Groundwater discharge to the Changjiang River, China, during the drought season of 2006: effects of the extreme drought and the impoundment of the Three Gorges Dam

Zhi-jun Dai · Jin-zhou Du · Ao Chu · Jiu-fa Li · Ji-yu Chen · Xiao-ling Zhang

Abstract Groundwater can play an important role in the compensation of runoff reduction due to extreme climate events such as droughts, as well as in response to anthropogenic actions such as the construction of a dam. The increase in ^{226}Ra specific activity and the runoff from September to December in 2006 is used to estimate the total discharge of groundwater along the mid-lower reaches of the Changjiang River. The total groundwater discharge was found to account for 31% of the increased discharge between Yichang and Datong. The groundwater discharge to lakes (i.e. Dongting Lake) constituted the major contribution of groundwater discharge to the mid-lower reaches of the Changjiang River. More importantly, the second impounding operation of the Three Gorges Dam from 20 September to 27 October 2006 induced a water level decrease in surrounding lakes and rivers, which led to an additional groundwater discharge of $63.3\times10^{8}\,m^{3}$, accounting for 85% of the total groundwater discharge in the same period. Taken together, these observations indicate that groundwater discharge along the mid-lower reaches plays an important role in maintaining stream flow in the drought season, especially in extreme drought years or in response to human activities.

Keywords Groundwater discharge · Runoff · Water balance · Extreme drought · China

Received: 19 December 2008 / Accepted: 25 September 2009
Published online: 16 October 2009

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Introduction

There are increasing concerns regarding the impacts of anthropogenic actions and extreme droughts on hydrologic systems. The response of groundwater systems to extreme climates such as drought and to anthropogenic actions such as the operation of a dam plays an important role in local hydrological systems. Most studies conducted to date have evaluated the potential effects on surface water hydrology, groundwater hydrology and the exchange between groundwater and surface water in response to changes in critical input parameters such as precipitation and runoff (Changnon et al. 1988; Malcolm and Soulsby 2000; York et al. 2002; Yusoff et al. 2002). Some studies indicated that the exchange between groundwater and surface water during extreme droughts could occur in only one direction (i.e. from groundwater to surface water) due to the difference in water levels (Loaiciga et al. 2000; Allen et al. 2004; Scibek et al. 2007). In addition, studies on evaluating the effects of anthropogenic behavior (e.g. land use and irrigation) on groundwater have also been conducted (Rejani et al. 2003; Panda et al. 2007; Seiler and Gat 2007). However, little work has been done on the exchange of groundwater and surface water to include the combined impacts of human interference and extreme climate change in rivers, and in particular in the Changjiang River under the impact of the Three Gorges Dam (TGD) and extreme climate events, e.g. the extreme drought in 2006.

The Changjiang River is about 6,300 km long and covers a catchment area of $1.8\times10^{6}\,km^{2}$, which can be divided into two parts: the upper reaches of the Changjiang River and the mid-lower reaches of the Changjiang River (MLRCR) due to the geomorphological characteristics. The MLRCR, from Yichang to Datong, has a catchment area of about $7\times10^{5}\,km^{2}$ with its discharge accounting for more than 50% of the total discharge into the sea. The geomorphology is characterized by mountains and hills in the upstream areas and by extensive fluvial plains with numerous lakes in the downstream areas. Moreover, discharge from the Dongting Lake drainage basin, the Hanjiang River basin and the Poyang

DOI 10.1007/s10040-009-0538-8

Lake drainage basin make a large contribution to that in the MLRCR (Fig. 1, Tables 1 and 2; Chen et al. 2001; Chen et al. 2008). The MLRCR is characterized by a typical meandering river pattern, and is wider and deeper than the upper part, with a width of 1–2 km and a depth of 6–15 m (Chen et al. 2001). The components of the banks of the MLRCR are mainly sand and gravel with useful water storage underground (He and Cai 1999).

In 2006, the extreme climate event of the worst drought along the Changjiang River in the last 50 years, with extreme high temperatures and low annual precipitation, significantly influenced the runoff of the river. At the same time, the human interference of the second impounding of the TGD, with $111\times10^{8}m^{3}$ of water stored and the water level raised from 135 to 156 m above sea level (BYRS 2006), also affected the runoff. These events resulted in a low runoff discharge along the MLRCR in 2006 compared with the mean annual discharge observed in 2000–2005 (Fig. 1). In previous studies, no stretches of the MLRCR were found to be dry during the drought season in 2006 (Dai et al. 2008). This could be a result of the discharge regulation of the TGD and/or other factors, e.g. groundwater discharge (GWD) along its banks and from the outflow of lakes, leading to replenishment of the runoff discharge. Therefore, this study was conducted to quantify the contribution of GWD to the Changjiang River in the drought season, as well as during the impounding period of the TGD in 2006.

Two traditional methods, hydrograph analysis and hydrological models, are applied to calculate the magnitude of GWD (Chow 1964). Hydrograph analysis is used to obtain the relationship between the river and the aquifer based on the time-series record of water level, flow or hydraulic properties (Hall 1968). This method aims to separate the observed hydrograph into two components, quickflow and baseflow, as the baseflow is assumed to be groundwater discharge from a shallow unconfined aquifer (Eckhardt 2008). Thus, hydrograph analysis has been widely applied to evaluate the magnitude of GWD. However, baseflow obtained in special catchments, e.g. lakes, wetlands and glaciers, contains other contributions besides the GWD. Therefore, the result from the hydrograph analysis can hardly reflect the real GWD due to the complicated geomorphology and hydrogeology of these catchments and their spatial and temporal variability (Chow 1964). The contributing systems, e.g lakes and tributaries, may act as a continuum or as separate entities in the hydrograph analysis, leading to large differences in the results (Griend et al. 2002). Moreover, high water consumption can significantly affect the baseflow over time, e.g. the high baseflow along the Mississippi River has resulted from the land use change and accompanying agricultural activities in the Mississippi basin (Zhang and Schilling 2006). Thus, considering the intensive human interference, as well as the large lakes and the tributaries along the river, the hydrograph analysis method is not

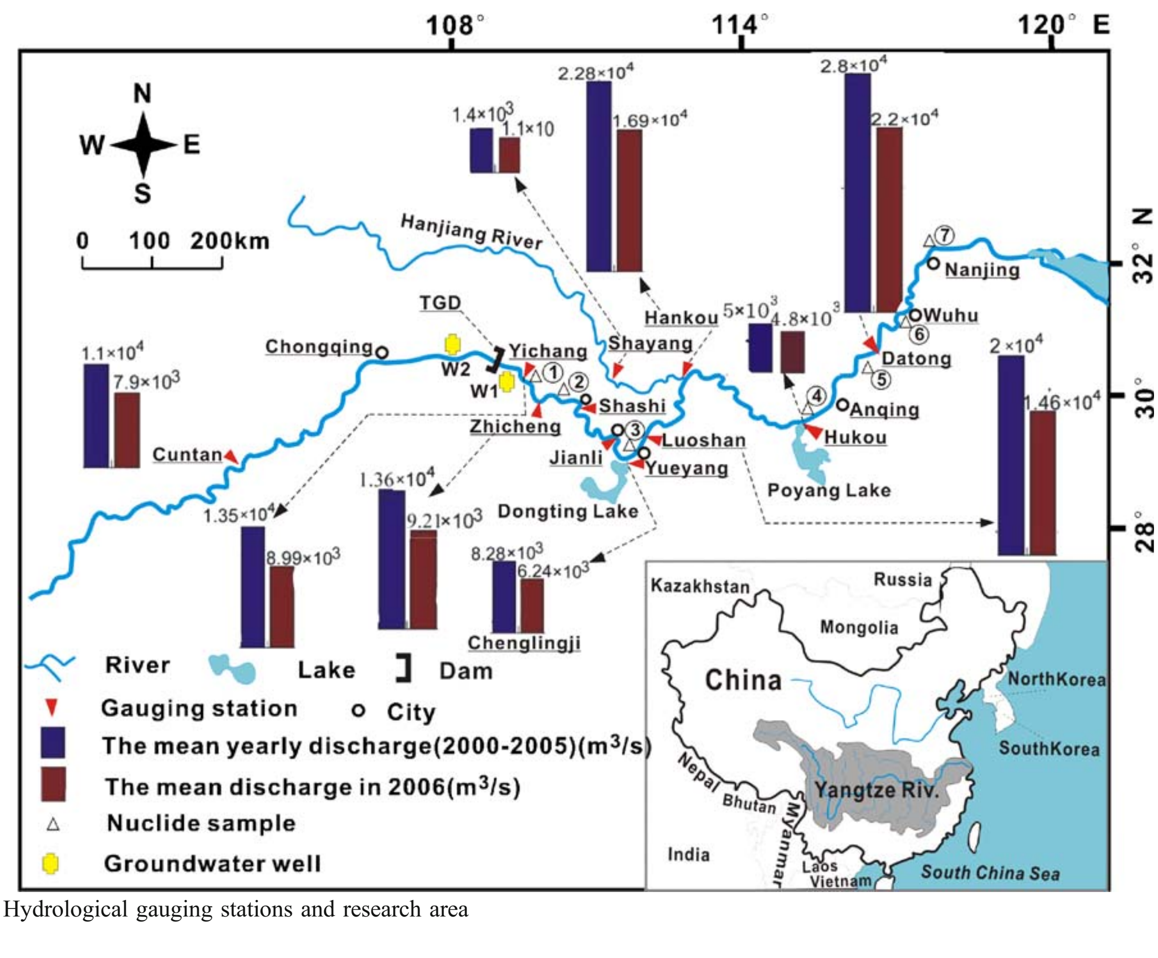

Fig. 1 Hydrological gauging stations and research area

Table 1 Hydrological properties at gauging stations around Dongting Lake (see Fig. 2 for locations)[a]

River	West Songzi	East Songzi	Hudu	Ouchi	Ouchi	Xiangjiang	Zijiang	Ruanshui	Lishui	Chenglingji
Average annual runoff ($10^8 m^3$)	315	116	137	329	25	760	245	730	180	3126

[a] Data obtained from the Hydrological Committee of the Changjiang (BYRS 2006)

applied to calculate GWD in this study. Hydrological models have been developed to analyze groundwater quantity and quality. These models could be effective management tools, but they focus on physical processes entirely with little consideration of ecological dynamics and are seldom calibrated and validated against field observations (Chapman and Malone 2002). The hydrological models can not represent the GWD accurately due to insufficient field data and lack of knowledge on model parameters. Recently, natural radionuclides, e.g. Radium-226 (^{226}Ra), have been shown to be useful for investigating the process involved in long-term radionuclide transport over large spatial areas (Hammond et al. 1988; Tricca et al. 2001; Hubert et al. 2006). ^{226}Ra was primarily used for the assessment of long-term processes involved in groundwater flow based on radionuclide disequilibria (Luo et al. 2000; Hubert et al. 2006), and then several other studies have been performed to evaluate the balance of radionuclides between surface water and groundwater, with particular attention given to ^{226}Ra (Moore 1996; Luo et al. 2000; Hubert et al. 2006). In previous work, the runoff properties in the MLRCR in the drought season of 2006 were reported (Dai et al. 2008). The aim of the present paper is to evaluate the GWD along the MLRCR in the same period by analysis of the water balance and ^{226}Ra isotopes. It is significant for water scientists and catchment area managers to recognize the impacts on GWD due to extreme drought and the TGD impoundment and to make appropriate decisions to deal with such water deficiency risks.

Methods

Data collection

Hydrological data collection

The discharge rates recorded at gauging stations along the Changjiang River are shown in Fig. 1. The discharge into the TGD can be represented by the measured discharge at Cuntan, 620 km upstream of the TGD, if the small tributaries from Cuntan to the TGD are neglected. In addition, the discharge rates measured at Yichang and Datong represent those from the upper and mid-lower reaches of the Changjiang River, respectively. Yichang and Datong are about 37 and 1,177 km, respectively, downstream from the TGD. The discharge rates at Chenglingji and Hukou were used to represent those from Dongting Lake and Poyang Lake into the Changjiang River, respectively. The discharge of sections representing the inflow and outflow of Dongting Lake are shown in Fig. 2 and Table 1. Meteorological data was obtained from the China Meteorological Administration (CMDSSS 2008). Groundwater level data measured in wells around the TGD were collected from the Institute of Geology, China Earthquake Administration (Fig. 1; Zhang et al. 2007). In addition, all data of water levels at gauging stations are related to a common base datum above sea level (Wusong base level of China).

^{226}Ra sample collection and laboratory measurements

The seven sampling points along the Changjiang River are shown in Fig. 1. Water surface samples for ^{226}Ra were taken from 20 October to 3 November 2006 using the large volume (200–400 L) method (Hong et al. 2002). Briefly, water was pumped directly through a 0.5-μm polypropylene cartridge prefilter to remove suspended particles, followed by two manganese dioxide (MnO_2) impregnated cartridges connected in series to concentrate the radium (Baskaran et al. 1993).

The MnO_2-fibers were then detached from the cartridge and washed with distilled water to remove the salts. Afterwards, they were heated at 550°C for more than 6 h in a muffle furnace. The ashes were then weighed and transferred into plastic vials sealed with olefin. Subsequently, the ashes were analyzed by γ-spectrometry (Model: Canberra BE3830) at the State Key Laboratory

Table 2 Discharge of groundwater into the region of Yichang-Datong

Period	Discharge using water balance analysis ($1\times10^8 m^3$)			Discharge using ^{226}Ra analysis ($1\times10^8 m^3$)		
	Input	Output	S.	Surf.	GWD	*P*(%)
Sept–Dec 2006	874.00	1610.00	736.00	505.00	231.00	31
TGD Impounding (20 Sept–27 Oct)	310.00	520.00	210.00	135.56	74.44	35
Recovered water during TGD Impounding	415.00	625.00	210.00	208.43	11.13	5

P(%) percentage of GWD from S; *S.* difference in discharge between input and output; *GWD* groundwater discharge to MLRCR calculated by ^{226}Ra method; *Surf.* discharge of surface water to MLRCR calculated by ^{226}Ra method

 DOI 10.1007/s10040-009-0538-8

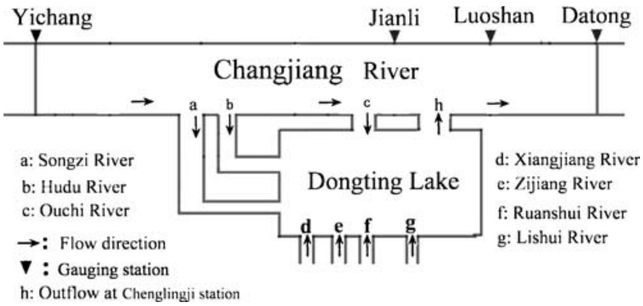

Fig. 2 Sketch map of gauging stations around Dongting Lake

of Estuary and Coastal Research of China (SKLEC). The extraction efficiency (η) of ^{226}Ra was calculated based on the relative efficiency of two MnO_2-fibers using the following formula (Baskaran et al. 1993; Hong et al. 2002):

$$\eta = 1 - A_2/A_1 \tag{1}$$

where A_1 and A_2 were the measured radium isotope activities of the first and second cartridge filters. The average of the extraction efficiency is around (63±10)%.

Calculation of GWD

Quantitative assessment of GWD to the Changjiang River was performed based on the fact that both the GWD and the ^{226}Ra it contains are mass-conservative. Here, a simple regional model can be applied, which is:

$$Q_{re} = Q_{ground} + Q_{surf} + P - E \tag{2}$$

where Q_{re} is the total discharge increase in the region, Q_{ground} is GWD and Q_{surf} is the increased surface water discharge in this region. P and E are regional precipitation and potential evaporation. E is calculated based on the Thornthwaite method (Thornthwaite 1948; Guo and Fu 2007).

Assuming that the total discharge increase in the region can be taken as the result of the discharge difference between the upper boundary and the lower boundary of the region, then

$$Q_{re} = Q_{output} - Q_{input} \tag{3}$$

where, Q_{input} and Q_{output} are the inflow and the outflow of the region. The contributions of precipitation and evaporation to the region in a statistically steady state are equal according to the comparable long-term mean precipitation and evaporation (Pan 1994). Therefore based on Eqs. 2 and 3,

$$Q_{surf} = Q_{output} - Q_{input} - Q_{ground} \tag{4}$$

Compared to the ^{226}Ra specific activity in surface water, the ^{226}Ra specific activity in P and E can be neglected due to the rapid oxidation of ^{226}Ra exposed to the air (Martina et al. 2003). Therefore, based on Eqs. 2 and 3, the increase of ^{226}Ra specific activity (ΔF_{Ra}) in the region can be expressed as follows:

$$\begin{aligned}\Delta F_{Ra} &= A_{output}Q_{output} - Q_{input}A_{input} \\ &= A_{ground}Q_{ground} + Q_{surf}A_{surf}\end{aligned} \tag{5}$$

Where, A_{input}, A_{output}, A_{ground} and A_{surf} are the ^{226}Ra specific activities corresponding to the different water bodies of the region. As Q_{surf} in Eq. 4 is substituted into Eq. 5, GWD can be obtained as follows:

$$Q_{ground} = \left(A_{output}Q_{output} - Q_{input}A_{input} + Q_{input}A_{surf} - Q_{output}A_{surf}\right)/\left(A_{ground} - A_{surf}\right) \tag{6}$$

In general, Q_{input} and Q_{output}, A_{input} and A_{output}, and A_{ground} and A_{surf} in Eq. 6 can be obtained from measured discharge data at gauging stations and from laboratory

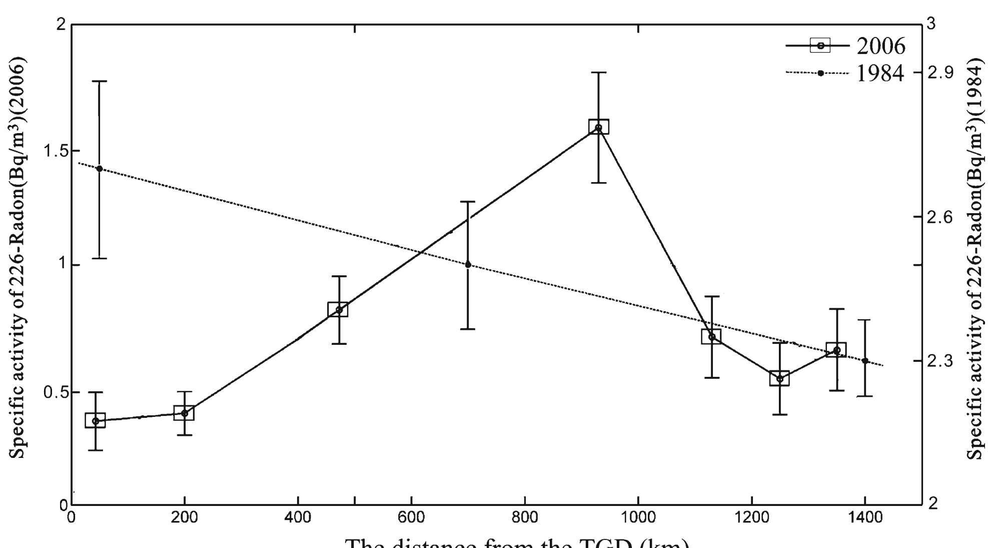

Fig. 3 Changes of ^{226}Ra specific activity in water body along the MLRCR (confidence intervals: 95%)

Table 3 Evaporation (E) and precipitation (P) during Sept–Dec of 2006 at the cities along MLRCR

	City	Chongqing	Yueyang	Wuhan	Nanchang	Anqing	Nanjing
2006	E(mm)	243.1	242.3	234.5	249.4	231.1	214.7
	P(mm)	190.5	214.1	178.8	122	179.2	192.7
	$P-E$ (mm)	−52.6	−28.2	−55.7	−127.4	−51.9	−22

experiments. Thus, Eq. 6 can be used to estimate GWD to the Changjiang River such as the GWD along the reaches from Yichang to Datong and the GWD of the Dongting Lake from September to December of 2006 (Fig. 2).

Results

Pattern of ^{226}Ra specific activity

The distribution pattern of ^{226}Ra specific activity along the MLRCR is plotted in Fig. 3. The ^{226}Ra specific activity ranged from 0.35 to 1.60 Bq/m^3 with an average of 0.70± 0.42 Bq/m^3. Overall, the values of ^{226}Ra specific activity obviously increased from Yichang to Nanjing. It is noted that the specific activity increased sharply downstream of the connections between the lakes and the main river (Fig. 3). This is different from the previous study in which the specific activity of ^{226}Ra was reported to decrease along the MLRCR (Li 1984) (Fig. 3). Moreover, according to the analysis results from the SKLEC experiments, the mean of ^{226}Ra specific activity in groundwater along the MLRCR is around 2.8 Bq/m^3, which is much higher than that in the surface water. So, it is expected that there should be GWD to the Changjiang River.

Discharge of groundwater along MLRCR

GWD along the MLRCR is expected to be much higher in the dry season than that in the flood season, especially under extreme drought conditions, e.g. the extreme drought event in 2006. If A_{surf}, the ^{226}Ra specific activity in the regional surface water flowing into the reach from Yichang to Datong, is assumed to be equal to A_{input}, the ^{226}Ra specific activity in the surface water entering the region from the upper boundary, the GWD (Q_{ground}) can be obtained according to Eq. 6. Thus, a total GWD along the MLRCR of 231×10^8m^3 is obtained from September to December in 2006, corresponding to 31% of the discharge difference between the upper and the lower boundaries of the study region (Table 2). This calculation is only valid with precipitation equal to evaporation, which is a reasonable approximation in the long term. However, Table 3 shows that the evaporation (E) was potentially larger than the precipitation (P) in the same period, resulting in the underestimation of GWD.

The GWD from the basin of Dongting Lake was analyzed as being representative of the contribution of the GWD from all the lake basins that contribute to the main stream of the Changjiang River. The Dongting Lake receives inflows from seven river branches and discharges water into the Changjiang River at Chenglingji (Fig. 2). Based on Eq. 6, the GWD from the basin of the Dongting Lake to the Changjiang River in September–December of 2006 was about 70×10^8m^3, which accounted for 22% of the discharge difference between Jianli and Luoshan, the upstream and the downstream boundaries of the outlet of the Dongting Lake (Fig. 2), and which also corresponded to 22% of the discharge (314×10^8m^3) from the Dongting Lake to the Changjiang River (Table 4). This indicates that the contribution of GWD from the lake basin into the Changjiang River is noticeable.

Discussion

Factors influencing GWD and ^{226}Ra specific activity

Owing to the different methods used in Li's work (1984) and the present study, the absolute values of ^{226}Ra specific activity are not comparable (Fig. 3). However, the ^{226}Ra specific activity is expected to be the same since the geological setting of the MLRCR remains unchanged despite the change in time. In general, the decrease of ^{226}Ra specific activity along the MLRCR is a result of soil erosion, which is greater in the upper reaches than in the MLRCR (Shi 2002; Xu et al. 2008). Thus, with the increase of discharge along the river and the reach being more downstream, the ^{226}Ra specific activity is lower. The increasing ^{226}Ra specific activity during the drought season of 2006, therefore, indicates an additional ^{226}Ra source along the MLRCR. ^{226}Ra specific activity is generally higher in groundwater than that in surface water. Thus, the increased ^{226}Ra specific activity observed in the surface water along the MLRCR may be the result of more GWD in a drought year than in normal years.

Table 4 Contribution of GWD to the total discharge from the Dongting Lake into the Changjiang River. The input is from Jianli gauging station, the output from Luoshan gauging station (Fig. 2)

	Discharge using water balance analysis (1×10^8m^3)			Discharge using ^{226}Ra analysis (1×10^8m^3)		
	Input	Output	S.	Surf.	GWD	P(%)
Jianli-Luoshan	855.0	1180.0	325.00	255.0	70	22

P(%) percentage of GWD from S.; *S.* Difference in discharge between input and output; *GWD* groundwater discharge to MLRCR from Dongting Lake calculated by ^{226}Ra method; *Surf.* discharge of surface water to MLRCR from Dongting Lake calculated by ^{226}Ra method

 DOI 10.1007/s10040-009-0538-8

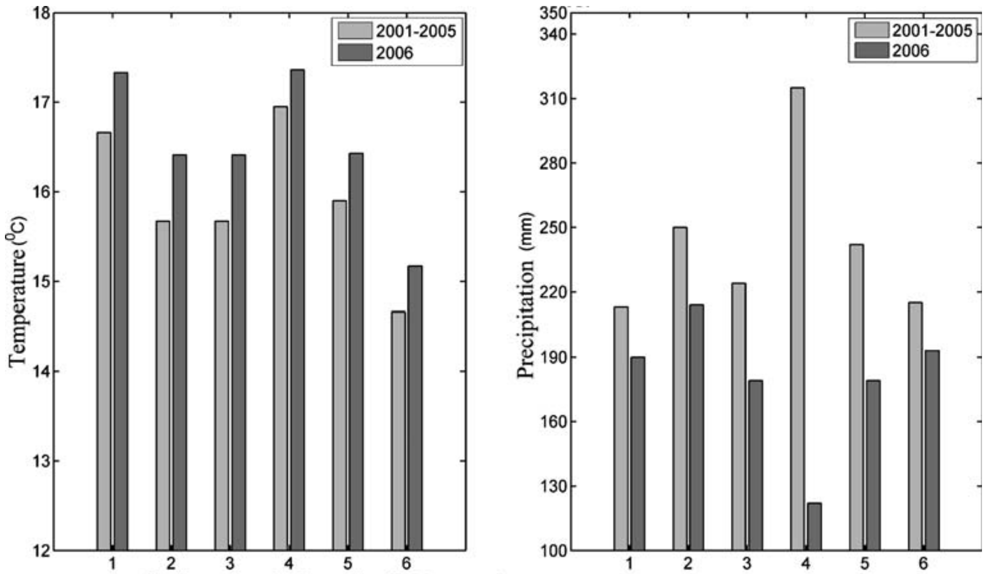

Fig. 4 The mean precipitation and temperature during September–December in different cities along MLRCR

The effects of precipitation and temperature

The average temperature in September–December of 2006 along the Changjiang River basin was higher than that in 2001–2005 (Fig. 4). For example, the average temperature in Chongqing in July–August of 2006 was 4°C higher than that of 2001–2005, which could have resulted in more evaporation in 2006. In addition, the precipitation along the MLRCR in 2006 was much lower than that of normal years. For example, the amount of precipitation in 2006 around Nanchang was 40% lower than that in 2001–2005 (Fig. 4). Both the higher temperatures and the lower precipitation resulted in a large decrease in water level in 2006 with the lowest records of the last 50 years occurring along the river (Dai et al. 2008).

In comparison with the daily water level change along the MLRCR in 2006, the variations in the well water levels were several orders of magnitude smaller than those in the surface waters. From Fig. 5, it can be seen that the well water levels even remained at the same level in contrast to the rapid decrease of surface water levels in the last 4 months of 2006 (Fig. 6). This indicates that groundwater along the Changjiang River is less directly affected by the extreme drought event in 2006 than the surface water. In other words, groundwater reacts much

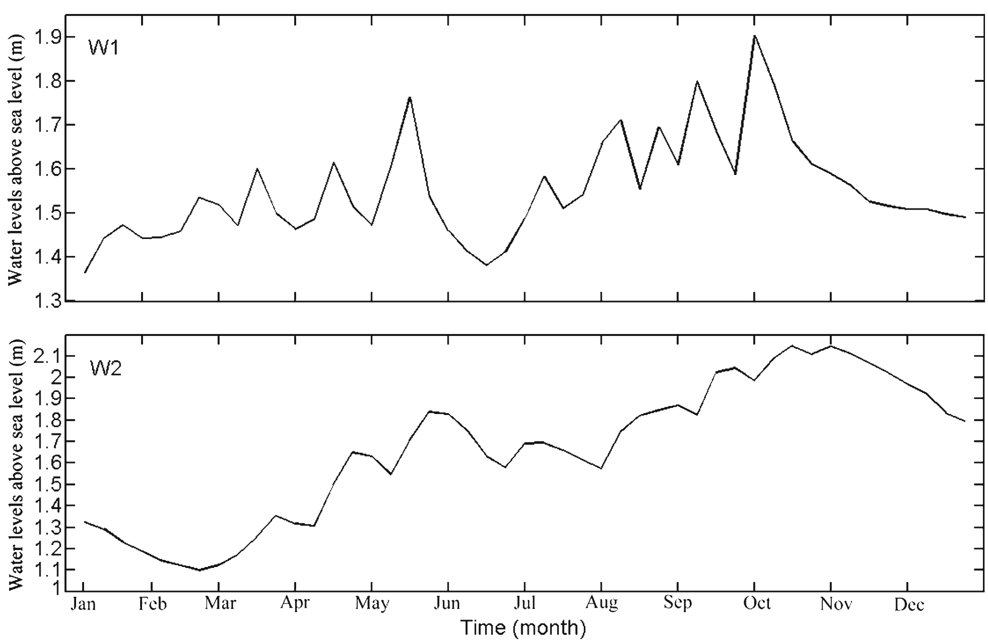

Fig. 5 Daily changes of groundwater level in wells in 2006

DOI 10.1007/s10040-009-0538-8

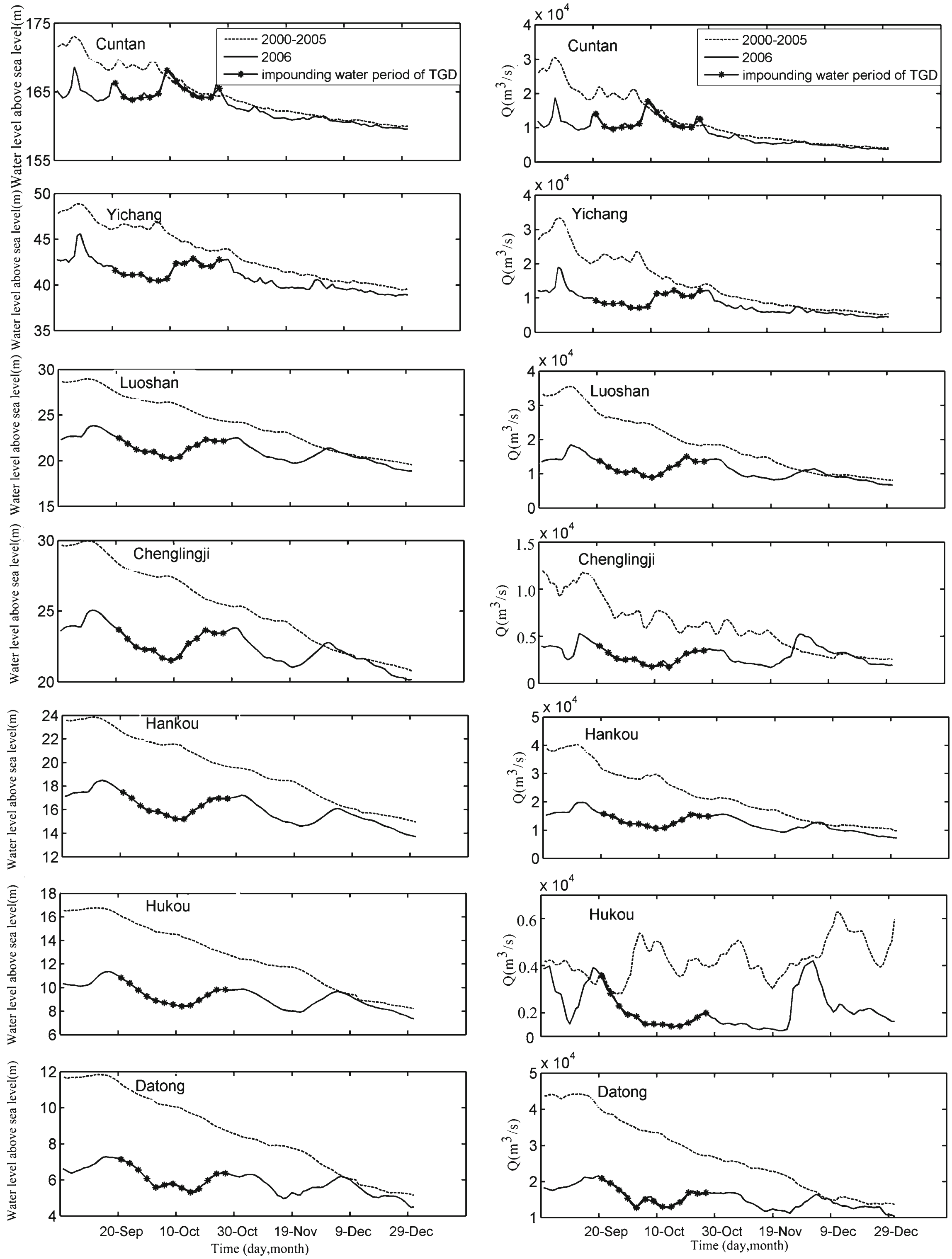

Fig. 6 Changes of discharge (Q) and water level (h) at each gauging station

more slowly than surface water to environmental change, and as has been pointed out (BGR 2008), only after prolonged droughts will groundwater levels show declining trends. Therefore, the level of the groundwater along the river can be relatively higher than the surface water level due to the impacts of extreme drought in 2006, resulting in more GWD than in normal years.

The effects of runoff along MLRCR

As already mentioned, the water level and discharge along the MLRCR from September to December in 2006 was much lower than that in 2000–2005 (Fig. 6), and reached the lowest value ever recorded (Dai et al. 2008). However, the water table remained nearly constant with small oscillations of 0.2 m in September–December in 2006

 DOI 10.1007/s10040-009-0538-8

(Fig. 5). Therefore, it is possible that the water table along the MLRCR was higher than the surface water level and resulted in a larger gradient between the groundwater and the stream, as more GWD flowed into the Changjiang River in 2006 than in normal years. Thus, the lower water level in the main stream in 2006 may have lead to a larger GWD, resulting in higher ^{226}Ra specific activity compared to those in normal years. A good correlation (r=0.95) can be obtained (Fig. 7) between ^{226}Ra specific activity and the mean surface-water level difference at sample points during September–December between 2006 and the mean of 2001–2005. This figure also demonstrates the above phenomena of the larger the mean water level difference, the greater the GWD and the higher the ^{226}Ra specific activity.

Effects of impounding on GWD

An extreme drought event occurred in the flood season of the Changjiang River in 2006, which resulted in the lowest surface water level at the end of August for last 50 years (Dai et al. 2008). From 20 September to 27 October 2006, $111\times10^{8}\,m^{3}$ water, accounting for 33.9% of the discharge at Yichang, was trapped by the TGD as a result of the second phase of the TGD impoundment. A dramatic decrease of discharge was observed along the MLRCR (Fig. 6). The decrease of water level at Yichang and Datong due to the effects of the TGD impoundment can also be quantified by the reduction of discharge based on the relationship between water level and discharge. As the daily discharge at Cuntan can represent the discharge flowing into the TGD, the difference of discharge between Yichang and Cuntan can be used to evaluate the volume of the daily water storage, which is equal to the daily

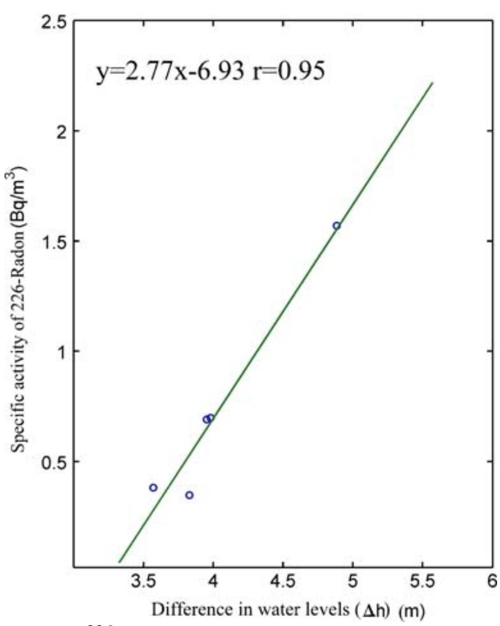

Fig. 7 Plots of ^{226}Ra specific activity vs. differences in water level (Δh/m) during September–December between 2006 and the mean of 2001–2005

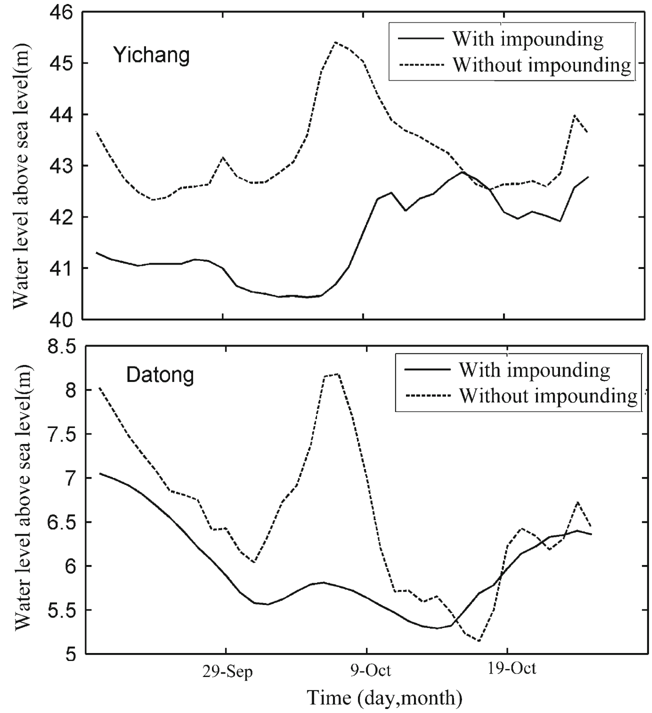

Fig. 8 The changes of water level during the impounding of TGD. *With impounding*: actual water level during the impounding of TGD; *without impounding*: assumed water level without impounding of TGD

reduction of discharge at Yichang and Datong due to the TGD. The ideal discharge at Yichang and Datong without the influence of the TGD can be equal to the sum of discharge with the TGD and the daily storage volume behind the TGD. Thus, the water level at Yichang and Datong without the TGD in 2006 can be obtained based on the relationship between water level and discharge in 2000–2005. Obviously, the impoundment of the TGD causes water levels to be about 0.5 m lower in comparison to those without the TGD (Fig. 8), which can result in more GWD into the river with higher ^{226}Ra specific activity in the surface water observed.

As mentioned above, runoff and TGD impounding led directly to the low surface water levels in 2006, which may have resulted in a larger GWD, represented by higher

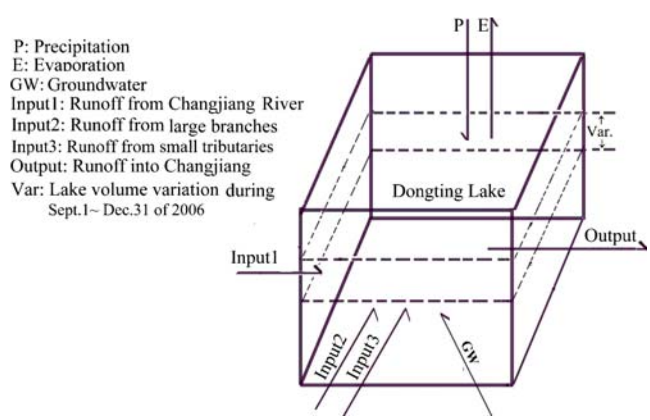

Fig. 9 Definition of the components of the water balance at Dongting Lake

DOI 10.1007/s10040-009-0538-8

^{226}Ra specific activity, than that in normal years. Based on the assumed surface water level without TGD impoundment (Fig. 8; 20 September–27 October), the ^{226}Ra specific activity can be calculated according to the relationship in Fig. 7. Then the recovered water GWD without impoundment along the MLRCR can be estimated as $11.13\times10^8 m^3$ based on Eq. 6, as is listed in Table 2. The total GWD during the second impounding phase of the TGD is $74.44\times10^8 m^3$, which indicates that the extra GWD of $63.3\times10^8 m^3$ was caused by the impoundment, accounting for 85% of the total groundwater discharge in the same period. The amount of GWD during the second impounding phase of the TGD also accounted for 35% of the discharge increase along the MLRCR (Table 2). Therefore, the enhanced GWD was induced by the drought or the impoundment themselves rather than the lower surface water level as a result of these two reasons. The TGD impounding can alter the water distribution at Yichang as well as influence the discharge at Datong through GWD in a dry season. One of the dominant effects of "no drought in the drought season" in 2006 along the MLRCR reported in a previous paper (Dai et al. 2008) is in fact a change in GWD. In addition, although there was an extreme drought and TGD impounding, the reduction of discharge in the Changjiang River can be partially compensated for by the considerable contribution of GWD. The total GWD replenished 31% of the discharge difference between Yichang and Datong in the last 4 months in 2006. This indicates that groundwater along the MLRCR in 2006 may have alleviated the damage caused by drought in the dry season by discharging to surface water. Furthermore, not enough groundwater due to insufficient recharge water in the flood season of a drought year, as well as a large amount of water trapped in the upper reservoirs, can break the water balance and cause a water crisis along the MLRCR.

Comparison between ^{226}Ra analysis and water balance analysis

The radionuclide ^{226}Ra is a long-lived daughter ($t_{1/2}$= 1,620 y) of the Uranium-238 (^{238}U) decay series, which is produced naturally in groundwater as a product of the radioactive decay of ^{238}U in uranium-bearing rocks and sediments (Watson et al. 1983). In comparison with groundwater, surface water contains very low concentrations of dissolved ^{226}Ra due to the lack of major contact of surface waters with uranium emanating mineral material. As a result, GWD into surface water leads to a rise in ^{226}Ra specific activity in the surface water. In addition, ^{226}Ra specific activity stays constant when ^{226}Ra is transported from the groundwater to surface water, and ^{226}Ra specific activity is also easily measured, even at very low concentrations (Moore 1996; Hubert et al. 2006). Hence, the radioisotope ^{226}Ra is a good tracer of groundwater flow into surface waters.

Water balance analysis to calculate GWD is based on the difference in different water bodies, which can be shown as follows:

$$Q_{\mathrm{ground}} = Q_{\mathrm{output}} - Q_{\mathrm{input}} - Q_{\mathrm{surf}} - \mathrm{P} + \mathrm{E} \tag{7}$$

Equation 7 includes the two unknown variables of P and E. Accurate P values along the MLRCR are not available due to insufficient field data, and the measuring of evaporation is the other difficult problem in hydrologic research. In addition, although Q_{surf} represents increased surface water in the assumed research area, measured data at the gauging stations may contain groundwater components due to the effects of extreme drought conditions or a low flow season. Such a case can occur at Dongting Lake, which is the largest lake along the Changjiang River.

The field data from Dongting Lake provide information regarding the water bodies from different components of the water balance (Fig. 9) such as lake P and E, the inflows of three tributaries from the Changjiang River to the lake ("Input1"), four large tributaries of the Dongting Lake ("Input2") and regional runoff from small tributaries around the Dongting Lake ("Input3") (Fig. 9), the outflow at Chenglingji ("Output") to the Changjiang River and the changes in volume of the lake ("Var."). Based on the previously mentioned components, GWD from Dongting Lake to the Changjiang River was obtained by the following equation:

$$GWD = Output - P + E - Input1 - Input2 - Input3 - Var. \tag{8}$$

Therefore, GWD from the lake and the surrounding region was around $48.48\times10^8 m^3$ based on the balance method (Table 5), which is 70% of the total GWD based on the ^{226}Ra method. It should be noted that the GWD determined using the water balance method did not take into account the GWD from tributaries such as inflow to the Dongting Lake. In contrast, the GWD determined based on the ^{226}Ra method represents the total GWD,

Table 5 Water balance of Dongting Lake during September–December 2006

	Outlet	Input1	Input2	Input3	Var.	*P*	*E*	GDW
Water component ($1\times10^8 m^3$)	314	13	205	31.4	15.5	2.29	2.03	48.48
Percentage (%)	100	4	65	10	5	0.7	0.6	16

Outlet outflow at Chenglingji station; *Input1* inflows of three tributaries from the Changjiang River as shown in Fig. 2; *Input2* inflows of four large tributaries of Dongting Lake as shown in Fig. 2; *Input3* regional runoff from small tributaries around Dongting Lake; *Var.* the change in volume in Dongting Lake between 1 Sept. and 31 Dec.; *E* evaporation and *P* precipitation; *GWD* groundwater discharge to MLRCR from Dongting Lake calculated by ^{226}Ra method

DOI 10.1007/s10040-009-0538-8

regardless of its source. Moreover, a direct method to obtain GWD could be taking the difference between groundwater level and surface water level at adjacent stations along the river. Due to the lack of groundwater level data, GWD cannot be evaluated directly from the difference between the groundwater level and surface water level. The data from two groundwater wells only were used here to testify whether GWD existed or not along the MLRCR in 2006. As groundwater is more and more important to the water resources along the river, the monitoring of groundwater is therefore critical and significant both for water resources management and scientific purpose. It will be an alternative for the future to assess the GWD based on groundwater level data. Thus, GWD is difficult to estimate with non-isotopic methods due to the lack of data. GWD determined with the ^{226}Ra method can be more convincing than that obtained with the water balance method under conditions of little hydrogeological data (Balázs et al. 2006).

Conclusions

Based on the increasing ^{226}Ra specific activity and the runoff distribution along the MLRCR in September–December of 2006, the total GWD was about 231×10^{8} m^{3}, which was 31% of the total water discharge difference between Datong and Yichang. In the same period, the GWD from the Dongting Lake basin was approximately $70\times10^{8}\,m^{3}$, which accounted for 30% of the total GWD. Furthermore, GWD along the MLRCR in the second impounding phase of the TGD was approximately $63.3\times10^{8}\,m^{3}$ due to the impacts of the impounding of the TGD, accounting for 85% of the total GWD in the same duration, from 20 September to 27 October 2006. These results provide the first quantitative estimation of the effects of the TGD impounding and the drought on the exchange between surface water and groundwater along the MLRCR. It indicates that impoundment in the extreme drought season could cause extra GWD, preventing drying out of the river. The response of stream-aquifer interactions to anthropogenic activities and to changes in climatic conditions has been a permanent topic in the field of hydrological research. Such a study on GWD along the Changjiang River with the TGD impounding and extreme drought simultaneously being taken into account, may provide an important contribution to the understanding of the hydrologic cycle. Moreover, in comparison to surface water, groundwater has in the past been paid less attention. As groundwater plays an important role at present and will do so in the future, groundwater monitoring and data analysis are highly recommended.

Acknowledgements This research was supported by the Funds for Creative Research Groups of China (No. 40721004), National Science Key Foundation in China (50939003) and the Science and Technology Committee of Shanghai (06PJ14035, 07DJ14003). We also highly appreciate the two editors and two anonymous reviewers who provided valuable comments that helped to greatly improve the manuscript.

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