Summary report of project Seminar

Comparative Research of Groundwater Management in the Coastal Areas in Southeast Asia

Date: 23-29 October 2014
Venue: Metro Cebu Water District, Philippines

Group photo of participants
1. Programme and activities

The two-year research project on Comparative Research of Groundwater Management in the Coastal Areas in Southeast Asia was concluded with a project seminar held in Cebu, Philippines from October 23 to 29, 2014. The objectives of the final project seminar were to disseminate project results to a wider public and to brainstorm possible following-up activities. Project members and many water managers and specialists from Philippines attended the seminar.

Project members attended the seminar are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Institute</th>
<th>Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr Yangxiao Zhou</td>
<td>UNESCO-IHE Institute for Water Education, Delft, The Netherlands</td>
<td>Groundwater monitoring, modelling, and management</td>
</tr>
<tr>
<td>Mr Nafyad Serre Kawo</td>
<td>UNESCO-IHE Institute for Water Education, Delft, The Netherlands</td>
<td>MSc student in Hydrology and Water Resources</td>
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<tr>
<td>Mr Binaya Raj Shivakoti</td>
<td>IGES, Institute for Global Environmental Strategies, Japan</td>
<td>Remote sensing and GIS application, Wastewater and groundwater management</td>
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<tr>
<td>Mr Hongwei Liu</td>
<td>Tianjin Center of China Geological Survey, China</td>
<td>Coastal hydrogeological and environmental assessment</td>
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<tr>
<td>Mr Haipeng Guo</td>
<td>China Institute for Geo-environmental Monitoring, Beijing, China</td>
<td>Land subsidence and seawater intrusion monitoring and modelling</td>
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<tr>
<td>Mr Haryadi Tirtomihardjo</td>
<td>Center of Groundwater Resources and Environmental Geology, Geological Agency, Ministry of Energy and Mineral Resources, Indonesia</td>
<td>Hydrogeological mapping, groundwater resource assessment, exploration and development</td>
</tr>
<tr>
<td>Mr Taat Setiawan</td>
<td>Ministry of Energy and Mineral Resources, Indonesia</td>
<td>Hydrogeological mapping, groundwater exploration and development</td>
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<tr>
<td>Ms Intining</td>
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<td>Groundwater modelling</td>
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<tr>
<td>Mr Lasaro Salvacion</td>
<td>Metro Cebu Water District, Philippines</td>
<td>Water resources management</td>
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<td>Mr Ronnel Magalso</td>
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<td>Groundwater modelling</td>
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<tr>
<td>Mr Bui Tran Vuong</td>
<td>Division for Water Resources Planning and Investigation for the South of Vietnam, Ho Chi Minh City, Vietnam</td>
<td>Hydrogeological mapping, assessment of groundwater quality and quantity, and groundwater flow modelling</td>
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<tr>
<td>Mr Phan Chu Nam</td>
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<td>Groundwater pollution investigation, modelling, and monitoring</td>
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The programme of the seminar is shown below.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>Friday</td>
<td>Whole day</td>
<td>Arrival participants&lt;br&gt;Macatan airport, Cebu City</td>
<td>Ronnell Magalso</td>
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<tr>
<td>24/10</td>
<td>09:00</td>
<td>Registration</td>
<td>Dr. Yangxiao Zhou</td>
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<td></td>
<td>09:30-09:10</td>
<td>Welcome speech by General Manager MCWD</td>
<td>Chair by Lasaro Salvacion</td>
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<td></td>
<td>09:10-09:30</td>
<td>Introduction of participants</td>
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<td>Saturday</td>
<td>09:30-10:00</td>
<td>Water resources, water supply and challenges in Philippines by National Water Resources Board</td>
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<td>25/10</td>
<td>10:00-10:30</td>
<td>Overview of project activities by Yangxiao Zhou/UNESCO-IHE</td>
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<td></td>
<td>10:30-11:00</td>
<td>Coffee break</td>
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<td></td>
<td>11:00-11:30</td>
<td>Saltwater intrusion in Thailand by Binaya Raj Shivakoti/IGES</td>
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<td></td>
<td>11:30-12:00</td>
<td>Strategies for mitigating impacts of saltwater intrusion by Yangxiao Zhou/UNESCO-IHE</td>
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<td></td>
<td>12:00-14:00</td>
<td>Lunch break</td>
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<td></td>
<td>14:00-15:00</td>
<td>Land subsidence in Cangzhou City, China by Guo Haipeng/CIGEM</td>
<td>Chair by Yangxiao Zhou</td>
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<td></td>
<td>15:00-15:30</td>
<td>Coffee break</td>
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<td></td>
<td>15:30-16:30</td>
<td>Saltwater intrusion in Laizhou Bay by Liu Hongwei/Tianjin GS</td>
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<tr>
<td>Sunday</td>
<td>8:00-12:00</td>
<td>Field visit to Mananga River artificial recharge and water supply project</td>
<td>Ronnell Magalso</td>
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<td>26/10</td>
<td>12:00-14:00</td>
<td>Lunch</td>
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<td></td>
<td>14:00-16:00</td>
<td>Field visit to production and monitoring wells in Central Cebu District</td>
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<td>Monday</td>
<td>8:30-9:30</td>
<td>Saltwater intrusion in Metro Cebu by Ronnell Magalso</td>
<td>Chair by Lasaro Salvacion</td>
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<td>27/10</td>
<td>9:30-10:30</td>
<td>Saltwater intrusion in Mekong Delta by Bui Tran Vuong</td>
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<td>10:30-11:00</td>
<td>Coffee break</td>
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<td>11:00-12:00</td>
<td>Saltwater intrusion in Jakarta Basin by Haryadi Tirtomihardjo and Intining</td>
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<td>12:00-14:00</td>
<td>Lunch</td>
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<td>14:00-15:00</td>
<td>Review of progress of final project reports by China, Indonesia, Philippines and Vietnam</td>
<td>Yangxiao Zhou</td>
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<td>15:00-16:00</td>
<td>Outline of a policy paper by Binaya Raj Shivakoti</td>
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<td>16:00-17:00</td>
<td>Outline of International Journal papers by every case studies</td>
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<tr>
<td>Tuesday</td>
<td>8:30-9:30</td>
<td>Overview of managed aquifer recharge by Yangxiao Zhou</td>
<td>Chair by Binaya Raj Shivakoti</td>
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<td>28/10</td>
<td>9:30-10:00</td>
<td>Outline of a follow-up project to be financed by ADB+UNESCO-IHE partnership fund by Yangxiao Zhou</td>
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<td></td>
<td>10:00-10:30</td>
<td>Coffee break</td>
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<td>10:30-12:00</td>
<td>Discussions on main components of the follow-up project</td>
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<td>12:00-14:00</td>
<td>Lunch</td>
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<td>14:00-17:00</td>
<td>Free</td>
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<tr>
<td>Wednesday</td>
<td>Whole day</td>
<td>Departure participants</td>
<td>Ronnell Magalso</td>
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<td>29/10</td>
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The general manager of MCWD, Engr. Armando Paredes, gave a welcome speech. He stressed importance of groundwater for drinking water supply in Metro Cebu and the urgency to solve the
seawater intrusion problem caused by overexploitation. Therefore, the results of the project are timely needed for managing groundwater development in Metro Cebu.

Mrs Susan, representative from National Water Resources Board of Philippines gave an overview on water resources situation, millennium development goal, national water policy, strategies, programs and projects in Philippines. The issues and challenges on groundwater management are:

- Over-extraction of groundwater resulting to lowering of water level, salt water intrusion and land subsidence
- Groundwater pollution limiting the source of water supply
- Groundwater contamination- leaching of industrial, agrochemicals and animal wastes in agro-industrial areas
- Discharges from latrines & septic systems and infiltration of polluted runoff
- Lack of reliable, updated and science-based groundwater information for well informed decision making

Dr Yangxiao Zhou from UNESCO-IHE reviewed the project progress and outlined the seminar programme. He also gave a presentation on strategies for mitigating salinity impact caused by salt (sea) water intrusion. Methodologies for conjunctive use of surface-ground water resources, managed aquifer recharge, sustainable development, and monitoring were highlighted.

Dr Binaya Raj Shivakoti from IGES presented the case history of saltwater intrusion in Bangkok, Thailand. The saltwater intrusion was caused by overexploitation of groundwater. Mechanisms of saltwater intrusion was simulated by a groundwater flow and transport model and identified as direct seawater intrusion in coastal lines, vertical leakage of shallow saline groundwater, and deep saltwater intrusion to upper layers.

Project experts of country case studies presented the final project results which will be summarised in next Chapter. The plan of producing knowledge products and the idea for developing new project will be also described in separate chapters.

A field visit to Mananga River Valley water supply project was organised on October 26. With ADB support with a loan of 332 million PHP, a water supply project was constructed from 1994 to 1997 by several contractors in Maghaway Valley. The system was designed by an international consortium (Kampsax-Kruger, DKK Consultants Inc., and Lahmeyer). The system consists of several components:

1) A weir for river water diversion in Jaclupan
2) A settling basin for sediment removal
3) An infiltration basin for artificial groundwater recharge to Maghaway valley aquifer
4) 15 production wells equipped with submersible pumps surrounding the infiltration basin
The design parameters and capacities are:

- Mananga River catchment area above the weir: 71 km\(^2\)
- Average river discharge: 135,000 m\(^3\)/d (1.6 m\(^3\)/s)
- Weir height: 5m
- Surface storage behind the weir: 500,000 m\(^2\)
- Design flood: 1,000 m\(^3\)/s

Aquifer:
- Aquifer area in the valley: 1 km\(^2\)
- Aquifer thickness: 20-30 m sand and gravel
- Aquifer storage: 3.2x10\(^6\) m\(^3\)

Artificial recharge:
- Settling basin: 86,000 m\(^2\)
- Infiltration basin: 45,000 m\(^2\)
- Infiltration rate under 1m head: 100,000 m\(^3\)/d (2.5m/d)

Production:
- Production capacity: 33,000 m\(^3\)/d
- Production in dry season: 22,000 m\(^3\)/d

The system has successfully operated since 1997, and provided drinking water for around 300,000 inhabitants.

With the increase of water demand, MCWD would like to investigate possibilities to increase productivity in the facility. An MSc student from UNESCO-IHE, Mr Nafyad Serre Kawo chooses this topic as his research topic. The research title is the optimization of an artificial recharge - pumping system for water supply in the Maghaway valley, Cebu, Philippines. The specific objectives of the proposed research are to:

- Analyze historical changes of water quantity and quality of production wells.
- Estimate artificial recharge rate from the infiltration basin.
- Simulate system dynamics under infiltration and abstraction.
- Optimize production rates.

In the afternoon, observation wells for monitoring seawater intrusion were visited. Both of two wells are close to coastal line and show clearly elevated values of EC.
2. Summary of project results

2.1 Laizhou Bay of China

Problem description
Groundwater over-abstraction induces a gradual increase of saltwater intrusion over recent years in Laizhou Bay of China. It causes damages to drinking water supply and agriculture production.

Saltwater intrusion occurred in several monitoring wells in the coastal areas of Laizhou Bay in 1976. From 1970s to 1980s, the rate of intrusion was very slow. Since the excessive pumping of groundwater in late 1980s, the intrusion became fast. Salt/seawater intrusion areas were connected on the east and southeast coasts of Laizhou Bay. Nowadays, the intrusion area reached more than 1200 km².

![Figure 1 Fresh/Salt water interface in Laizhou Bay area](image)

Objectives of the research
- Set-up of a monitoring network for monitoring saltwater intrusion.
- Identification of sources of saltwater intrusion.
- Prediction of fresh/salt water interface movement.
- Development of integrated measures for controlling saltwater intrusion.

Data and analysis
Monthly precipitation data from 3 stations (Weifang, Changyi and Shouguang) during 2010 -2013 were collected and analyzed. Monthly discharges from 3 bigger rivers (Weihe River, Jiaolaihe River and Mihe River) during 2010 -2013 were collected and analyzed. The data of 91 groundwater level observation wells were collected. Among them, there are 5 time series with daily observation frequency with the monitoring period from 2010 to 2013. There are 3 time series with an observation frequency of every 5 days with the monitoring period from 2007 to 2013. There are 83 time series with an observation frequency of every 20 days with the monitoring period from 2013 to 2014.
The TDS data of 37 wells were collected with the monitoring period from 2010 to 2013, the measuring frequency is every 20 days.

38 boreholes data and 40 geophysical profiles were collected and analyzed.

3. Results and discussions

- SWI monitoring networks were set up with 3 profiles and 20 boreholes. CTD Divers which measure water level, temperature and EC values were installed in every borehole.
- Based on hydrochemistry and isotopes (\(^2\)H, \(^18\)O, \(^3\)H) analysis, saltwater intrusion comes mainly from brine water in saltwater layers.
- Since the abstraction of brine water for industrial use in recent years, saltwater intrusion seems controlled. A groundwater model predicted seaward movement of fresh/saltwater interface due to the abstraction of the brine water; this is still to be verified with the field measurements.
- Four scenarios of controlling saltwater intrusion were analyzed: (1) reduction of groundwater abstraction in areas of deep cones of depression; (2) increase of brine groundwater abstraction; (3) artificial recharge at alluvial fans with surface water during rainy season (infiltration basins, riverbeds with dikes); and (4) a combination of above 3 methods.

4. Conclusions and recommendations

- The combined method can effectively prevent the saltwater intrusion.
- The groundwater model needs to be further improved with data from hydrogeological tests and measurements of salinity.

2.2 Cangzhou of China

Problem description

Land subsidence can be defined as the sinking of the ground surface with respect to surrounding terrain or sea level. Land subsidence is the result of consolidation of soil strata caused by natural
causes such as tectonic motion and sea level rise or man-induced causes such as the withdrawal of groundwater, oil and gas.

Due to rapid development of industrialization and urbanization, land subsidence occurs in Cangzhou City, Hebei province, China, and has become the main factor impacting regional sustainable economic and social development. Investigation has shown that the land subsidence in this area has been caused primarily by extensive pumping of deep groundwater. Partially due to the subsidence, ground fissures have occurred in some uneven subsidence areas.

**Objectives of the research**

- Systematic review of the current situation of land subsidence and then put forward and expounds the formation mechanism of land subsidence in Cangzhou.
- Prediction of groundwater for different scenarios by numerical modeling.
- Identification of best measures (structural and no-structural) to control land subsidence;
- Policy recommendations for prevention and controlling of land subsidence.

![Figure 3 Distribution map of accumulative land subsidence from 2007 to 2010 in Cangzhou](image)

**Data and analysis**

Data were collected from previous hydrogeological survey reports, including maps of geological formations; elevation (top and bottom elevation, land surface elevation); groundwater levels and groundwater balance, parameters of aquifer and aquitard; zone maps of parameters, and so on. To construct the groundwater model, the collected data have been analyzed and reorganization.

A 3D transient groundwater flow model has been established and used to simulate various groundwater resources development schemes in Cangzhou. The trends of the groundwater levels and the storage in the subsidence areas were investigated for each development scenario. In the numerical model, the research area was divided by 164 rows, 191 columns and 8 layers with grid size of 1km×1km. Totally 18,296 grids were produced. The simulation time was 5 year. Modeling result of 2016 was for parameter adjusting, and that of 2007-2010 was for verification. Stress period was set as monthly. Four scenarios were simulated:

S1: The current abstraction pattern and rates remain unchanged.
S2: Shut down pumping wells in the downtown area; shut down pumping wells in the area with accumulative subsidence greater than 1000 mm; shut down pumping wells in the groundwater depression zones. The total abstraction decreases by $3.07 \times 10^8$ m$^3$/year.

S3: Increase artificial recharge along the high-speed railway; increase artificial recharge in the downtown area; increase injection in the groundwater depression zones. The total artificial recharge is $2.96 \times 10^8$ m$^3$/year.

S4: Increase artificial recharge by $1.48 \times 10^8$ m$^3$/year along the high-speed railway, in the downtown area, and in the groundwater depression cones; stop abstraction by $1.54 \times 10^8$ m$^3$/year in the downtown area, in the subsidence area, and in the groundwater depression cones.

**Results and discussions**

For S1, the current abstraction pattern and rates would remain unchanged, groundwater storage will be consumed continually, leading to water level decline and then the drainage of the aquifer.

For S2, abstraction is reduced in areas with great land subsidence or groundwater depression, and groundwater levels in these areas increase greatly compared with S1.

For S3, artificial recharge is conducted in some areas, and groundwater levels of these areas increase greatly compared with S1.

For S4, both abstraction limitation and artificial recharge are conducted, and groundwater levels in most areas increase greatly compared with S1.

**Conclusions and recommendations**

The results of groundwater simulation indicate that out of four scenarios, S4 has the advantages of S2 and S3. The joint scenario S4 consists of merits of reduced abstraction and increased recharge scenarios. It can sustain the required abstraction rate for water supply and recover the depleted aquifer, and eventually lead to a sustainable development of groundwater resources in Cangzhou. Thus, S4 may be the best scenario for sustainable development.

### 2.3 Jarkata Basin of Indonesia

**Problem description**

Over-exploitation of groundwater in Jakarta basin has caused the following problems:

- Groundwater depletion: the cone of groundwater depressions occurs in the north area Kapuk and Cakung with the maximum groundwater heads at 40 m below sea level (mbsl).
- Seawater intrusion: in 2011, the zone of slightly brackish water within artesian groundwater covering most of the northern part of Jakarta Plain and has the maximum distance at 8 km from coastline in the North Jakarta and Central Jakarta.
Objectives of the research
Objectives of research on groundwater depletion are achieved by using groundwater model (MODFLOW):
- to understand about sub-surface process;
- to establish groundwater budget;
- to analyze the problem holistically for developing management scenarios.

Objectives of research on saltwater intrusion are achieved by using density-dependent groundwater model (SEAWAT):
- to identify source of saltwater intrusion;
- to obtain relation between freshwater and saline water interface and it changes; as well as lateral distance of intruded freshwater by seawater;
- to establish the best scenario for controlling seawater intrusion.

Data and analysis
Data collection and analysis is shown in Figure 5. Data on geology, hydrology, meteorology, and groundwater were collected and analysed. The main problem in data is lack of long-term systematic groundwater monitoring.
Results and discussions

The aquifer system in the Jakarta Basin can be divided into 4 groups: the top unconfined aquifer, the upper confined aquifer, the middle confined aquifer, and the deep confined aquifer (Figure 6). A groundwater flow model is constructed to simulate the seawater intrusion. The model is still under calibration.

Conclusions and recommendations

Like other groundwater dependent areas, Jakarta Basin has already been affected by groundwater related problems mainly related to over-pumping and pollution of aquifers.

Four major problems are lowering of groundwater levels, seawater intrusion, land subsidence, and groundwater pollution.
Simulation of scenarios show that Scenario 1 (Qabs=0 at the cone of depression) is the most effective measure to increase groundwater level in the study area.

Groundwater governance index assessment of current situation shows the score of component varies from 3.25 (poor to acceptable) for “cross-sector policy coordination” to 7.5 (good) for “right and responsibilities”. The overall assessment shows the calculated score were 5.2 which can be classified into acceptable.

### 2.4 Cebu of Philippines

**Problem description**

The main problems in Metro Cebu are:
- Seawater intrusion;
- Depletion of groundwater in the aquifer.

![Figure 7 Groundwater salinity in Metro Cebu: groundwater in the area between Cl contour line of 250 ppm to shoreline has high salinity.](image)

**Objectives of the research**

The objectives of the research are to:
- Determine extent and local situation of saltwater intrusion by well/water quality surveys and establishing monitoring wells’ network for SWI
- Identify critical areas affected by saltwater intrusion.
- Resolve the issue on groundwater sustainability, determine aquifer potential, current rate of aquifer withdrawal. Identify hotspots in aquifer abstraction.
- Develop well-calibrated model to address major issues of saltwater intrusion and aquifer sustainability.

**Data and analysis**
The data collected are as follows:

**Hydrologic/Hydrometrologic Monitoring**
- 27 rainfall gauging stations
- 5 evaporation/river flow monitoring stations
- 40 contracted private wells for groundwater monitoring for water levels
- 30 administered dedicated monitoring wells for aquifer elevation
- 10 deep coastline observation wells for saltwater intrusion

**Operational Monitoring**
- 120 pumping wells regularly monitored every month for:
  - Static/pumping water levels
  - Extraction rates in cmd
  - Water quality i.e. (salinity-Cl, Ec, TDS, E-coli, Nitrate)
  - Complete Chemical Analysis annually
  - Efficiency tests for low performing wells to investigate / isolate well deterioration from aquifer deterioration

**Results and discussions**

The conceptual hydrogeological model of the Cebu is shown in Figure 8. The target aquifer consists of alluvial sandy to gravelly sediments and limestone. The inflow to aquifer is mainly from natural recharge composed of upland runoff or coastal rainfalls, and return flow from artificial activities. The outflow from aquifer consists of abstraction from limestone inducing seawater intrusion.

**Conclusions and recommendations**

Groundwater over-exploitation has caused serious seawater intrusion in Cebu Metro. Salinity in abstracted groundwater is increasing. Control of groundwater abstraction, especially non-Cebu Water District wells, is urgent to stop the seawater intrusion. Alternative water sources, for example, artificial groundwater recharge in surrounding river valleys, must be studied and implemented.

### 2.5 Mekong Delta of Vietnam

**Problem description**

Groundwater provides valuable services to the Mekong Delta (MD). These include the supply of drinking water to millions and the prevention of salt water intrusion. About 4.5 million people depend upon groundwater for drinking. Due to the going up of population, surface water resources is polluted and not able to meet the demands, groundwater abstraction has increased rapidly and declining groundwater levels and saline groundwater intrusion now pose an immediate threat to
drinking water supplies, farming systems, and livelihoods in the delta. Furthermore, climate change might add more pressure on groundwater by affecting groundwater recharge rates and changes the availability of groundwater.

Although groundwater plays an important role, there has been quite little research conducted on groundwater comparing to surface water resources, especially in the climate change impact assessment context in Vietnam. Most of the climate change impact research concentrated on surface water. It is also true in the case of MD, where there are very few studies of climate change impacts on groundwater. Therefore, investigating and modelling the temporal variance of rainfall, both of intensity and frequency, temperature and associated changes in evaporation and evapotranspiration, and the impacts these factors have on groundwater recharge and resources across different aquifer types in Mekong Delta under different climate change scenarios are needed and urgent.

**Objectives of the research**

The objectives of this study is to assess the impacts of groundwater abstraction and climate changes on groundwater resources through the change of future climate variables such as temperature, precipitation, evaporation and sea levels.

**Data and analysis**

MD in Vietnam is of 39,700 km² area, located at the southern part of Vietnam, limited by Gulf of Thailand to the southwest, East Sea to the south and southeast, Cambodia boundary to the north. MD is relative plain and low. The average elevation is from 0.3 – 2.0 m, except some mountains in the southwest (An Giang, Kien Giang provinces), the rest of area elevation is below 5m. In addition, there are some hilly area and coastal dune which are quite high.

The climate of MD is equatorial monsoon climate and is devised in two seasons: the rainy season and dry season. The annual rainfall varies from 1,400 – 2,400 mm/year. Rain time very unevenly distributed in the year, more than 90% of the annual rainfall is in rainy season from May to November, and less than 10% of the annual rainfall is in dry season from December – April. The open pan evaporation ranges from 800 to 1,300 mm/year with the lowest evaporation in October and the highest in March. The humidity is generally high varying from 75% during the dry season to more than 90% in the wet season. The temperature varies between 24-25.5°C in the coolest month January and 28-30°C in the hottest month of May.

MD river system consists of the natural river systems and the manmade canal systems. The main natural river systems are the Tien river and Hau river system; the Vam Co river system; and Cai Lon and Cai Be river system. The system of manmade canals in MD was developed primarily during the past century, with the primary purpose to develop agriculture and transportation. Until now, the canal system has developed into a dense network with 3 levels of major, primary and secondary canals. The primary and secondary canal systems have a high density, with some 80-10 m/ha, and a total of 30,000-40,000 km of canals in all MD.

Stratigraphy of MD consists of intrusive, extrusive rocks and sedimentary formations of Devon to Quaternary age. They were formed in different tectonic phases. The intrusive and extrusive rocks act as a basement, while the sedimentary formations are the cover layers. The intrusive rocks consist of upper Trias (T₃) and upper Jura - Creta (J₃-K) formations. The extrusive rocks consists of Devon- lower Carbon (D-C₁), Permi- lower Trias (P-T₁), upper-middle Trias (T₂₃), and Paleogen (Eocen-Oligocen, E₂₂₃) formations. The sedimentary formations consists of middle-upper Miocene (N₁₂₃), upper Miocene (N₁₃), lower Pliocene (N₂₁), middle Pliocene (N₂²), lower Pleistocene (Q₁¹), middle- upper Pleistocene (Q₁²³), upper Pleistocene (Q₁³), lower- middle Holocene (Q₂¹²), middle-upper Holocene (Q₂²³), and upper Holocene (Q₃³) formations. Each formation is sub-divided into
units that the sediments have different origins. Generally, each formation has been divided into two parts. The upper part is composed of a low permeable silt, clay or silty clay. A lower rather permeable part consists of fine to coarse sand, gravel, and pebble.

There are eight distinguished aquifers in MD, namely Holocene ($qh$), Upper Pleistocene ($qp_3$), Upper- middle Pleistocene ($qp_{2-3}$), Lower Pleistocene ($qp_1$), Middle Pliocene ($n_2^3$), Lower Pliocene ($n_2^1$), Upper Miocene ($n_1^3$) and Upper-Middle Miocene ($n_1^{2-3}$) aquifers. Generally, lithology of each aquifer consists of fine to coarse sand, gravel, and pebble.

Basically, the aquifer system in MD has an artesian basin structure (Figure 9). The deepest area of the basement is located below the Tien and Hau Rivers and rises to the NE, N and NW borders.

Recent investigation shows that the amount of groundwater abstraction in MD is about 1,924,000 m³/day, of which the amount of groundwater abstraction in $qh$, $qp_3$, $qp_{2-3}$, $qp_1$, $n_2^3$, $n_2^1$, and $n_1^3$ are 17,851; 114,945; 977,514; 130,077; 477,359; 87,652; 118,235 m³/day, respectively. The number of abstraction wells is more than 550,000 of which, about 932 abstraction wells having a capacity of greater than 200 m³/day.

Three scenarios of future climate change (low CO₂ emission senario - B1, medium CO₂ emission senario - B2; and high CO₂ emission senario - A2), were generated by SimClim. The simulated results of SimClim are spatial maps of temperature, precipitation as well as sea levels rise by 2100. Present and future climate together with some unchanged input maps such as land-use, topography, soil texture, slope and wind-speed are put in a hydrological model called Wetspass to simulate the present and future groundwater recharge. A calibrated groundwater model using GMS (Groundwater Modeling System) software will be set up to estimate the impacts of groundwater abstraction on groundwater resources. Then the calibrated model was used to simulate the impacts of climate change on groundwater resources under different scenarios.

Results and discussions

Amount of groundwater recharge
The amounts of groundwater recharge during the period of 2000-2010 calculated by WetSpas are shown in Table 1. The amount of groundwater recharge varies from 2,568,586 to 4,636,836 m³/day. The amount of groundwater recharge in the rainy season is greater than that in the dry season from twofold to sevenfold.
The amounts of groundwater recharge during the period of 2020–2100 under three different scenarios of climate calculated by WetSpass are shown in Table 2. The amount of groundwater recharge varies from 1,721,031 m³/day for scenarios B1, from 1,425,213 to 3,445,469 m³/day for scenarios B2 and from 1,034,479 to 3,543,892 m³/day for scenarios A2. In the same year, amount of groundwater recharge in rainy season is greater than that in dry season. In one scenario, amount of groundwater recharge decreases in time. The amount of groundwater recharge decreases from low to high emission scenarios in period of 2050 – 2100. The amount of groundwater recharge in period of 2020-2100 is less than that of 2010. The average reducing rates of the amount of groundwater recharge are 20,421; 23,708 and 28,050 m³/day for B1, B2 and A2 scenarios, respectively. The trend of groundwater recharge in both dry season and rainy season are decrease, however, the change in recharge is different by spatially.

### Table 1. Amount of groundwater recharge during period of 2000 to 2010.

<table>
<thead>
<tr>
<th>Year</th>
<th>Groundwater recharge, m³/day</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In dry season</td>
<td>In rainy season</td>
</tr>
<tr>
<td>2000</td>
<td>1,194,760</td>
<td>3,008,343</td>
</tr>
<tr>
<td>2001</td>
<td>866,875</td>
<td>2,640,258</td>
</tr>
<tr>
<td>2002</td>
<td>460,823</td>
<td>2,039,961</td>
</tr>
<tr>
<td>2003</td>
<td>605,083</td>
<td>3,239,920</td>
</tr>
<tr>
<td>2004</td>
<td>462,229</td>
<td>2,106,357</td>
</tr>
<tr>
<td>2005</td>
<td>487,293</td>
<td>2,892,062</td>
</tr>
<tr>
<td>2006</td>
<td>728,361</td>
<td>2,648,899</td>
</tr>
<tr>
<td>2007</td>
<td>764,326</td>
<td>3,872,510</td>
</tr>
<tr>
<td>2008</td>
<td>944,835</td>
<td>3,184,626</td>
</tr>
<tr>
<td>2009</td>
<td>817,986</td>
<td>2,215,478</td>
</tr>
<tr>
<td>2010</td>
<td>439,592</td>
<td>3,119,590</td>
</tr>
</tbody>
</table>

The indicators for assessing the impacts of groundwater abstraction on groundwater resources are the decrease in groundwater levels and depletion of groundwater storage.
The groundwater levels decreases dramatically in all aquifers, several cones of depressions were shaped in the maps of groundwater level in the year of 2010. The rate of groundwater level decrease at the center points of the cones of depression (the black stars) are 2.80, 1.76, 1.24, 1.98, 1.42 and 2.58 m/year for \( n_{13} \), \( n_{32} \), \( n_{21} \), \( n_{2} \), \( n_{1} \), and \( n_{13} \), respectively. Fig.4 shows an example of the decrease in groundwater levels due to groundwater abstraction in aquifer \( n_{13} \).

Fig. 10. Maps of groundwater levels on 2000 and 2010 in \( n_{13} \)

Fig. 11. Changes of groundwater storage from 2000 to 2010 in the whole aquifer system

Fig. 11 shows the depletion of yearly groundwater storage for the whole MD from 2000 to 2010. On the year of 2000 the change in storage in the whole MD is 515 Mm\(^3\), on the year of 2010, this number is -337 Mm\(^3\) resulting the average rate of depletion of groundwater storage is -77 Mm\(^3\)/year. Yearly changes in storage are of negative values since 2004, it means that since 2004 the groundwater resources are under depletion.

Impacts of climate changes on groundwater resources
The indicators for assessing the impacts of climate changes on groundwater resources are i) the decrease in groundwater levels, ii) depletion of groundwater storage and and iii) the increase of area having TDS greater than 1000 mg/l.
Fig. 12 shows an example of the differences in groundwater levels in aquifer $n_1^3$ on 2010 and on 2100 under different climate scenarios. It is clear that the cones of depression are enlarged by 2100 in comparison with those of 2010 for all three scenarios of climate.

![Maps of groundwater level](image)

Figure 12. Maps of groundwater level of aquifer $n_1^3$ on 2010 (a) and on 2100 under B1 scenarios (b), B2 scenarios (c) and A2 scenarios (d)

The absolute values of the differences in groundwater level between 2010 and 2100 and the rates of decrease in groundwater levels of three scenarios at the center of the cones of depression for each aquifer are shown in Table 3. The differences between groundwater levels of 2010 and 2100 and the rates of decrease in groundwater levels of aquifer $qP_3$, $qP_2-3$, $n_2^2$ and $n_1^3$ are increase from B1 to B2 and A2 scenarios. While these of aquifer $qP_1$ and $n_2^1$ is on the contrary.

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Difference between GW levels in the year of 2010 and 2100</th>
<th>Average rate of decrease in groundwater level, m/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Climate scenarios</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>B2</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>B2</td>
</tr>
<tr>
<td>$qP_3$</td>
<td>8.148</td>
<td>8.45</td>
</tr>
<tr>
<td>$qP_2-3$</td>
<td>14.51</td>
<td>15.00</td>
</tr>
<tr>
<td>$qP_1$</td>
<td>4.93</td>
<td>5.47</td>
</tr>
<tr>
<td>$n_2^2$</td>
<td>37.27</td>
<td>39.08</td>
</tr>
<tr>
<td>$n_2^1$</td>
<td>1.61</td>
<td>1.53</td>
</tr>
<tr>
<td>$n_1^3$</td>
<td>20.53</td>
<td>20.69</td>
</tr>
</tbody>
</table>

Fig. 13 shows an example of the yearly changes in storage for the whole MD aquifer system under three different climate scenarios. There is a decrease trend of the yearly change in storage for all three scenarios of climate. The yearly changes in storage are of negative values (except for those in 2030 and in 2040 of scenarios A2), it means that the groundwater resources in MD will still be under depletion situation.
The area having the total dissolved solid (TDS) in groundwater greater than 1000mg/l is considered to be area having saline groundwater.

Table 4 shows the increase and the average rate of increase in areas having saline groundwater in 2100 in comparison with that of 2010 of all aquifers. These areas increase in all aquifer, except for aquifer qh. The rate of increase in these areas is largest for scenarios A2 and is almost the same for scenarios B1 and B2.

Table 4. Increase in area having saline groundwater in 2100 in comparison with that of 2010

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>qh</th>
<th>qp3</th>
<th>qp2-3</th>
<th>qp1</th>
<th>n2</th>
<th>n2'</th>
<th>n3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in areas having saline GW in comparison with that of 2010, km²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario B1</td>
<td>-1214</td>
<td>753</td>
<td>5389</td>
<td>4033</td>
<td>1471</td>
<td>1695</td>
<td>2637</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>-1064</td>
<td>771</td>
<td>5407</td>
<td>4051</td>
<td>1472</td>
<td>1694</td>
<td>2638</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>766</td>
<td>2538</td>
<td>7174</td>
<td>5818</td>
<td>3188</td>
<td>3156</td>
<td>3429</td>
</tr>
<tr>
<td>The rate of increase in areas having saline groundwater, km²/year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario B1</td>
<td>-13.49</td>
<td>8.37</td>
<td>59.88</td>
<td>44.82</td>
<td>16.35</td>
<td>18.83</td>
<td>29.31</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>-11.82</td>
<td>8.57</td>
<td>60.08</td>
<td>45.02</td>
<td>16.36</td>
<td>18.83</td>
<td>29.31</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>8.51</td>
<td>28.20</td>
<td>79.71</td>
<td>64.64</td>
<td>35.43</td>
<td>35.07</td>
<td>38.10</td>
</tr>
</tbody>
</table>

Fig. 14 shows that the increase in these areas is largest in aquifer qp2-3 and qp1. The reason for this maybe due to the two aquifers is still impacted by not only the climate changes but also by the continuous groundwater abstraction.

Figure 14. Increase in areas having saline groundwater in 2100 in comparison with that of 2010.
Discussion

The rate of decrease in groundwater levels in periods of 2000-2010 (impacts by groundwater abstraction) is greater than that of the periods 2010-2100 are 5, 9, 20, 4, 89 and 10 folds for aquifers q\(p_3\), q\(p_{2,3}\), q\(p_1\), n\(2\) \(^2\), n\(2\) \(^1\) và n\(1\) \(^3\), respectively (Table 5). It is clear that groundwater abstraction is main reason to make groundwater elevation to decrease dramatically, and impact of groundwater abstraction is much larger than that of climate changes.

Table 5. Comparison of the rate of the decrease in groundwater elevation in period 2000-2010 and 2010-2100

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Rate of decrease in groundwater elevation in periods of 2010 -2100, m/year</th>
<th>Rate of decrease in groundwater elevation in periods of 2000 -2010, m/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>q(p_3)</td>
<td>0.091 - 0.114</td>
<td>0.50</td>
</tr>
<tr>
<td>q(p_{2,3})</td>
<td>0.161 - 0.194</td>
<td>1.76</td>
</tr>
<tr>
<td>q(p_1)</td>
<td>0.055 - 0.061</td>
<td>1.24</td>
</tr>
<tr>
<td>n(2) (^2)</td>
<td>0.414 - 0.495</td>
<td>1.98</td>
</tr>
<tr>
<td>n(2) (^1)</td>
<td>0.016 - 0.018</td>
<td>1.42</td>
</tr>
<tr>
<td>n(1) (^3)</td>
<td>0.228 - 0.248</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Among three scenarios of climate, both the groundwater levels and the yearly changes in storage are decreased and the yearly changes in storage is of negative values, while the areas having TDS values greater than 1000 mg/l increase from low emission scenarios to high emission scenarios. The reasons for that can be explained by the decrease of groundwater recharge under three scenarios of climate.

Conclusions and recommendations

Impacts of groundwater abstraction and climate change on groundwater resources in Mekong Delta can be quantified by the groundwater flow and transportation models. Among the required inputs for these models, groundwater recharge was calculated by WetSpass package in which all the climate change variables such as rainfall, evaporation, temperature… are included. In order to improve the accuracy of the models, data for calibration and validation of WetSpass model to calculate GW recharge, data of river stages, sea level, surface water saline intrusion, flood…are needed to collect. And groundwater abstraction in future has not yet been included in all scenario simulations to assess more accuracy the impacts of both GW abstraction activities and climate change on GW resources.

The results show that, groundwater abstraction is of much more strong impacts on groundwater resources than the climate changes and in the future groundwater resources of the study area is under depletion. Therefore the orientation for development of groundwater resources in future should concentrate to reduce the groundwater abstraction, to improve groundwater potential by means of artificial recharge and to use more surface water resources.
3. Project information dissemination products

The project has accumulated a wide range of knowledge and experiences over its two year period. Mainly three types of publication will be targeted for wider dissemination.

**Final project report**: this report will be mainly used for submission to the ADB, which has provided funding to this project. This report will incorporate details about the project outline, experiences and findings of the series of planning and implementation workshop that was an integral part of the project design, findings of the case studies and key conclusions and recommendations.

**Academic journals**: This is also a part of the capacity development of the project members who were directly involved in implementing case studies. All case studies have accumulated significant amount of scientific data during the course of the development of the groundwater models. Similarly, the groundwater models were used to analyse various scenarios in order to find solutions to groundwater problems. This rich information will be utilised to draft journal papers for the scientific community. Necessary technical support for publishing the journal paper will be provided by UNESCO-IHE.

**Policy Report**: The policy report will be a synthesis of the main findings. The main purpose of this report is for outreach purpose as well as to inform relevant policy and decisions makers about the results, opportunities for financing interventions for ADB and cities, and to show potential follow-up actions. The report will also highlight the methodological approach that was mainly designed to carry out participatory research for capacity building. It will also summarize the similarities and differences of the cases studies that also acted as a learning experience to all project members. Then it will summarise the key lessons and suggest measures for solving coastal groundwater management in Asian cities.

All of the publications will be shared through various channels such as conferences, forums, online networks, in addition to IGES Groundwater Knowledge Hub and UNESCO-IHE webpages.

4. Development of the new projects

A new project proposal on Feasibility study and pilot implementation of artificial groundwater recharge schemes in Southeast Asia was presented and discussed as a follow-up of the current project.

Artificial groundwater recharge is increasingly seen as a viable technology for mitigating climate change impacts, especially drought. Artificial groundwater recharge technology has not yet widely used in Southeast Asia, in particular, not applied in the case study areas. Demonstrations of effectiveness of the artificial groundwater recharge schemes in controlling groundwater depletion, seawater intrusion and land subsidence through pilot projects will stimulate applications of this technology in the region.

The objectives of the proposed project are:

- Test effectiveness of using artificial groundwater recharge in restoring depleted aquifer storage, protecting seawater intrusion, and sustaining urban water supply;
- Select best site and suitable technology for artificial recharge in each case study area through a comprehensive feasibility study;
Pilot implementation of artificial recharge schemes where it is feasible;
Learn experiences from implementing artificial groundwater recharge schemes in different physical and social environments;
Develop knowledge bases for artificial groundwater recharge in Southeast Asia.

The project activities will include:
1) Training workshop at UNESCO-IHE: training of project members on design and implementation of artificial groundwater recharge schemes.
2) Feasibility study of artificial recharge schemes: identification of objectives, selection of suitable sites; choice of water sources; selection of recharge methods, cost estimate, impact assessment, and management.
3) Design and construction of the schemes: including water intake structure; constructed wetlands for pre-treatment of water sources; and infiltration basin/wells.
4) Test and monitoring of the schemes: installation of monitoring wells; measuring recharge rate; measuring groundwater levels; water quality sampling and analysis.
5) Evaluation of performance of schemes: compare different pilot schemes in terms of recharge efficiency and water quality improvement.

A project proposal will be developed and submitted to UNESCO-IHE and ADB for finance.

5. Conclusions
Coastal areas in Southeast Asian countries are facing serious problems of groundwater depletion, contamination, saltwater intrusion, and land subsidence. In Cangzhou and Laizhou Bay of China, rapid population and economic growth in last 30 years have put great pressure on groundwater over-exploitation. Regional cones of groundwater depression have been formed. Negative consequences are saltwater intrusion and land subsidence. In Jakarta Basin of Indonesia, deep groundwater abstraction in the coastal zone has caused seawater intrusion and land subsidence. In Metro Cebu of Philippines, unmanaged groundwater abstraction has caused seawater intrusion. In Mekong Delta of Vietnam, deep groundwater is sensitive to extensive abstraction and climate change.

A lack of good quality data in space and time limits in-depth analysis of pressures and impacts. Preliminary modelling studies in this project have reviewed the possible causes of the problems and identified management scenarios for mitigating the impacts. Models should be improved with additional data collection in the fields to improve accuracy and reliability in predictions.

Project members have shared experiences and learned methodologies in solving groundwater problems in coastal areas. A following-up project will up-scale project impacts by implementing some effective mitigating measures in the region.

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