DETERMINATION OF SUSTAINABLE YIELD IN URBAN GROUNDWATER SYSTEMS

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ABSTRACT.

As the world's population becomes increasingly urbanized and many cities rely on local aquifers for water supply, the issue of sustainable groundwater development is critical. But several complicating factors in urban areas increase the difficulty of determining the sustainable yield: infiltration following precipitation is changed by the reduction of evapotranspiration together with the augmentation of runoff, and additional artificial water sources contribute to groundwater recharge. "Safe yield" has long been the principle for groundwater exploitation. However, ignoring the changes in the groundwater regime caused by abstraction, it has limits and often leads to the overexploitation of groundwater. This paper develops a water budget equation for sustainable groundwater systems, taking into consideration the boundary conditions of a city and potential urban recharge and discharge. A case study of Beijing City, China, is presented. Sustainable yield of groundwater resources of urban Beijing is estimated to be 666~1964 Mm^3/year in 1990 and 773~2090 Mm^3/year in 2000.

1 INTRODUCTION

With the rapid growth of population and industry, water demand in urban areas has greatly increased during the past decades. But as the pollution of surface waters is quite serious in many cities, groundwater has become one of the most important water resources. Therefore, sustainable use of groundwater becomes more and more imperative for sustainable development of cities.

There are surprisingly still many misconceptions about the concept of a sustainable groundwater resource potential, as *Bredehoeft et al*. [1982] have shown. "Safe yield", which allows water users to abstract no more than the natural recharge, is the most widely used principle instructing groundwater abstraction. But, focusing only on natural recharge, it ignores the change of the groundwater flow system brought by exploitation. *Bredehoeft et al*. [1982] showed that the pumping rate should be dependent on the increase in natural recharge and the decrease in natural discharge, but independent of the magnitude of natural recharge. Unfortunately, since this theory has often been neglected, "safe yield" is still the basis of groundwater development [*Bredehoeft,* 2002].

The application of this principle often causes extensive abstraction and depletes groundwater storage, especially in developing countries, leading to environmental, engineering, social and economical problems. Overexploitation has brought seawater intrusion in coastal cities and damage groundwater-dependent ecosystems. The declining of groundwater levels often resulted in land subsidence, damage to urban infrastructure, and even failure of well casings. In addition, the lowering of groundwater levels also induced contamination from surface waters and other sources of pollution in urban areas, such as landfill leachates, leakage from sewage systems, underground storage tanks, etc., degrading the quality of groundwater. If the source of contamination is not discovered and addressed in time, the water supply will threaten the health of city dwellers. To meet water demand and reduce groundwater problems, cities have to import water from periurban or even further areas, thus leading to conflict between urban and agricultural water uses. These negative effects slow, or even obstruct the development of the economy and society.

This paper develops a water budget equation for sustainable urban groundwater systems, taking into consideration the artificial sources of groundwater recharge and alteration of groundwater systems due to development in an urban context. As an example, the water budget equation is applied to Beijing City to determine the sustainable yield of groundwater resources in its urban area. Nevertheless, there are uncertainties in this budget equation, such as the leakage from the water mains, the possible role of sewer systems as a source of recharge or discharge, etc. This paper gives a preliminary estimate of the range of fluxes for the groundwater budget equation; hence the sustainable yield is determined.

2 THE WATER BUDGET MYTH

Sustainable development of groundwater requires reliable management of groundwater abstraction and quality control. What quantity of groundwater can be reasonably used without impacts on its quality and the use of next generations is a key issue. "Safe yield", defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge [*Sophocleous*, 1997], has long been the principle of groundwater abstraction. However, this approach is limited, ignoring the change of a groundwater flow system caused by abstraction. *Sophocleous* [2000] found that the safe-yield policy has slowed the decline of groundwater levels in Western Kansas, but has not stopped it.

Actually, as early as 1982, the work of *Bredehoeft et al.* [1982] points to sustainable groundwater development. As Figure 1a shows, under virgin conditions, the groundwater system keeps equilibrium when the natural recharge is equal to the natural discharge:

$$R_0 - D_0 = 0 \qquad (2.1)$$

where R_0 (=P-E-R) is the mean recharge under virgin conditions; D_0 is the mean discharge under virgin conditions; P is precipitation; E is evapotranspiration; and R is runoff. When groundwater is abstracted from aquifers, the equilibrium condition is disturbed and natural recharge and discharge change (Figure 1b). The groundwater budget equation becomes:

$$\frac{dV}{dt} = \Delta R_0 - \Delta D_0 - Q_P + \sum \Delta Q_i \qquad (2.2)$$

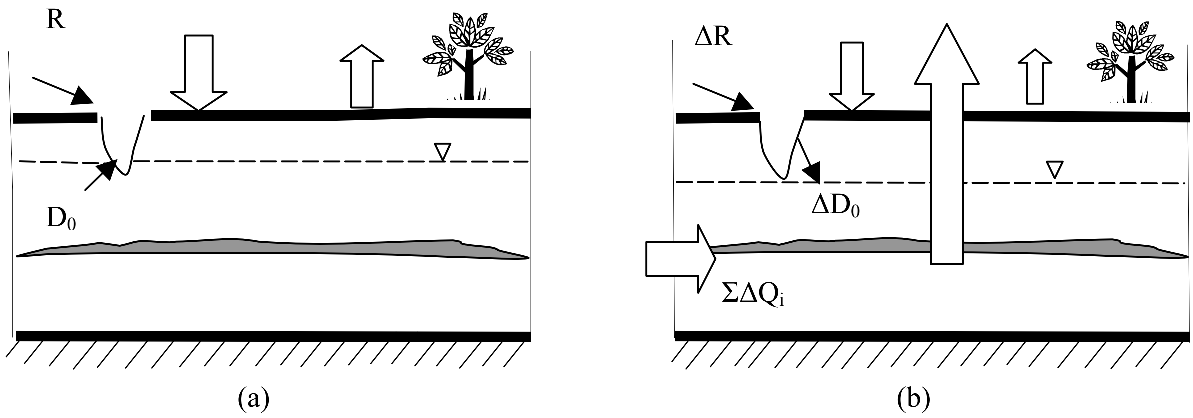

Figure 1. The water budget of a multi-aquifer system: (a) virgin conditions; (b) after pumping begins.

where ΔR_0 is the positive change in the mean recharge [L^3T^{-1}];

ΔD_0 is the positive change in the mean discharge [L^3T^{-1}];

Q_P is the pumping rate [L^3T^{-1}];

ΔQ_i is the change in groundwater flux from the virgin conditions $[L^3T^{-1}]$; ;

dV/dt is the rate at which water is removed from groundwater storage $[L^3T^{-1}]$.

When there is no change in groundwater storage, a new equilibrium is reached. *Bredehoeft et al.* [1982] conclude that the natural recharge and discharge have no effects on the sustainable yield, which is different from the long-time predominant principle of groundwater abstraction. Instead, the changes in natural recharge and discharge are the determinants of sustainable groundwater abstraction.

3 SUSTAINABLE WATER BUDGET FOR URBAN GROUNDWATER SYSTEMS

In urban areas, much of the surface becomes impermeable with trees cut down and buildings and roads constructed, thus changing the infiltration rate of precipitation. Other than altering natural recharge and discharge, urbanization has created extra sources of groundwater recharge. These factors make the groundwater regime more complex in urban areas

3.1 Change in natural recharge and discharge

Urbanization can change the components of natural recharge: precipitation, evapotranspiration, and runoff. Although precipitation may have a tendency to increase due to heat islands effect [*Changnon et al.,* 1977], in most cases precipitation is considered unaffected under urbanization [*Jia et al.,* 2002; *Kim et al.,* 2001; *Mitchell et al.,* 2001]. Evapotranspiration is reduced greatly as cities expand; *Howard* [1997] suggests that evapotranspiration will decrease by 32% for a typical urban context with 50% impermeable land. Another effect of urbanization is the increase in surface runoff. Runoff is reported to increase 230% after a non-forested watershed became urbanized in California and increased 190%, 210% and 240% for watersheds with 21%, 27% and 38% impervious cover, in Austin, Texas [*Ritzenthaler,* 2002]. It seems that the overall effect of urban development is to decrease natural recharge.

However, this decrease may be compensated by other pathways. *Lerner et al.* [1990] categorize the recharge into three types: direct, indirect, and localized recharge. On one hand, the impermeabilization of land surface reduces direct recharge, i.e., the infiltration of precipitation into groundwater reservoirs; on the other hand, the decline of the water table may accelerate the downward fluxes into groundwater from surface water and increases indirect recharge, i.e., the percolation to the water table through the beds of surface water.

3.2 Urban recharge

In urban areas, groundwater gains recharge from additional sources: (1) leakage from water supply networks; (2) leakage from sewerage systems when they are installed above the water table; (3) seepage from septic tanks, cesspools, ditches and other wastewater disposal devices; (4) returning of groundwater by irrigation and gardening; (5) artificial recharge for the purpose of groundwater recovery.

Hydrologists have conducted many studies of these factors; however, the increased recharge to groundwater has rarely been quantified. In every city, the sources and quantity of urban recharge are quite different [*Foster et al*., 1998; *Lerner*, 1986; 2002; *Lerner et al.*, 1996].

In sewered cities, water supply leakage may be a main source of urban groundwater recharge. It is common for a leakage rate of 20~25% and even as high as 50% [*Lerner*, 1986]. For example, it is estimated that 10~25% of the water distributed in the pipe system leaks into groundwater in London, UK [*Cox*, 1994] and a leakage rate of 25% is reported in Göteborg, Sweden [*Norin et* *al.*, 1999]. The role of sewer systems is variable, either as a source or a sink of groundwater. In Munich, leakage from sewage pipelines recharges groundwater with a leakage rate of 5% [*Lerner,* 1996]. Seoul, Korea is another case, where sewage system acts as a sink due to the shallow water table. Numerous broken sections of sewage pipelines receive 530 Mm^3 inflows from groundwater storage every year [*Kim, et al,* 2001].

In developing countries, discharged wastewater is often treated through sewer systems such as septic tanks and cesspools, instead of through municipal sewage pipelines. Thus, groundwater often acts as a receptor for industrial effluents and domestic wastewater. This not only recharges, but also contaminates groundwater significantly. It is estimated that 90% of the water provided will become recharge to groundwater, given the domestic water consumption is around 5~10% of the total water use [*Foster et al*, 1998].

Artificial recharge has been used to increase groundwater resources, especially in places where aquifers have been depleted. Other than surface water, treated wastewater is also used to recover aquifers. Urban stormwater is an attractive means of artificial recharge to increase groundwater supply. In Auckland, New Zealand, stormwater supplies 80% of the recharge to shallow aquifer underlying the city, augmenting groundwater resources, however, at the same time, bringing potential impacts on groundwater quality [*Howard,* 1997].

3.3 Water budget in urban areas

Taking into consideration the above sources of urban recharge and discharge, equation (2.2), in an urban context can be expressed as:

$$\frac{dV}{dt} = \left(\Delta R_0 + R_u + \sum \Delta Q_i\right) - \left(\Delta D_0 + Q_p\right) \tag{3.1}$$

where: ΔR_0 is the total change in natural recharge from virgin conditions $[L^3T^{-1}]$;

ΔD_0 is the total change in natural discharge from virgin conditions $[L^3T^{-1}]$;

$\Sigma\Delta Q_i$ is the total net change in lateral groundwater flow from virgin conditions $[L^3T^{-1}]$;

and R_u is net anthropogenic urban recharge (Figure 2) given by

$$R_u = R_w + R_s + R_{iw} + R_{sw} + R_g \tag{3.2}$$

R_w is the leakage from water mains $[L^3T^{-1}]$;

R_s is the net leakage from sewerage and stormwater systems in sewered areas $[L^3T^{-1}]$;

R_g is the returning groundwater by irrigation and gardening $[L^3T^{-1}]$;

R_{iw} is the infiltration of artificial recharge $[L^3T^{-1}]$;

R_{sw} is the seepage of septic systems in unsewered areas, e.g. via septic tanks $[L^3T^{-1}]$. When there is no change in groundwater storage, i.e., $\frac{dV}{dt}$ equals zero, the groundwater system reaches a new equilibrium. Therefore, the sustainable pumping rate can be determined from:

$$Q_p = \left(\Delta R_0 + R_u + \sum \Delta Q_i\right) - \Delta D_0 \tag{3.3}$$

Following equation (3.3), the sustainable pumping rate can be calculated in four steps:

1) Determine the change in natural recharge over the project area, including change in precipitation, evapotranspiration, runoff, and seepage of surface waters, which may be caused by groundwater abstraction and the discharge of stormwater and wastewater;

2) Determine the change in natural discharge, including change in streams, lakes, rivers and groundwater-dependent ecosystems in the project area;

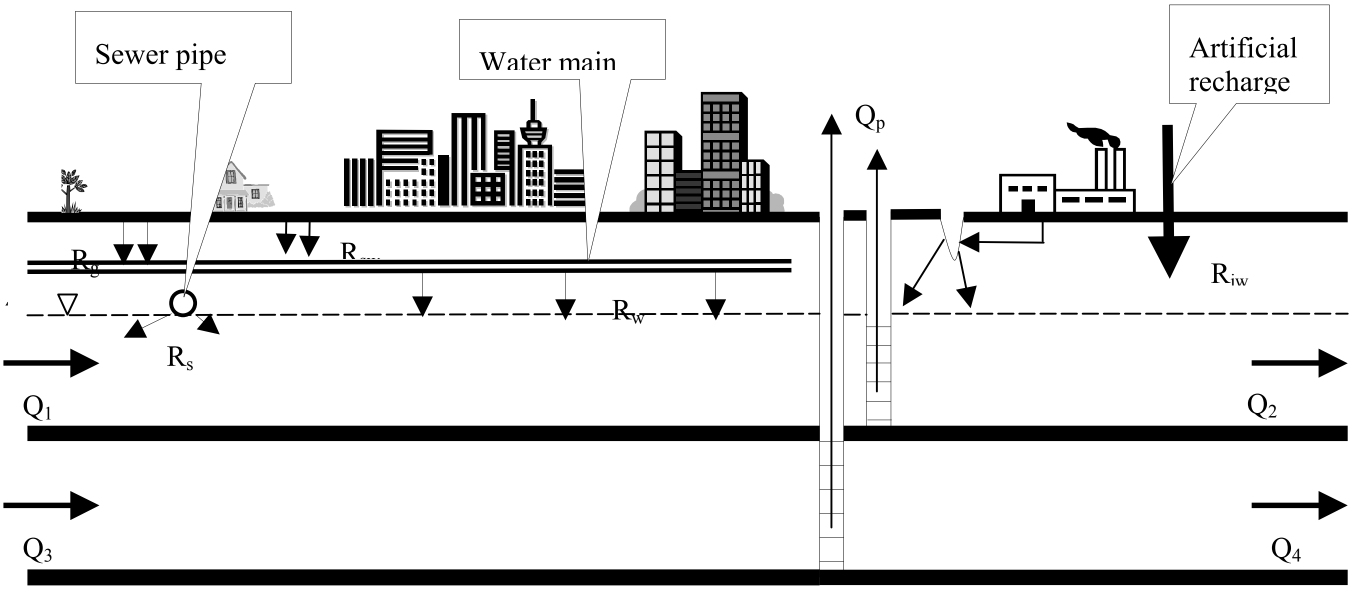

Figure 2. Potential recharge and discharge sources in urban areas

3) Determine the urban recharge, including leakage from water mains sewage pipelines, seepage of septic systems, returning water from vegetation and infiltration of artificial recharge, according to equation (3.2);

4) Calculate change in groundwater fluxes across the boundaries of the project area.

Substituting the values of above calculations into equation (3.3), sustainable yield of groundwater resources in the urban areas is determined.

4 DETERMINATION OF SUSTAINABLE YIELD OF GROUNDWATER RESOURCES IN URBAN BEIJING

4.1 Groundwater utilization in Beijing

Beijing, capital of China, has a long history of groundwater utilization, which dates back to the West Han dynasty 2000 years ago. Since that time, groundwater has been an important source of water supply in Beijing City [*Yang et al.,* 1996]. With the rapid development of industries and growth in population, water demand increased significantly [*UGD*, 1998]. As the contamination of surface water became serious, water supply in Beijing depended more on groundwater as a resource. Groundwater abstraction increased by 54 times during a period of 32 years, from 50 Mm^3/year in 1949 to about 2,709 Mm^3/year in 1981 [*Volker and Henry*, 1988].

This long-term extensive exploitation has depleted groundwater resources and caused several problems. In some places with heavy groundwater withdrawal, the water table dropped from 5 m below the ground surface in 1950 to 50 m below the surface in the early 1990s [*Chang,* 1998]. This has led to the cessation of pumping, abandoning of shallow wells, and land subsidence in some places [*Volker and Henry*, 1988]. Furthermore, overexploitation is one of the main causes of the degradation of water quality. For example, the hardness of groundwater is found to increase in confined aquifers due to the downward flow of contaminated water from the upper unconfined aquifer [*Volker and Henry*, 1988].

A key issue is to find the sustainable yield of groundwater resources. Several Investigations have been conducted to evaluate the exploitable groundwater resources in Beijing Municipality [*Wang*, 1992; *Jiao*, 1992; *BEMPS,* 1996; *Lu,* 1997]. However, these previous studies adopted the principle of "safe yield" to determine sustainable yield by calculating the water balance, neglecting the change in groundwater system due to development. Furthermore, these studies focused on the whole municipality and often ignored the effects of urbanization.

4.2 The project area

This study focuses on the urban area in Beijing Municipality, consisting of four urban districts and a majority area of four suburban districts (Figure 3). The project area is bounded by Qing River, Beiyun River, Yongding River, and administrative boundaries. The area of the project zone is 1,250 km^2.

This area is composed of alluvial sediment from the five river systems. The thickness of alluvium increases from the edge of the mountains to the plain. Figure 4 indicates the aquifer system changes from a single thin gravel alluvium into thicker alluvium with layers of sand and clay. Meanwhile, it changes from an unconfined aquifer to a complex multi-layer aquifer system.

4.3 Change in natural recharge

Natural recharge is determined by several components: precipitation, evapotranspiration, runoff, and seepage of surface waters.

Precipitation: Beijing is located in northeast China and has a semiarid climate [*BEMPS*, 1996]. Data collected from mid 19^{th} to mid 20^{th} century indicates that the average annual precipitation was 649.6 mm [*Jiao,* 1992]. However, during the period of 1971 to 2000, the average annual rainfall was 575.2 mm [*JIN*, 2001]. Precipitation has decreased significantly. It is assumed that the value of 649.6 mm is close to that for virgin conditions, and precipitation decreased to 572.5 mm because of urbanization. Therefore, the change in precipitation is 74.4 mm, which is equivalent to 93 Mm^3/year in the project area.

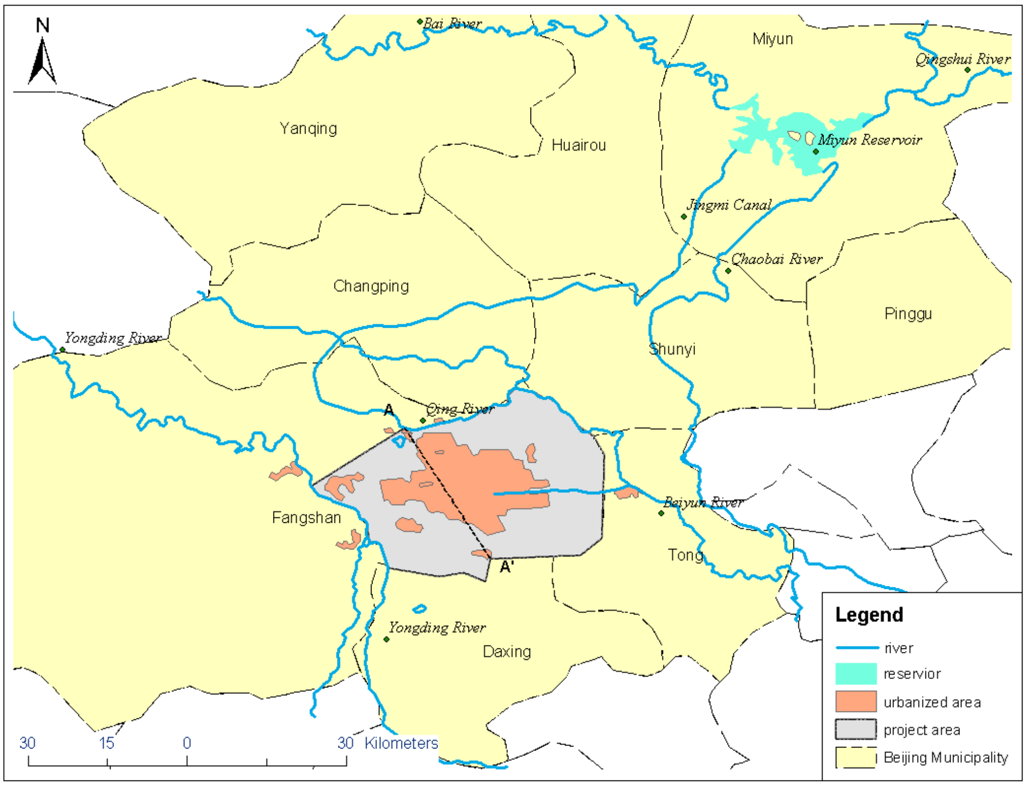

Figure 3. The urban area of Beijing Municipality

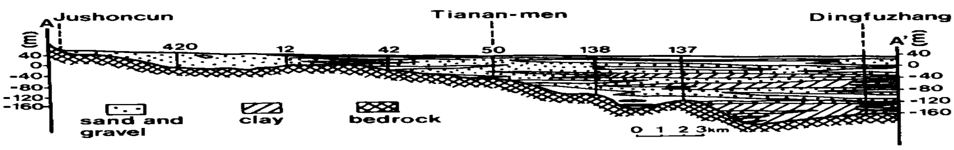

Figure 4. The West-East cross section of Beijing aquifers [*Volker and Henry*, 1998]

Evapotranspiration: Average annual evapotranspiration ranged from 400 to 500 mm/year from 1956 to 1979 [*Jiao,* 1992]. It is assumed that the upper limit (500 mm/year) is the evapotranspiration in pre-urbanization period, and the decrease in the rate of evapotranspiration ranges from 20% to 50%, based on *Howard* [1997]; therefore, the decrease in evapotranspiration is 100~250 mm/year, which is equivalent to 125~312.5 Mm^3/year over the project area.

Runoff: Although there is no record of runoff for the virgin conditions, based on studies in other urbanized regions, the original surface runoff is assumed to be 3%~8% of the precipitation, which equals 20~52 mm/year. Studies show that runoff will increase significantly after urbanization [*Laenen*, 1983; *Ritzenthaler,* 2002]. In this case, the increase rate is assumed to range from 150% to 250%. Therefore, the increase in runoff is estimated to vary from 38 Mm^3/year to 163 Mm^3/year over the project area.

Seepage: The increase in runoff adds seepage to groundwater through riverbeds. This increase is estimated to range from 8 to 33 Mm^3/year, determined by multiplying an infiltration coefficient with the amount of increase in runoff. Change in seepage due to increased pumping was not calculated. But in addition, wastewater discharged into drainage systems becomes an important source of groundwater recharge. Based on the same method, wastewater recharged groundwater at a rate of 156 Mm^3/year in 1990 and 189 Mm^3/year in 2000.

4.4 Change in natural discharge

It is difficult to find the data of total groundwater discharge to streams, rivers, lakes, and groundwater-dependent ecosystems. *Yang et al.* [1996] estimate the baseflow was about 12.5% of precipitation in the plain areas. However, in recent years, it has been reduced to 7% of precipitation, mainly due to the decrease in groundwater levels. Therefore, the decrease in natural discharge is estimated to be 41 mm/year, or 51 Mm^3/year over the project area.

4.5 Urban recharge

Leakage from water mains can be determined by multiplying the leakage rate with the amount of tap water. The leakage rate of water mains is estimated to be 5.34% in 1991 and 8% after 2000 [*BEMPS*, 1996]. However, according to *Lerner* [1986], a leakage rate ranging from 20% to 25% is very common, hence, an upper limit of 20% is applied to estimating leakage from water mains. Therefore, the leakage from water mains is estimated to be 26~97 Mm^3/year in 1990 and 53~158 Mm^3/year in 2000.

Since the water table has dropped significantly with intensive groundwater exploitation, it is assumed that municipal sewage pipelines recharge groundwater through leakage. The amount of leakage is determined by multiplying the leakage rate, which is estimated to be 3% [*BEMPS,* 1996], with the amount of municipal sewage. The leakage from sewerage pipelines in the study area can be estimated to be 23 Mm^3/year in 1990 and 29 Mm^3/year in 2000.

A certain amount of water for irrigation and gardening finds its way to under the ground, thus recharging groundwater. With the application of advanced techniques of irrigation, the water quota is decreasing. Consequently, the returning water from irrigation and gardening is reducing. It is estimated that returning water from vegetation is 25~100 Mm^3/year in 1990, and will be reduced to 21~81 Mm^3/year in 2000 [*Zhang*, 2003].

A large quantity of wastewater is discharged directly into the ground through small sewer systems instead of via municipal sewage pipelines. The quantity of this discharged wastewater can be determined by subtracting the amount of municipal wastewater from the total amount of wastewater discharged in the study area [*Zhang,* 2003]. With urban development, more places have access to municipal sewage system, however, the increase in discharged wastewater leads to an increase in seepage through septic systems. Therefore, the seepage of septic systems is 212 Mm^3/year in 1990 and 257 Mm^3/year in 2000.

Groundwater is artificially recharged through natural watercourses, channels, and the sandy gravel pits, at seven locations in the western groundwater basin [*BEMPS,* 1996]. According to different recharge schemes, artificial recharge is estimated to be 56~131 Mm^3/year in 1990 and will increase to 130~161 Mm^3/year in 2010 [*Zhang,* 2003].

4.6 Groundwater fluxes

The line A-A' [Figure 3] divides the project area into two parts: an unconfined aquifer in the west and a complex multi-layer aquifer in the east [*Volker and Henry*, 1988]. The original flow direction is from northwest to southeast. However, in the past decades, a depression zone had been formed due to intensive withdrawal in the central part. The flow direction over the south boundaries has been reversed. According to Darcy's Law, the change in groundwater fluxes is 240~980 Mm^3/year over the project area, based on the hydraulic properties of the aquifers (Table 1).

4.7 Sustainable yield

From the above calculation, the sustainable yield of groundwater resources in urban Beijing is estimated to be 666~1964 Mm^3/year in 1990 and 773~2090 Mm^3/year in 2000 (Table 2). These results provide water resources managers with a possible range of sustainable yield in this area.

Boundary	Hydraulic conductivity (m/s)	Hydraulic gradient	Aquifer thickness (m)	Aquifer width (km)
Northwestern (unconfined)	9.3~35 x10-4	0.002~0.003	50	20.4
Southwestern (unconfined)	9.3~35 x10-4	0.002~0.003	50	16.7
Northeastern (unconfined)	5.8~17.4x10^{-4}	0.002~0.003	68	28.7
Northeastern (confined)	5.8~17.4x10^{-4}	0.002~0.003	23	28.7
Southeastern (unconfined)	5.8~17.4x10^{-4}	0.0015	68	28.5
Southeastern (confined)	5.8~17.4x10^{-4}	0.0015	23	28.5

Table 1. Hydraulic properties of aquifers in urban Beijing

Component	1990 (Mm^3/year)	2000 (M^3/year)
Change in natural recharge(ΔR_0)	33~371	66~404
Change in natural discharge (ΔD_0)	-51	-51
Urban recharge (R_u)	342~562	416~655
Change in Groundwater fluxes($\Sigma\Delta Q_i$)	240~980	240~980
Sustainable yield	666~1964	773~2090

Table 2. Sustainable yield of groundwater resources in urban Beijing

5 CONCLUSION

Groundwater is an important and valuable resource for water supply in cities. The worldwide trend of urbanization makes it necessary to achieve sustainable groundwater systems in urban areas. The long-time prevalent "safe yield" principle has limits and has brought problems such as overexploitation. The urban groundwater budget equation constructed in this paper takes into consideration additional sources of urban recharge and the boundary conditions of the aquifers. Applying this water budget equation, the sustainable yield of groundwater resources in urban Beijing is estimated to be 666~1964 Mm^3/year in 1990 and 773~2090 Mm^3/year in 2000.

The results vary over large ranges because uncertainties exist when using this budget equation, including hydrologic data such as precipitation, evapotranspiration and runoff, and the properties of aquifers such as hydraulic conductivity, thickness and hydraulic gradients. Future work is necessary to analyze and tighten the range of these parameters, thus providing a better estimate of the sustainable yield of groundwater resources.

6 REFERENCES

Beijing Environmental Master Plan Studies (BEMPS), 1996.

Bredehoeft, J.D., Papadopulos, S.S., and Cooper, H.H. Jr., Groundwater—The water-budget myth, in *Scientific Basis of Water-Resource Management, Studies in Geophysics*, National Research Council, National Academy Press, Washington, D.C., 51-57,1982.

Bredehoeft, J.D., The water budget myth revisited: Why hydrogeologists model, *Ground Water, 40(4),* 340-345, 2002.

Chang, S.D., Beijing: perspectives on preservation, environment, and development, *Cities, 15(1),* 13-25, 1998.

Changnon, S.A., Huff, F.A., Schickedanz, P.T., and Vogel, J.L., *Summary of METROMEX, vol.1: Weather anomalies and impacts*, Illinois State Water Survey Bulletin, 62, 260.

Cox, D.W., The effects of changing groundwater levels on construction in the City of London, in *Groundwater Problems In Urban Areas,* edited by W.B. Wilkinson, Thomas Telford, London, 263-277, 1994.

Foster, S.S., Morris, B.L., Laurence, A.R., *Groundwater in urban development: World Bank Technical Paper, No. 390,* The World Bank, Washington D.C., 1998.

Howard, K.W.F., Impacts of urban development on ground water, in *Environmental Geology of Urban Areas*, edited by N. Eyles, St. John's, Nfld, Canada, 93-103, 1997.

Japan Information Network (JIN), International Comparison of Average Precipitation, 2001, available at http://www.jinjapan.org/stat/stats/01CEN16.html

Jia, Y.W., Ni, G.H., Yoshitani, J., Kawahara, Y., and Kinouchi, T., Coupling simulation of water and energy budgets and analysis of urban development impact, *Journal of Hydrologic Engineering,* 302-311, 2002.

Jiao, D.S. ed., *Water Resources Assessment for China*, China Water and Power Press, 1992.

Kim, Y.Y., Lee, K.K., and Sung, I.H., Urbanization and the groundwater budget, metropolitan Seoul area, Korea, *Hydrogeology Journal, 9(4),* 401-412, 2001.

Laenen, A., Storm runoff as related to urbanization based on data collected in Salem and Portland, and generalized for the Willamette Valley, Oregon: United States Geological Survey Water-Resources Investigations Report, 83-4143, 1983.

Lerner, D.N., Identifying and quantifying urban recharge: a review, *Hydrogeological Journal, 10(1),* 143-152, 2002.

Lerner, D.N., and Barrett, M.H., Urban groundwater issues in the United Kingdom, *Hydrogeological Journal, 4(1),* 80-89, 1996.

Lerner, D.N., Issar, A.S., Simmers, I., *Groundwater recharge, A guide to understanding and estimating natural recharge*, International Contributions to Hydrogeology, 8, Heise, Hannover, 1990.

Lerner, D. N., Leaking pipes recharging groundwater, *Ground Water 24(5),* 654-662, 1986.

Lu, X.J., Conjective use of groundwater and surface water, Central Beijing, China, in *Proceedings of the 30th International Geological Congress: Beijing, China, 4-14 August 1996, vol. 22,* Utrecht, The Netherlands, 15-21, 1997.

Mitchell, V.G., Mein, R.G., and McMahon, T.A., Modelling the urban water cycle, Environmental Modelling & Software, 16, 615-629, 2001.

Norin, M. H., and Svensson, C., Groundwater studies conducted in Göteborg, Sweden, in *Groundwater In Urban Environment,* vol.2, edited by J. Chilton, A.A. Balkema, Rotterdam, 209-216, 1999.

Ritzenthaler, E.A., The effects of urbanization on water quality in three mercer island drainage basin, Washington, Presented at the NABS Annual meeting, Pittsburgh, Pennsylvania, 2002.

Sophocleous, M., From safe yield to sustainable development of water resources – the Kansas experience, *Journal of Hydrology., 235,* 27-43, 2000.

Sophocleous, M., Managing water resources systems: Why safe yield is not sustainable, *Ground Water 35(4),* 561, 1997.

UGD (Urban Groundwater Database), last updated July 2,1996, available at http://www.clw.csiro.au/UGD/DB/Jakarta/Jakarta.html

Volker, A., and Henry, J.C. ed., Side effects related to groundwater management, in *Side Effects of Water Resources Management*, IAH Press, Institute of Hydrology, Wallingford, 123-204, *1988.*

Wang, Z.X., ed., *Groundwater Resources Development in China*, 1992.

Yang, Y., Lerner, D.N., Battett, M.H., and Tellam, J.H., Quantification of groundwater recharge in the city of Nottingham, UK, *Environmental Geology 38(3),* 183-198, 1997.

Yang, Z.Y., Ye, C., and Wang, S.M., Groundwater supply in Beijing, in *Field Trip Guide, 30th International Geological Congress 4-14 August 1996, Beijing, China,* vol.6, Deng, N.G. ed., T221.1-T221.11.

Zhang, L, Sustainable Groundwater Systems in Urban Areas, Master of Applied Science Thesis, University of Toronto, 2003.