

INTEGRATED MANAGEMENT OF URBAN GROUNDWATER IN ASIAN CITIES

M. Taniguchi¹

(1) Research Institute for Humanity and Nature, Kyoto 603-8047, Japan, makoto@chikyu.ac.jp

ABSTRACT

This paper discusses an integrated management approach of urban groundwater in Asian cities from the points of view of climate change, development stages of cities, and new methods in evaluating groundwater in urban area. Changes in reliable water resources between groundwater and surface water occurred due to climate change and urban development. New techniques such as Satellite GRACE and stable isotope/chemical tracers allow us to evaluate the changes in groundwater storage and groundwater flow systems in urban areas. A new concept of groundwater "too slow water", which is dependent on residence time is important in water management and in the sustainable use of groundwater.

Key words: groundwater, climate change, development stage of cities, subsurface environmental problems, too slow water

1. INTRODUCTION

Changes in reliable water resources between groundwater and surface water have occurred in many Asian cities depending on the development stages of urbanization and climate change (Taniguchi 2005). Although surface water is relatively easy to evaluate, changes in regional groundwater storage and integrated management of urban groundwater remain a difficult task under the conditions of climate change. Recent techniques using remote gravity measurement and isotope data to evaluate groundwater flow systems may be able to evaluate the regional scale of groundwater issues in urban areas.

Regarding material (contaminant) transport to the coast, direct groundwater discharge is recently recognized as a significant water and material pathway from land to ocean (Burnett *et al.*, 2001, Taniguchi *et al.*, 2002). Most of the major cities in Asia are located in the coastal zone, therefore material and contaminant transports by groundwater is a key to understanding coastal water pollution and its effects on associated ecosystems.

Recent global warming is considered an environmental issue only above the ground. However, subsurface temperatures are also affected by global warming (Huang *et al.*, 2000). In addition, the heat island effect due to urbanization creates subsurface thermal contamination in many cities. The combined effects of heat island and global warming reaches up to more than 100 meters below the surface (Taniguchi *et al.*, 1999), and the increased rate of subsurface temperature in cities by heat island effect is much larger than that of global warming. The heat island effect on subsurface temperature is an important global groundwater quality issue, because it may alter the groundwater systems chemically and microbiologically (Knorr *et al.*, 2005, Taniguchi *et al.*, 2007).

Subsurface environmental problems such as land subsidence due to excessive groundwater pumping, groundwater contamination and subsurface thermal anomalies have occurred repeatedly in large Asian cities with a time lag depending on the development stages of urbanization. Therefore, we may be able to assess future scenarios if we can evaluate the relationships between subsurface environmental problems and the development stage of the city. In addition to the effects of urbanization on subsurface environment, the effects of climate change should be incorporated in an integrated management of urban groundwater. The primary goal of this study is to formulate an integrated management of urban groundwater under the condition of climate change and various subsurface environmental problems, such as extreme subsidence, groundwater contamination, and subsurface thermal anomalies.

2. CHANGES IN RELIABLE WATER RESOURCES BETWEEN SURFACE WATER AND GROUNDWATER UNDER THE CONDITION OF INCREASED DEMAND AND CLIMATE CHANGE

Subsidence due to excessive groundwater pumping has occurred repeatedly in large Asian cities due to the increase in demand for water resources. (Fig.1 and Fig.2). Changes in reliable water resources, from groundwater to surface water, have been done in many cases, however, subsidence has not been prevented in many areas. This resulted in a greater risk of flooding in many coastal cities in Asia under the condition of climate change.

On the other hand, although land subsidence in the Tokyo and Osaka areas have ceased due to regulation of groundwater pumping, the associated increase in groundwater level has caused new types of damages, brought by buoyant forces to the underground infrastructures (e.g., subways), which were constructed during the drawdown period (Fig.3).

Increases in variation of precipitation due to global warming have caused a change in water resource, from surface water to groundwater, in some Asian countries. Taiwan is now using more groundwater because of the decrease in reliability using surface water stored behind dams (Wang, 2005, Fig.4).

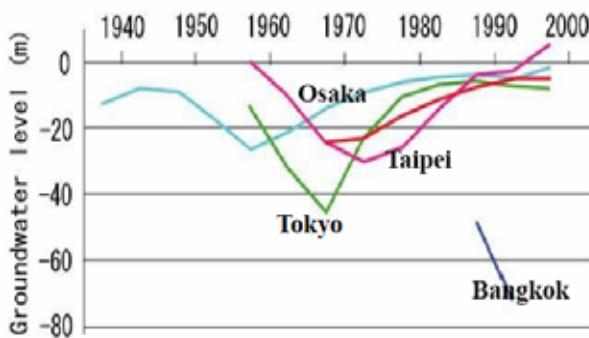


Fig.1 Changes in groundwater levels

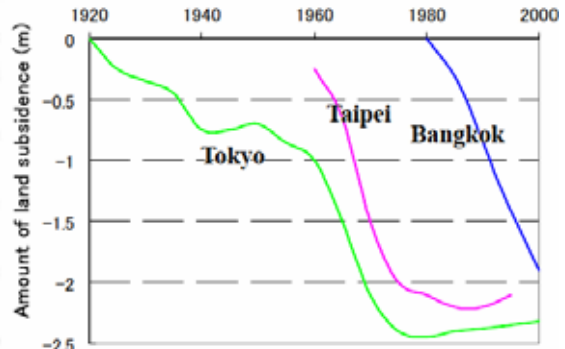


Fig.2 Changes in the amount of land subsidence

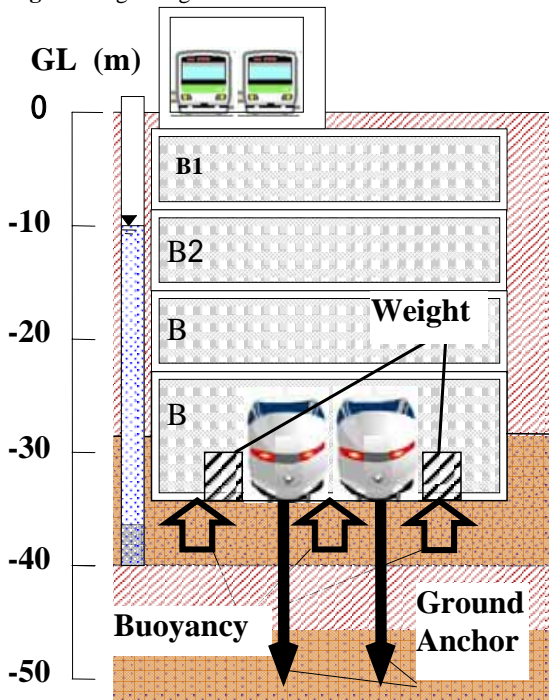


Fig.3 Procedures against buoyancy due to increase in groundwater level by using weight and ground anchor (Nikkei Construction, 2005)

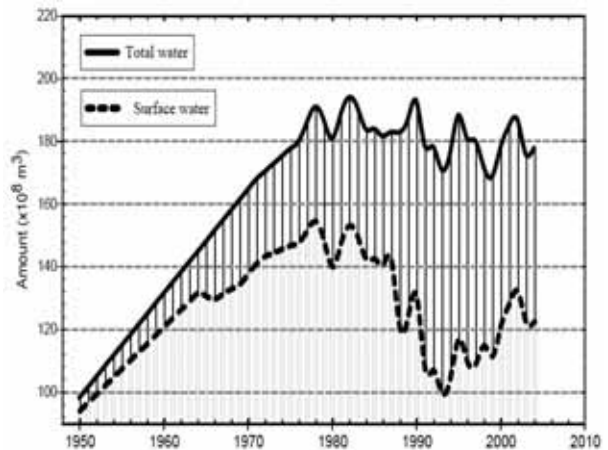


Fig.4 Change of water uses in Taiwan (Wang, 2005)

3. GRAVITY MEASUREMENT IN SITU AND SATELLITE GRACE FOR EVALUATING GROUNDWATER STORAGE CHANGE

In order to establish a new technique for monitoring groundwater variations in urban areas, precise in-situ gravimetry measurement and satellite gravimetry can be applied. For precise gravimetry on land, the effects of groundwater variations are one of the largest sources of gravity anomalies, especially for high-precision gravity measurements using superconducting gravimeters and/or absolute gravimeters. Conversely, this means that the gravitational effects give us important information about the hydrological characteristics in the area concerned, if the effects are appropriately analyzed. On the other hand, satellite gravimetry is a new technique which is expected to reveal global water circulations. In our study, we will attempt to utilize this new technology for analysis of local as well as regional scale phenomena.

Satellite gravity missions are new techniques of the 21st Century (National Research Council, 1997). The GRACE (Gravity Recovery And Climate Experiment) mission which was launched in March 2002 is important in terms of time varying gravity fields. It has been shown that GRACE data provided temporal variations of the Earth's gravity fields due to groundwater changes in the earth (Tapley *et al.*, 2004). Even though it may be difficult to employ GRACE data directly for studies of local or urban scale phenomena, it is important to see more large-scale gravity changes as a background. There is no doubt that GRACE data contributes to the study of global-scale water circulations and/or larger scale gravity variations.

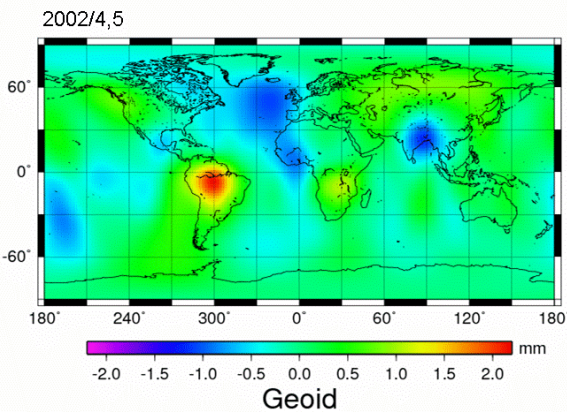


Fig.5 Gravity anomalies obtained from GRACE for April and May 2002 with mean radius of 1000km (Fukuda *et al.*, 2005).

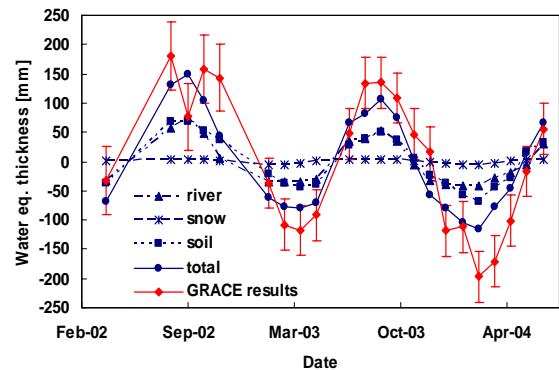


Fig.6 Comparisons of GRACE and model data for four river basins (Chao Phraya, Mekong, Salween and Irrawaddy) (Fukuda *et al.*, 2005)

4. TRACERS TO EVALUATE REGIONAL GROUNDWATER FLOW SYSTEM AND RESIDENCE TIME

Evaluations of changes in groundwater storage and groundwater flow systems are important in the management of water in an urban area. Recent techniques using hydrological and geochemical data including isotopic compositions (e.g. Kr-85, O-18, D, C-14) will allow us to understand the origin of the water and the residence time of the water which is a key factor in water management. Residence time of groundwater is essentially important in order to elucidate the hydrological processes in a certain region. The radio isotope of ^3H has been used for dating of groundwater and surface water since the 1960s, however the ^3H is ineffective recently, because the ^3H concentration of precipitation has been approximately under 5 T.U. during the last 10 years.

Chlorofluorocarbons (CFCs) have been broadly used for dating of young groundwater instead of ^3H since the 1990s, because (1) the atmospheric mixing ratios of these compounds are known and/or

have been reconstructed over the past 50 years (Fig. 7); and (2) concentrations in air and young water are relatively high and can be measured (Busenberg and Plummer, 2000).

Sampling of spring and ground water was performed by Tsujimura *et al* (2007) to apply CFCs in Shiranui catchment, a region along the coastal area in Kumamoto Prefecture, southwest of Japan, and Ashigara, a suburban region in Kanagawa prefecture, 60 km southwest of Tokyo where the groundwater flow system has been observed by potential measurement using boreholes and tracer approaches. The observed CFCs concentrations of spring and ground water are within the range of those in the present atmosphere in Shiranui, whereas those of Ashigara are much higher than those of the present atmosphere. A contamination by factories using CFCs should affect those of the groundwater in Ashigara. Residence times of spring and ground water were estimated to be 15 years in headwater and 25 years in mid-stream region of Shiranui. These results are reasonable considering the groundwater flow system in the Shiranui catchment.

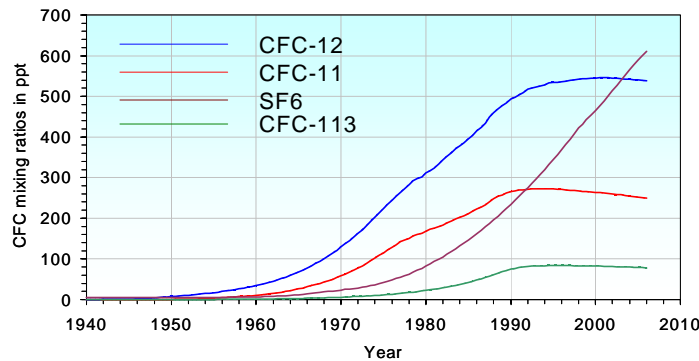


Fig. 7 Temporal change of CFCs concentration in the atmosphere (USGS, 2006).

5. GROUNDWATER CONTAMINATION IN COASTAL CITIES AND MATERIAL TRANSPORTS INTO THE OCEAN

Many Asian cities are located at the coastal zone which is vulnerable to climate change. The main anthropogenic source of nitrate is agricultural fertilizer around the city and wastewater within the city. On the other hand, the main sources of trace metals are air pollution, industrial waste, and mineral processing. The development stage of the mega-cities is related to contaminant type and flux. During the early stages of development, urban areas have inferior infrastructures, therefore various wastes are released. Some wastes are discharged directly to the ocean through rivers, but some are accumulated in the subsurface zone and will discharge via groundwater pathways. The later discharge will occur a long time after the development of infrastructures.

To reconstruct contaminant fluxes, Sr-Pb isotopic ratios can be used as powerful tracers to reconstruct the source and pathway of trace metals in underground environment, which has been changed with the expansion of mega-cities. Especially, the ratio of Ar and N in subsurface waters and the N isotopic ratio may be used for reconstruction of nitrate concentration before reactions as denitrification.

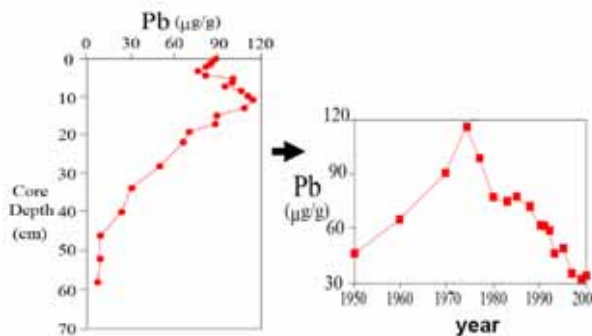


Fig.8 Reconstruction of contaminant flux (Graney and Eriksen, 2004).

Another important aspect of the subsurface environment concerns material (contaminant) transport to the coast. Research over the last few years has shown that direct groundwater discharge to the coastal zone is a significant water and material pathway from land to ocean (Moore, 1996; Taniguchi *et al.*, 2002; Burnett *et al.*, 2003). We hypothesize that many water quality and associated problems influencing coastal environments around the world today are related to past and on-going contamination of terrestrial groundwater because that groundwater is now seeping out along many shorelines. For example, chronic inputs of fertilizers and sewage on land over several decades have resulted in higher groundwater nitrogen, and the slow yet persistent discharge along the coast, may eventually result in coastal marine eutrophication. Such inputs may thus contribute to the increased occurrences of coastal hypoxia, nuisance algal blooms, and associated ecosystem consequences. Since most Asian cities are located along the coast, material and contaminant transport by groundwater is a key to understanding present and future coastal water pollution and its effects on associated ecosystems (Capone and Bautista, 1985).

While investigations of groundwater discharge into the coastal zone have increased dramatically over the last several years, few studies were performed in and around the urban centers and very few were conducted in Asia except Japan (Taniguchi *et al.*, 2002). This may be a significant oversight as the region is characterized by many features that are typically present in areas of high SGD. For example, many parts of Southeast Asia contain regions of high rainfall, karst terrains, and high relief.

6. HEAT ISLAND EFFECTS ON SUBSURFACE DUE TO URBANIZATION AND GLOBAL WARMING

Although global warming is considered a serious contemporary environmental issue, discussion of the phenomena is limited to the issues above the ground. However, subsurface temperatures are also affected by surface warming (Huang *et al.*, 2000). In addition, the “heat island effect” due to urbanization creates subsurface thermal anomalies in many cities (Taniguchi and Uemura, 2005). The combined effects of these two processes may reach up to more than 100 meters below the surface, and can have potential consequences on groundwater system. The effect of heat island due to urbanization and global warming on subsurface temperature is one of the global groundwater quality issues because increased subsurface temperature alters groundwater system chemically and microbiologically through geochemical and geobiological reactions (e.g., Knorr *et al.*, 2005) that are temperature sensitive, which may increase degradation of groundwater resources. This is related to the groundwater quality issue of UNESCO-GRAPHIC (Groundwater Resources under the Pressures of Humanity and Climate Change) project (Aureli and Taniguchi, 2006).

Subsurface temperature is used to reconstruct past climate change because the signature of changes in ground surface temperature is preserved in the subsurface thermal regime (Pollack *et al.*, 1998; Huang *et al.*, 2000, Taniguchi *et al.*, 2003). Recent air temperature in cities is increased by global warming and heat island effects due to urbanization. Studies on the effects of heat from urban area on subsurface temperature are limited, but have been done in some urbanized areas. Other studies on the effects of surface warming due to urbanization are also limited to studies within local areas. We may also be able to separate both urbanization and global warming effects by comparing the results with global meteorological studies (Kalnay and Cai, 2003; Kalnay *et al.*, 2006) and both surface warming and fluid flow effects, however we certainly need additional future work.

Average subsurface temperature profiles in four Asian cities (Tokyo, Osaka (Figure 9), Seoul, and Bangkok) were compared by Taniguchi *et al.*, (2007) and analyzed to evaluate the effects of surface warming. The magnitude of surface warming is largest in Tokyo (2.8 C), followed by Seoul (2.5 C), Osaka (2.2 C), and Bangkok (1.8 C). Comparisons between analytical solutions and observations show that the mean depth of deviation from the regional geothermal gradient in each urban area may be one of the indicators of the history of urbanization, such as the time from the start of the additional heat from urbanization. These results agreed with air temperature records in the cities during the last

100 years. Measurement of subsurface temperature data provides important information for understanding the joint effects of urbanization and global warming on groundwater systems.

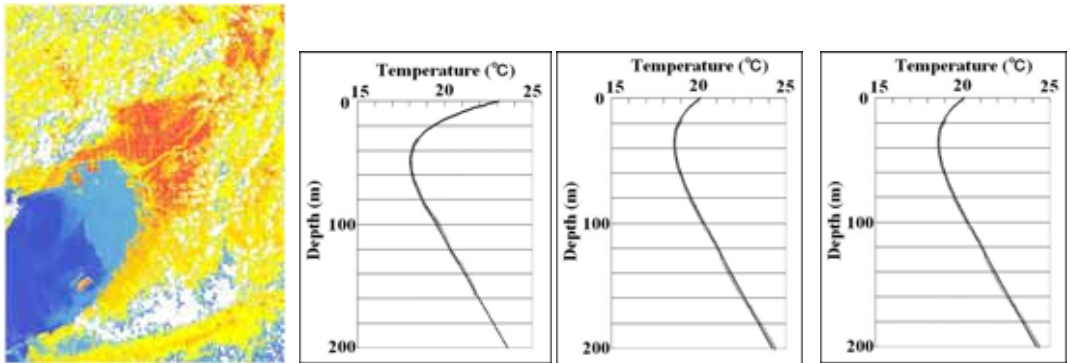


Fig.9 Subsurface thermal anomalies in urban area of Osaka

7. INTEGRATED WATER MANAGEMENT UNDER “WATER IMBALANCE” CONDITION

One of the key factors in integrated water management is management under the condition of “water imbalance”. Water imbalances exist in various scale of time and space including urban area, and bring us problems of “too much water” such as flooding and “too little water” like drought. Water imbalances in space are caused by nature globally (climatic zone) and locally (access to the water bodies), and by human (population, industries, agriculture etc.). Water imbalances in time are caused by changes such as climate change, and seasonal and annual variations. Water imbalances in nature-human relationship also exist in society (economy, governance etc.) and culture (tradition, local knowledge, etc.). Is the current status of “water imbalance” acceptable for future societies? Is it better to balance “water imbalance” on the earth including urban areas?

The first RIHN international symposium on “Water and Human Life” discussed this water imbalance (Taniguchi, 2007), and found that “too far water” such as virtual water or “too slow water” such as deep groundwater has an impact on water imbalance, therefore we should pay more attention to these aspects to ensure sustainability. (Fig.9). This is true when we use deep groundwater as fossil resources, however, the regulation of groundwater pumping such as in Tokyo has caused new types of damages by buoyant force to the underground infrastructures (e.g., subways) which were constructed during the drawdown period (Fig.3). This is attributed to the fast water circulation in the shallow aquifer at humid region. Therefore, precious groundwater resources should be considered and not only “too much – too little water”, but also “too fast – too slow water”, taking into account the residence time of the water cycle.

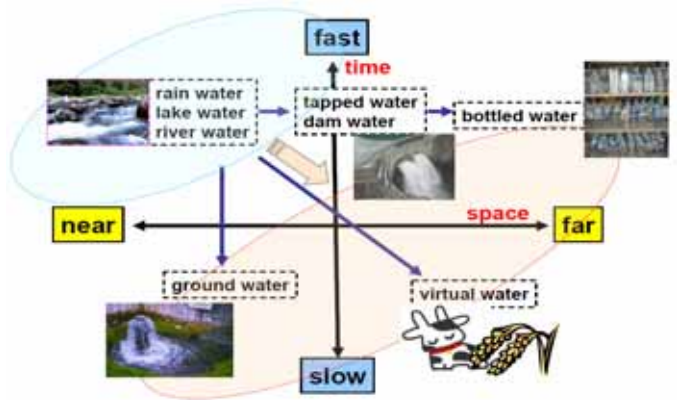


Fig.9 Water imbalance; “fast-slow” water and “near-far” water

8. CONCLUSIONS

We have discussed here an integrated management approach of urban groundwater in Asian cities by taking into consideration changes in reliable water resources depending on climate change and development stage of the city, new methodologies for evaluating the changes in groundwater storage and groundwater flow system using Satellite GRACE and tracers such as CFC, groundwater contamination and subsurface anomalies, and a new concept for groundwater as “too slow water” in water imbalance situation. Complex global-local linkages on water are found in many Asian cities, and local studies with global perspective are required in making policy decisions to solve the problems.

Acknowledgement

This study has been done under the framework of UNESCO-GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate) project. The author acknowledges Dr. Alice Aureli, and Dr. Jose Luis, UNESCO/IHP, for their support from the GRAPHIC project. This study is also supported by the RIHN (Research Institute for Humanity and Nature) project 2-4 “Human impacts on urban subsurface environment”.

REFERENCES

- Aureli, A. and Taniguchi M. (2005): Groundwater Assessment under the Pressures of Humanity and Climate Change, UNESCO, 19p.
- Burnett, W.C., Taniguchi, M., Oberdorfer J.A. (2001): Measurement and significance of the direct discharge of groundwater into the coastal zone. *J. Sea Res.* 46(2), 109-116.
- Burnett, W.C., Bokuniewicz, H., Huettel, M., Moore, W.S., and Taniguchi, S. (2003): Groundwater and pore water inputs to the coastal zone, *Biogeochemistry*, 66, 3-33.
- Busenberg, E. and Plummer, L.N. (2000): Dating young groundwater with sulfur hexafluoride: Natural and anthropogenic sources of sulfur hexafluoride. *Water Resources Research*, 36, 3011-3030.
- Capone DG, and Bautista MF. 1985. A groundwater source of nitrate in nearshore marine sediments, *Nature*, 313, 214-216.
- Fukuda, Y. Yamamoto, K., Nakaegawa, T. and Nishijima, J. (2005) Monitoring of the ground water variation in urban area by combining GRACE data and in-situ gravity measurement, *Human impacts on Urban Subsurface Environment*. Proceeding of RIHN International Symposium, 26-31.
- Huang, S., Pollack H.N. and Shen, Po-Yu (2000): Temperature trends over the past five centuries reconstructed from borehole temperatures, *Nature*, 403, 756-758.
- Moore, W.S. (1996): Large groundwater inputs to coastal waters revealed by ²²⁶Ra enrichments. *Nature* 380, 612-614.
- Kalnay, E. and Cai, M. (2003): Impact of urbanization and land-use change on climate, *Nature*, 423(6939), 528-531.
- Kalnay E., Cai, M., Li, H., and Tobin, J. (2006): Estimation of the impact of land-surface forcings on temperature trends in eastern United States, *J. Geophys. Res.*, 111, D06106, doi:10.1029/2005JD006555.
- Knorr, W., Prentice, I. C., House, J. I. and Holland E. A. (2005): Long-term sensitivity of soil carbon turnover to warming. *Nature* 433, 298-301, doi:10.1038/nature03226.
- Moore, W.S. (1996): Large groundwater inputs to coastal waters revealed by ²²⁶Ra enrichments. *Nature* 380, 612-614.
- National Research Council (NRC) (1997): Satellite gravity and the geosphere, National Academy Press, Washington, D.C., 1-112.
- Nikkei Construction (2005): Underground structure in Tokyo.
- Pollack, H.N., Huang, S., and Shen, P.Y. (1998): Climate Change Record in Subsurface Temperatures: A Global Perspective. *Science*, 282: 279-281.
- Taniguchi, M, Shimada, J., Tanaka, T., Kayane, I., Sakura, Y., Shimano, Y., Dapaah-Siakwan, S. and Kawashima, S. (1999): Disturbances of temperature-depth profiles due to surface climate-change and

- subsurface water flow: (1) An effect of linear increase in surface temperature caused by global warming and urbanization in the Tokyo metropolitan area, Japan, *Water Resour. Res.*, 35, 1507-1517.
- Taniguchi, M., Burnett, W.C., Cable, J.E, and Turner, J.V. (2002): Investigation of submarine groundwater discharge, *Hydrol. Process.*, 16, 2115-2129.
- Taniguchi M. (2005): Introduction of RIHN project 2-4, *Human impacts on Urban Subsurface Environment*. Proceeding of RIHN International Symposium, 1-8.
- Taniguchi, M. and Uemura T. (2005), Effects of urbanization and groundwater flow on the subsurface temperature in Osaka, Japan. *Physics of Earth and Planetary Interior*, 152, 305-313.
- Taniguchi, M., Uemura T., and Y. Sakura, Y. (2005): Effects of urbanization and groundwater flow on subsurface temperature in three mega cities, Japan., *J. Geophys. Eng.*, 2, 320-325.
- Taniguchi, M. (2007): Water Imbalances, Proceeding of 1st International Symposium of RIHN, 72-73.
- Taniguchi, M., Uemura T., and Jago-on K. (2007): Combined effects of urbanization and global warming on subsurface temperature in four Asian cities *Vadose Zone Journal*, (in press).
- Tapley et al., (2004): GRACE Measurements of Mass Variability in the Earth System, *Science*, Vol. 305, 23, July 2004, 503-505.
- Tsujimura M. Asai, K., Ohta, K., Hasegawa, K., Shimada, J., and Taniguchi, M. (2007): Age dating of groundwater using CFCs as a tracer, News Letter for RIHN Project “*Human impacts on Urban Subsurface Environment*” Vol. 3, 12-15.
- Wang, C-H (2005): Subsurface environmental changes in Taipei, Taiwan: Current status, *Human impacts on Urban Subsurface Environment*. Proceeding of RIHN International Symposium, 55-59.
- United States Geological Survey (2006): Chlorofluorocarbon Analysis, Web Site: <http://water.usgs.gov/lab/chlorofluorocarbons/> (accessed on Jan. 16, 2006).