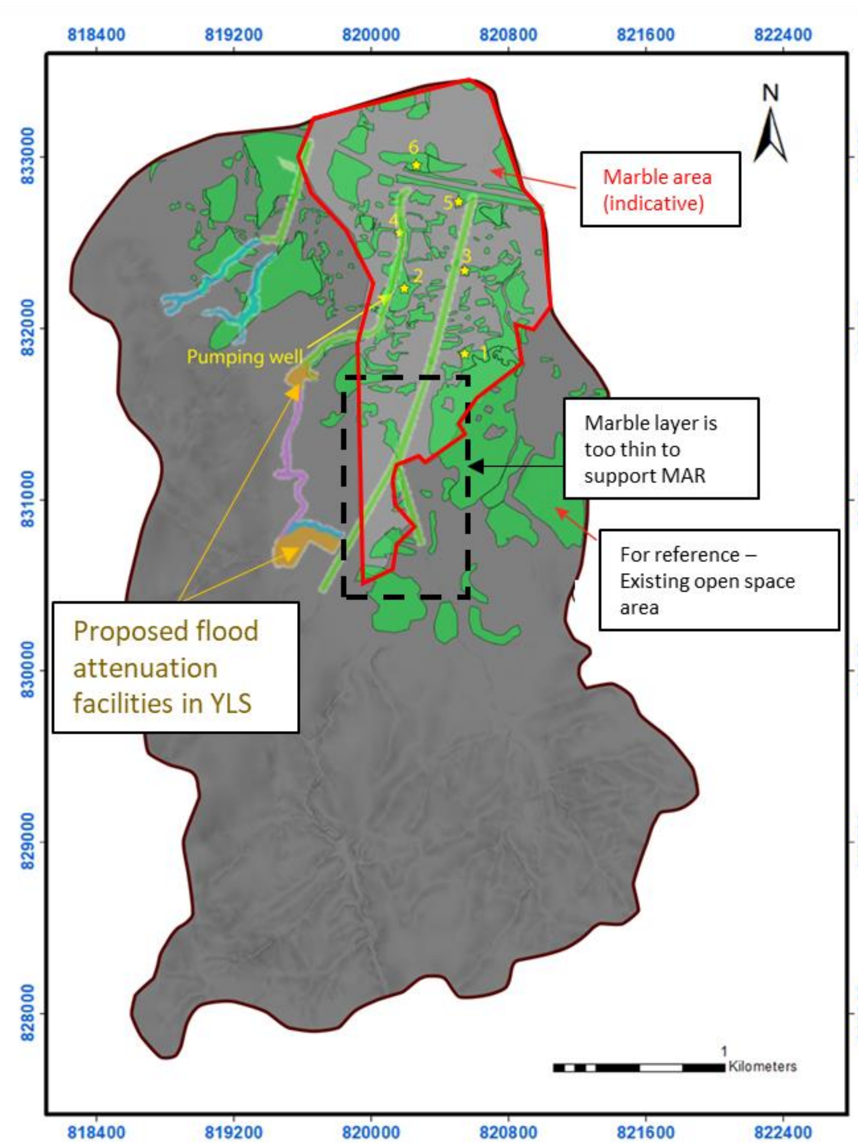
- The recovery efficiency is **sensitive** to the **location change** of the injection well in direction **perpendicular** to the overall flow direction.

- The recovery efficiency is **not sensitive** to the **distance to pumping well**



(a)	Injection at the reference location
(b)	Injection at 195 m east of the reference location
(c)	Injection at 409 m east of the reference location
(d)	Injection at 276 m south of the pumping well
(e)	Injection at 516 m south of the pumping well
(f)	Injection at 882 m south of the pumping well

Findings in Stage I



- **Hydrogeological conditions**
  - Groundwater flows towards the Yuen Long Town Center from the mountain front with a hydraulic gradient of ~ 0.006 at the flat area and over 0.02 at the mountain front area
  - Groundwater recharged from the mountain front has a travel time over 100 years outside the marble area and < 50 years in the marble area
  - Simulated travel distance under different MAR scenarios ranges from 158 to 296 m
- **Groundwater pumping rate**
  - Aquifer can support an extraction rate of 6000 m^3/d if the ground settlement constrain is not considered
  - The maximum drawdown (at the end of the pumping period) in the pumping well is 9 ~ 18 m under a pumping rate of 6000 m^3/d
- **Applicability of different MAR methods**
  - ASR leads to much less water level increase than ASTR and pond infiltration due to groundwater pumping prior the water injection.
  - **ASTR and pond infiltration have a smaller depression cone** compared to ASR due to the recharge from upstream
  - ASR case has a recovery efficiency of injected water less than 60%. However, the **ASTR and Pond Infiltration cases have a recovery efficiency as high as 85%.**

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Conclusions

- Managed aquifer recharge (MAR) has been widely used in the world, including China
- Marble aquifers & reclaimed islands in HK have a great potential for MAR due to their high permeability and stoativity
- Numerical study shows that marble aquifer in Yuen Long South can store significant amount of rain or treated water that can be then pumped subsequently for other uses