Basin-scale groundwater response to precipitation variation and anthropogenic pumping in Chih-Ben watershed, Taiwan

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Abstract The sustainable use of groundwater has become increasingly challenging due to extreme hydrological events and anthropogenic activity. In this study, the basin-scale groundwater response to precipitation variation was analyzed using an integrated model that comprises lumped models for land and river recharges and a distributed model for groundwater. The integrated model was applied to the Chih-Ben watershed, Taiwan, using 20years (1988–2007) of data. The hydrological data were analyzed for trends using statistical tests. Based on decreasing trends in precipitation and groundwater levels and an increasing trend in stream flow, the oblique-cut method was applied to precipitation and excess infiltration to assess land and streambed recharge. Distributed numerical groundwater modeling was used to simulate the basin-scale groundwater responses to precipitation variation and anthropogenic pumping. The model was calibrated using stable-isotope and groundwater-level data. The safe yields were estimated for the Chih-Ben watershed for dry, wet, and normal precipitation scenarios. The safe yield of groundwater was shown to vary with precipitation, which does not guarantee the sustainable use of groundwater resources. Instead, water resources should be assessed at a basin scale, taking into account the whole ecosystem, rather than only considering water for human consumption in the alluvium.

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Introduction

Water resources are vital for all life. Water withdrawals from freshwater systems have increased eight-fold due to anthropogenic activity as the global human population has quadrupled in the past century (Gleick 2006). The situation could become even worse with projected changes in temperature and rainfall in the twenty-first century (Von Holle 2008), coupled with the likelihood that climate change will exacerbate extremes (Alley et al. 2003). Potential consequences of global climate variation and the rapid increase of water demand include an imbalance between supply and demand, due to changes in spatial and temporal distribution of water resources, and a decrease in water quality due to saline-water intrusion, blooms in microbial populations, and the spread of pathogens and pollutants. This may increase the risk of water-resource depletion, increasing conflict between agricultural irrigation, industrial development, urban water supply, and a broad spectrum of aquatic and riparian ecosystems.

In order to assess the available groundwater resources, the concept of safe yield has been proposed (Lee 1915; Meinzer 1923). Safe yield, which is commonly applied to water-resources management, is defined as the quantity of water that can be pumped regularly and permanently without dangerous depletion of the storage reserve. Although the concept is clear, its implementation is not simple. A yield that is safe with respect to groundwater storage might not be safe with respect to natural discharge from aquifers. The concept of safe yield has been criticized for being unsuitable for application to sustainable groundwater use. The sustainability of groundwater resources is defined as the development and use of groundwater in such a manner that this can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al. 1999). Application of the concept of sustainability

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rather than safe yield has been advocated (Bredehoeft 1997; Sophocleous 1997, 2000; Alley and Leake 2004; Zhou 2009) for long-term reasonable water use (UNESCO 1999; Loucks 2000; Alley and Leake 2004). Even though defining and measuring sustainability are still major challenges, the importance of managing water at the basin scale has emerged along similar lines to the concept of sustainable development (Alley and Leake 2004; Anderson and Acworth 2009).

Natural climate variability ranges over multiple time-scales (Gurdak et al. 2009) and can affect the quantity and quality of various components of the hydrological cycle, including atmospheric water-vapor content, precipitation and evaporation patterns, snow cover and the melting of ice and glaciers, soil temperature and moisture, and surface runoff and stream flow (Bates et al. 2008). Precipitation is the main source of surface water and groundwater in watersheds in Taiwan. As in other areas of the world, climate change in Taiwan has manifested itself in changes in the spatial and temporal characteristics of precipitation (Hsu and Li 2010). Various temporal changes in precipitation have been found in Taiwan. Droughts and strong-intensity rainfall have appeared more frequently in recent years (Liu et al. 2009). The inter-annual to multi-decadal precipitation variation is often the result of El Niño/La Niña-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in Taiwan, and the variation can have substantial influence on groundwater resources in terms of the resulting changes in the amount, time-span, and locations of recharge, discharge, and water-table fluctuation (Green et al. 2011).

The impact of climate change on groundwater recharge is complicated. Surface water and groundwater dynamically interact with each other. Kundzewicz (2007) indicated that decreasing rainfall and increasing air temperature may lead to substantial declines in groundwater recharge. Owor et al. (2009) showed that increases in rainfall intensity may promote groundwater recharge in tropical environments. Ferguson and Maxwell (2010) studied the role of groundwater in watershed responses and land-surface feedback under climate change. They reported that the hydrologic sensitivity to climate change depends on the feedback between groundwater, overland flow, and the land-surface water and energy balance. The lowering of the groundwater table due to lower regional recharge reduces, or even stops, stream flow. The lowering of the long-term water level of a stream due to less precipitation also induces discharge from aquifers to streams and causes regional groundwater levels to drop. A proper understanding of the groundwater response to precipitation variation and anthropogenic activity can improve water-resources management.

The dynamic response of groundwater to precipitation variation and anthropogenic pumping is related to recharge from precipitation and the groundwater flow in aquifers. These hydrological components can be simulated by lumped or distributed models. The advantage of using a distributed model is that the physical laws can be explicitly incorporated; however, detailed spatial information on media properties is required. Although a hydrological system can be modeled using an integrated and distributed surface water–groundwater approach, the downscaling of precipitation is a source of uncertainty and may produce misleading results in the groundwater response (Stoll et al. 2011). Unlike a distributed model, a lumped model responds to the hydrological system as a whole. Although a lumped model is simple, it can reasonably reflect the system response and is especially suitable for ungauged watersheds or those with few hydrological data (Wilson and Gelhar 1974).

This study analyzes the basin-scale groundwater dynamic response to precipitation variation and anthropogenic activity. An integrated lumped-distributed model was constructed to estimate land and streambed recharge and groundwater movement for a data-poor watershed. The model was calibrated and verified with available groundwater-level and stable-isotope data. The effects of applying the safe yield on the basin-scale water resources are examined.

Study site

Geography

The Chih-Ben watershed is located in southeastern Taiwan (Fig. 1). Its geographic location is between longitudes 121°20′E and 121°50′E and latitudes 22°35′N and 22°45′ N. The Chih-Ben watershed is surrounded by mountains and composed of alluvium and colluvium, with an area of 198.45 km^2, as shown in Fig. 1. It is bound to the east by the Pacific Ocean; to the north by Kadala, Jueifen, and Shemagan mountains; to the south by Gueina, Taimali, and Chichuan mountains; and to the west by Dawu and Wu-Tau mountains. The northeast is connected to an alluvial fan created by the Li-Chia stream. The highest mountain located to the west is Wu-Tau mountain, with an elevation of 2,735 m above sea level (asl), about 25 km inland from the Pacific Ocean. The Chih-Ben stream is the only stream in the watershed and flows eastwards to reach the Pacific Ocean. The total length of the Chih-Ben stream is 39.3 km, with an average slope of 1:20. The gradient of the stream is steep, especially above an elevation of 400 m asl, and alluvium appears in the downstream section.

Geology

The geology of the Chih-Ben watershed is mainly composed of metamorphic rocks such as Miocene argillite, slate, and phyllite. Late-Paleozoic schist is located in the central region. Eocene argillite and green slate, intercalated with beds of sandstone, appear in the east. The rock layers dip towards the east, and the orientation of rock cleavage is northeast to southwest. The northern side of the downstream region is mainly sandy, with the southern side being rocky. There are hot springs along or close to the Chih-Ben fault in the downstream region of the watershed. East of the Chih-Ben fault is the Taitung alluvial delta, with the area to the

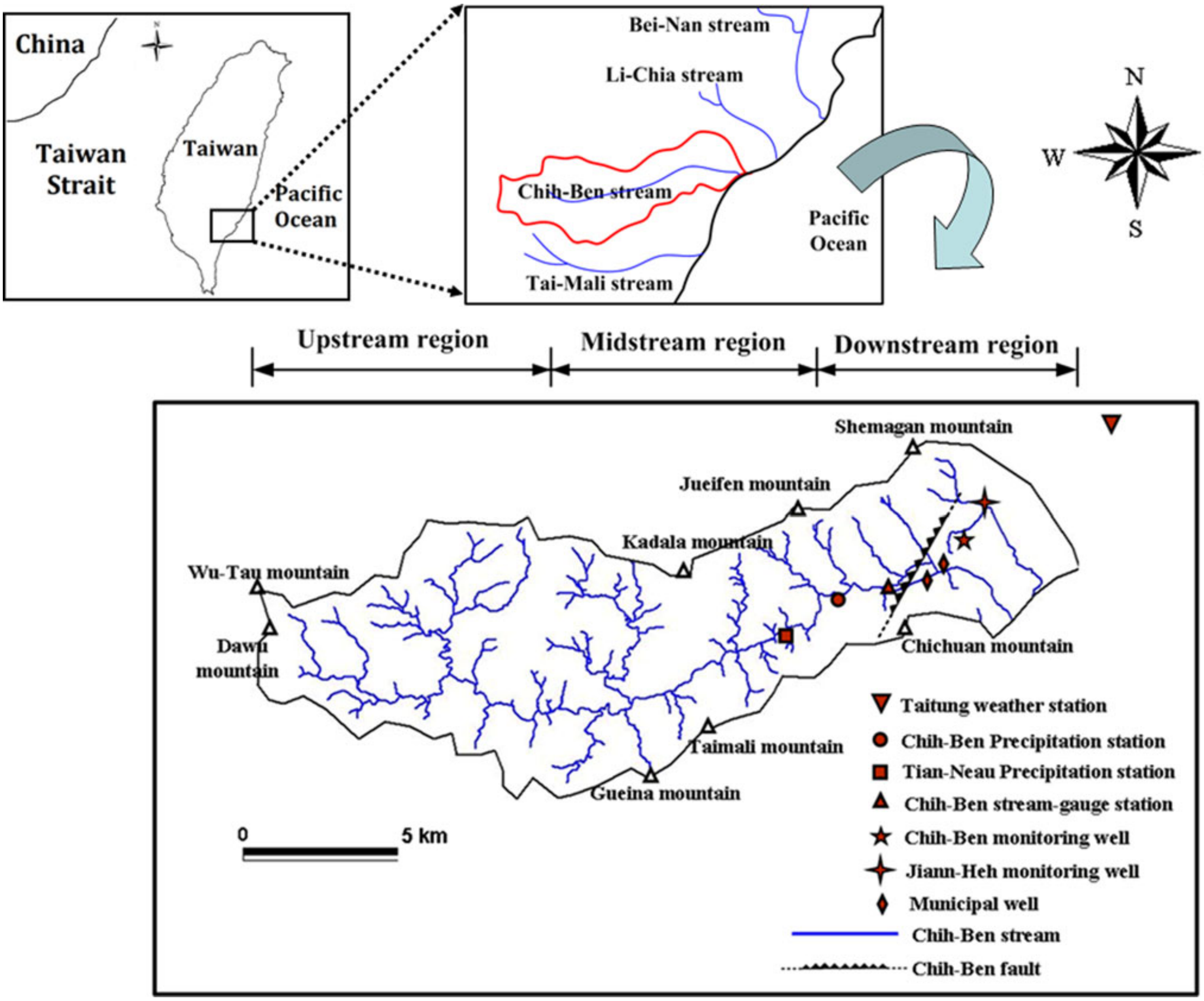

Fig. 1 Geographic location of the Chih-Ben watershed in Taiwan, showing hydrological stations

west of the fault largely consisting of mountains. Bedrock is exposed in the upper and middle reaches due to the high slope of the streambed. The regolith in the mountain area is thin (about 1–5 m), due to the high geographic relief. The alluvium in the downstream region can reach a thickness of 110 m.

Ecology

The difference between the extremes of elevation within the Chih-Ben watershed is more than 2,500 m, covering tropical, subtropical, warm-temperate, temperate, and cold-temperate zones. The geography, well-preserved forest, and humid climate make the Chih-Ben watershed a biodiverse habitat (Wang 2005). Vascular plants abound within the watershed, accounting for one fifth of Taiwan's vascular species. Wild animals are abundant, including six endangered bird species and several rare species in Taiwan (two fish, one amphibian, three reptile, eleven bird, eight mammal, and one butterfly). The plants and wild animals are preserved in their natural condition and rely heavily on the water resources of the forest in the midstream and upstream regions of the Chih-Ben watershed. Any change in groundwater level in the watershed may lead to variation in soil-water content, and deterioration of the ecosystem (Danyar et al. 2004).

Hydrometeorology

The Chih-Ben watershed has a tropical-marine climate. The annual average temperature is 24°C. Due to the Kuroshio Current passing the ocean east of the Chih-Ben watershed, both the temperature and humidity of the watershed are higher than those found in western Taiwan. Southwest monsoons and typhoons bring heavy rains from May to September. Less precipitation is brought by northeast monsoons in February, March and April. The wet season is from May to October and the dry season is from November to April. The dry and wet seasons can be clearly distinguished.

Precipitation is the major source of freshwater for the Chih-Ben watershed. There are only two precipitation stations in the Chih-Ben watershed, as shown in Fig. 1. The Tian-Neau and Chih-Ben precipitation stations are located in

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the midstream and downstream regions respectively. The sampling rates for the two stations are different. Monthly precipitation data have been manually collected at the Tian-Neau station since 1981 and daily precipitation data have been automatically collected since 1964 at the Chih-Ben station. The average annual precipitations are 2,200 and 2,400 mm for the Chih-Ben and Tian-Neau stations respectively. Annual precipitation data for the Tian-Neau and Chih-Ben stations are shown in Fig. 2. The 1981–2007 data for the Tian-Neau station (Fig. 2(b)) show variation similar to that of the Chih-Ben station (Fig. 2a) for the same data period. Therefore, long-term trends are expected to be similar for the two stations. In view of the accuracy and longer representative recording period, data from the Chih-Ben station were used to derive the long-term trend for precipitation. The Mann-Kendall test (Kendall and Stuart 1961) was first applied to the 1964–2007 annual precipitation data of the Chih-Ben station. The results showed there to be a decreasing trend at the 90% (α=10%) confidence level. Then, regular regression was applied to calculate the rate of decrease in annual precipitation, which was found to be 13.26 mm/year for the Chih-Ben station. This value was subsequently applied to the whole watershed in the modeling. The negative slope of the trend indicates that the annual precipitation in the Chih-Ben watershed is gradually decreasing. The annual precipitation intensity data for the Chih-Ben station during the study period is shown in Fig. 2c. The Mann-Kendall test was applied and results showed there to be an increasing trend at the 70% (α=30%) confidence level. The stronger intensity in precipitation may result in more surface runoff and a shorter residence time of freshwater. The lower quantity and stronger intensity of annual precipitation may indicate a shortage in the freshwater resources for the Chih-Ben watershed in the future.

Evapotranspiration

No evapotranspiration data are available for the Chih-Ben watershed, so pan-evaporation data for the period 1990–2005 from the nearby Taitung weather station (Fig. 1) were used instead. The data show that high evaporation occurs from May to October and low evaporation occurs from November to April. The evapotranspiration was calculated from the pan evaporation using the coefficient of evapotranspiration. Yeh et al. (2006) determined that the coefficient of evapotranspiration for this area is 0.82. The estimated annual evapotranspiration of the Chih-Ben watershed is 749.5 mm, which is about 31–34% of the total precipitation.

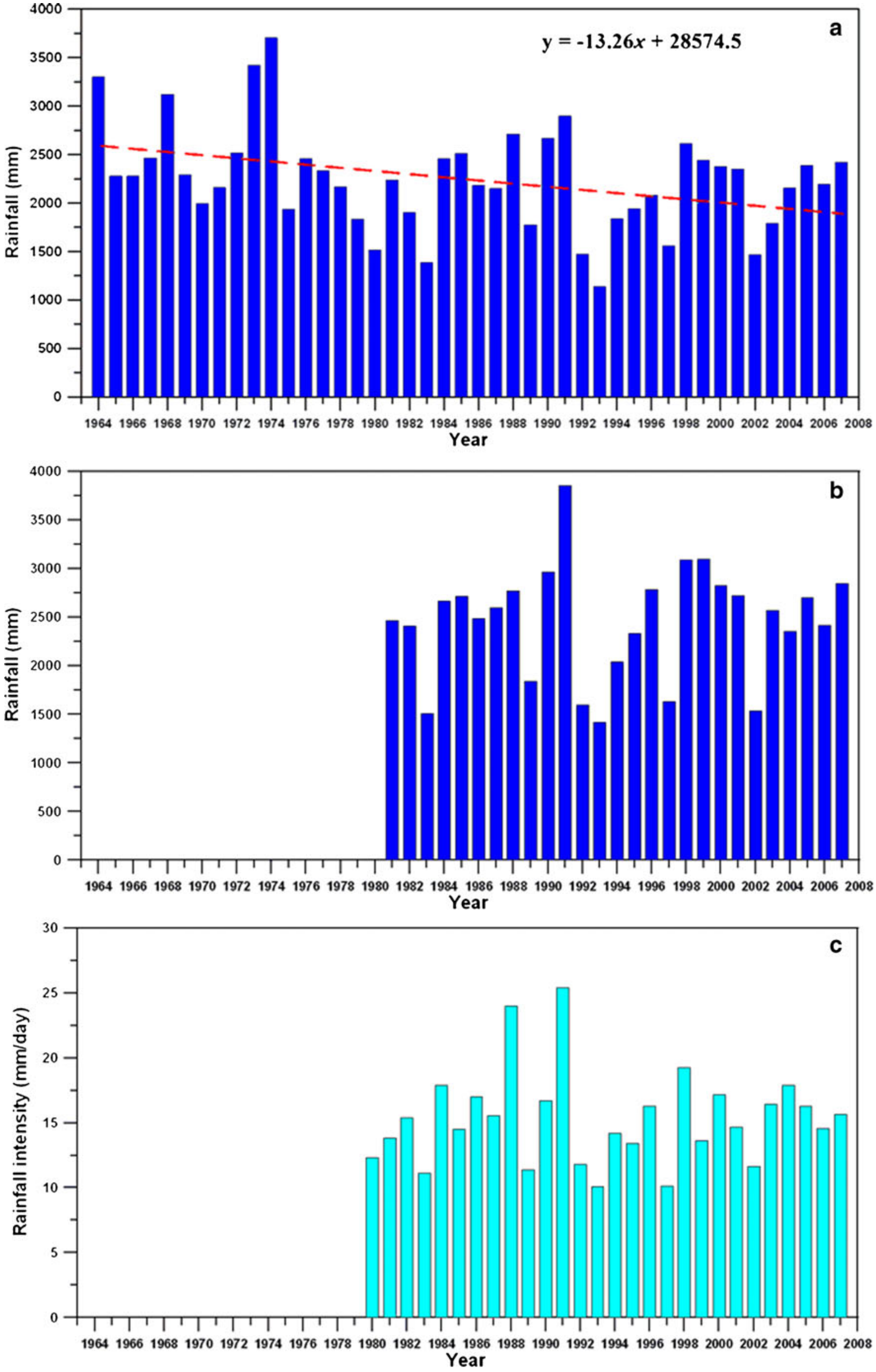
Stream flow

There is only one stream-gauge station in the Chih-Ben watershed, located in the downstream region, as shown in Fig. 1. Daily data of the stream water level for the period 1980–2007 were collected and transformed into stream flow using a rating curve. The annual stream flow and the ratio of annual stream flow to annual rainfall are shown in Fig. 3. The mean annual stream flow is 12.44 m^3/s and the standard deviation is 4.40 m^3/s. The Mann-Kendall test was applied to both the stream flow data and the ratio data. The results showed the trend for the stream flow did not pass the Mann-Kendall test, possibly due to the short data period. The Mann-Kendall test results showed there to be an increasing trend in the ratio data at the 80% (α=20%) confidence level. This indicates that the proportion of precipitation becoming stream flow increases with time. Regular regression was applied to the stream flow data to calculate the trend for annual change, and the rate of increase was found to be 0.19 m^3/s/year. The linear trend is significant at the 90% (α= 10%) confidence level according to the *t*-test (Davis 2002). The change may be due to an increase of colluvium in the landscape in the Chih-Ben watershed. Bai (2007) reported that the area subject to landslides increased from 86.09 ha in 1996 to 224.47 ha in 2007, an increase from 0.4% to more than 1% of the total land area. The landslides were mainly caused by typhoons. The increase in stream flow may not guarantee an increase in available surface water in the Chih-Ben watershed due to the lack of storage facilities, such as reservoirs or retention ponds, along the course of the stream.

Fig. 2 **a** 1964–2007 annual precipitation data for Chih-Ben station; **b** 1981–2007 annual precipitation data for Tian-Neau station, and **c** 1980–2007 annual average precipitation intensity for Chih-Ben station. The *dashed line* in **a** indicates the decreasing trend, and the regression equation for the trend line is also given ▶

Groundwater

Groundwater recharge in the Chih-Ben watershed has been studied using a mass-balance model (Water Resource Agency 2009). The recharge rate depends heavily on the precipitation and ranges from 3 to 55% of the total precipitation, with an average value of 27%. There are two monitoring wells in the Chih-Ben watershed, installed in the alluvium, as shown in Fig. 1. Monthly groundwater levels were measured manually for the period 1988–2007 for the Chih-Ben monitoring well and for the period 1972–2007 for the Jiann-Heh monitoring well. The annual average groundwater levels of the two monitoring wells are shown in Fig. 4. For the Jiann-Heh well, the mean groundwater level is 9.18 m asl, with a standard deviation of 2.61 m. For the Chih-Ben well, the mean groundwater level is 6.34 m asl, with a standard deviation of 1.77 m. The Mann-Kendall test was applied to the groundwater level data for the Jiann-Heh well, because it had a longer data period. The results showed there to be a decreasing trend at the 95% (α=5%) confidence level. Regular regression was applied to the data, and a decrease of 0.03 m/year in the annual groundwater level was found. The time-series of the ratios of the annual average groundwater level of the Jiann-Heh well to the annual rainfall and to stream flow are shown in Fig. 5. The Mann-Kendall test results showed that for the Jiann-Heh well, the ratios of the annual average groundwater level to the annual rainfall and to stream flow are decreasing at the 90% (α=10%) and 70% (α=30%) confidence levels respectively. This indicates that the proportions of precipitation to


a
y = -13.26*x* + 28574.5
Rainfall (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
Year
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
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15
20
25
30
Year

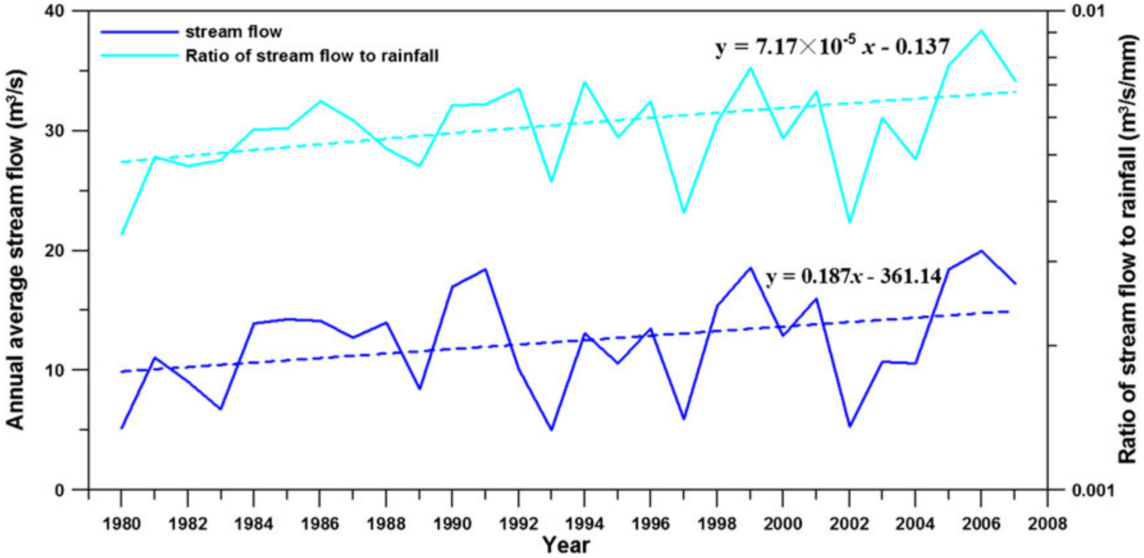

Fig. 3 Time-series of annual average stream flow and the associated ratio of stream flow to annual precipitation in the Chih-Ben watershed. *Dashed lines* indicate the trends, and regression equations for the trend lines are also given

groundwater and stream flow to groundwater decrease with time. The decrease of the groundwater level seems to be directly related to the decrease of recharge from land and stream recharge, because the water use in the Chih-Ben watershed remained about the same during the study period, as described in the next section.

Water use

Freshwater in the Chih-Ben watershed is mainly derived from groundwater and stream flow. The freshwater is mainly consumed by agriculture and tourists. Data from the county government show that the area devoted to agriculture and the annual total number of tourists were stable during the study period. The mean value of discharge from thermal springs for tourism is 0.087 m^3/s, which is small compared to the stream flow. Domestic water is abstracted from the stream and two municipal wells (as shown in Fig. 1) and treated. In the dry season, when stream flow is too low to be utilized, groundwater may serve as a source of water supply. During the wet season, when surface water is abundant, water is mainly taken from the stream. However, even in the wet season, higher stream flow does not guarantee the availability of water, due to the turbidity of the water and the destruction of water-supply facilities by floods. For example, Typhoon Morakot (August 8, 2009) brought precipitation equal to Taiwan's average annual precipitation in 3 days,

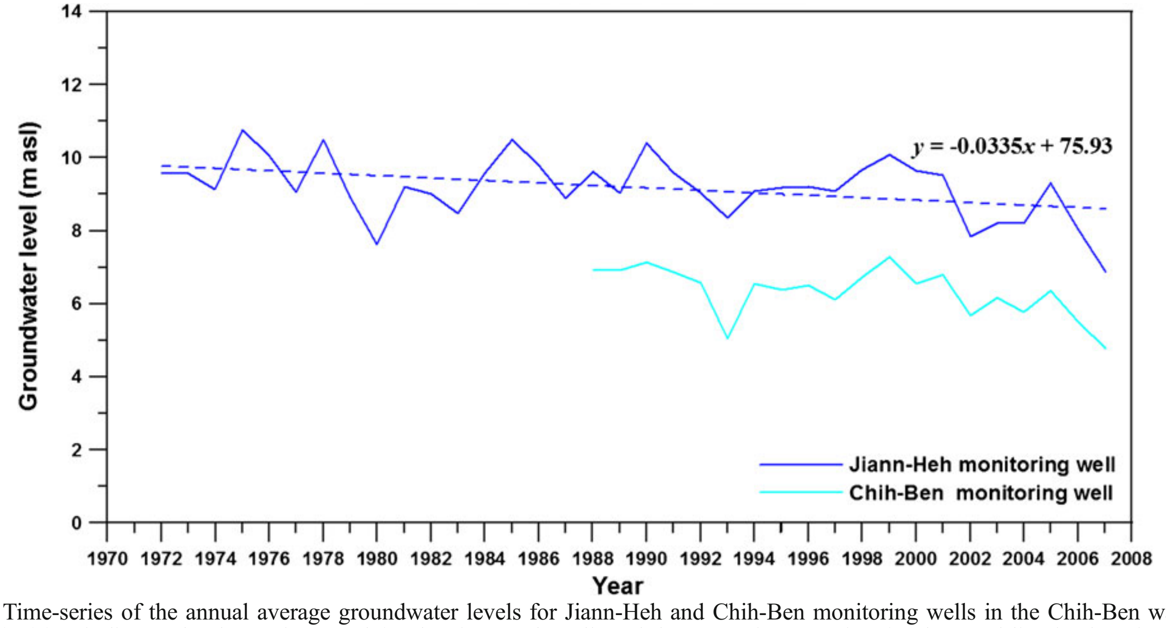

Fig. 4 Time-series of the annual average groundwater levels for Jiann-Heh and Chih-Ben monitoring wells in the Chih-Ben watershed. The *dashed line* indicates the decreasing trend for the Jiann-Heh well, and the regression equation for the trend line is also given

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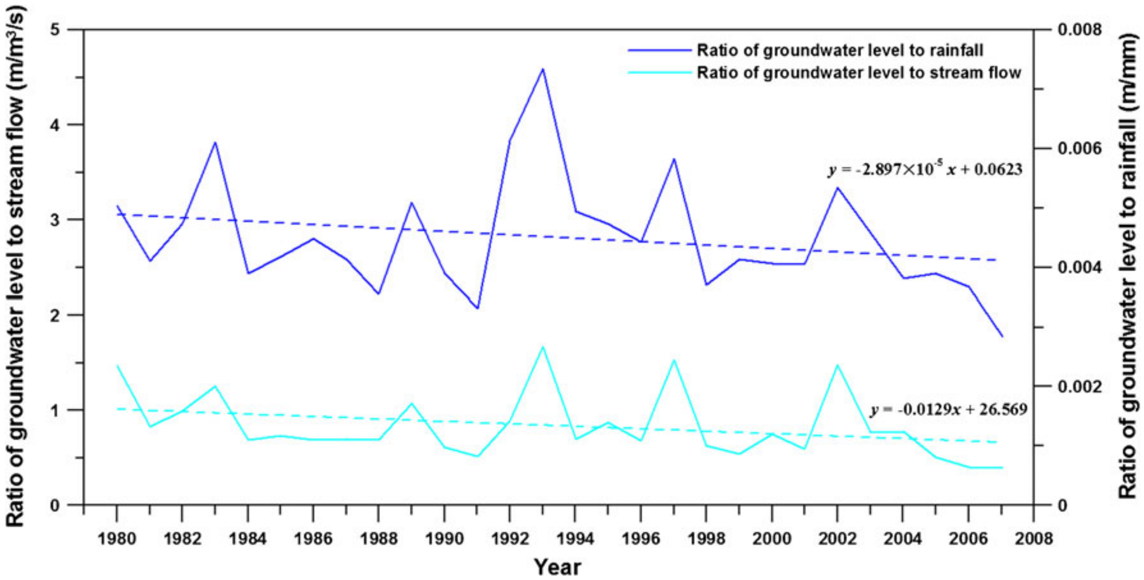

Fig. 5 Time-series of the ratios of annual average groundwater levels for Jiann-Heh well to annual rainfall and stream flow in the Chih-Ben watershed. *Dashed lines* indicate the trends, and regression equations for the trend lines are also given

causing serious damage to both public and private property within the Chih-Ben watershed. Compared to surface water, groundwater is a more reliable water source. Although the present data do not show an increase in the groundwater abstraction, future urbanization may deplete the groundwater resource.

Isotope data

Data for seasonally stable isotopes of oxygen and hydrogen were collected for Chih-Ben stream and groundwater from the two municipal wells of the local water-supply company during the period 2006–2007. Isotope data for precipitation were collected for each precipitation event. The isotope data for precipitation, groundwater, and stream flow are shown in Fig. 6. The stable-isotope mass-balance model (Gat 1980) was applied to the data in order to identify water sources. The δ^{18}O mass of groundwater is the sum of its sources from mountain recharge and precipitation on the plain. The proportions of water from different sources can be calculated once the stable-isotope values are measured for the components of the model. Based on isotope-data analysis (Yeh et al. 2009), the groundwater consists of 76% wet-season precipitation and 24% dry-season precipitation, representing a distinct seasonal variation of groundwater recharge in the study area. In the Chih-Ben watershed, 68% of the recharge to groundwater is derived from the mountain area above an elevation of 471 m asl, and 32% of the recharge is derived directly from precipitation on the alluvium (Water Resource Agency 2009). The stable-isotope analysis allows the spatial and temporal complexities of the flow-field to be integrated, offering an alternative to traditional time- and labor-intensive methods (Krabbenhoft et al. 1990)

Lumped recharge models

The Chih-Ben watershed is covered by thin regolith in the mountain area and thick unconsolidated or semi-consolidated deposits in the alluvial plain. Land recharge and streambed recharge both play important roles in the recharge of groundwater. Due to the lack of spatial soil-moisture and precipitation data, lumped models were adopted to analyze the recharge in the Chih-Ben watershed.

Lumped model for land recharge

The interaction between surface water and groundwater is complex and can be modeled by sophisticated models that combine stochastic spatial-temporal weather generators with a groundwater model (Stoll et al. 2011). This study adopted an alternative solution—the index of effective infiltration—that bypasses the complexities of the stochastic approach and the extra uncertainties that arise from imposing restrictive, predefined model structures, to account for the temporal variation in precipitation. The concept of the index of effective infiltration is similar to the α index for infiltration (Viessman and Lewis 2003) and the loss-rate of rainfall (Brutsaert 2005) for a rainfall event, but it also considers the temporal variation. The index of effective infiltration, ω [L], is defined as:

$$\omega = \alpha \cdot t + \beta \tag{1}$$

where t [T] is the time, α [L/T] is the rate of increase or decrease, and β [L] is the constant infiltration. The index of effective infiltration separates the precipitation into two parts: precipitation greater than the value of the index is defined as excess rainfall, which contributes to surface runoff; precipitation less than the value of the index is the amount of precipitation that is actually added to the soil,

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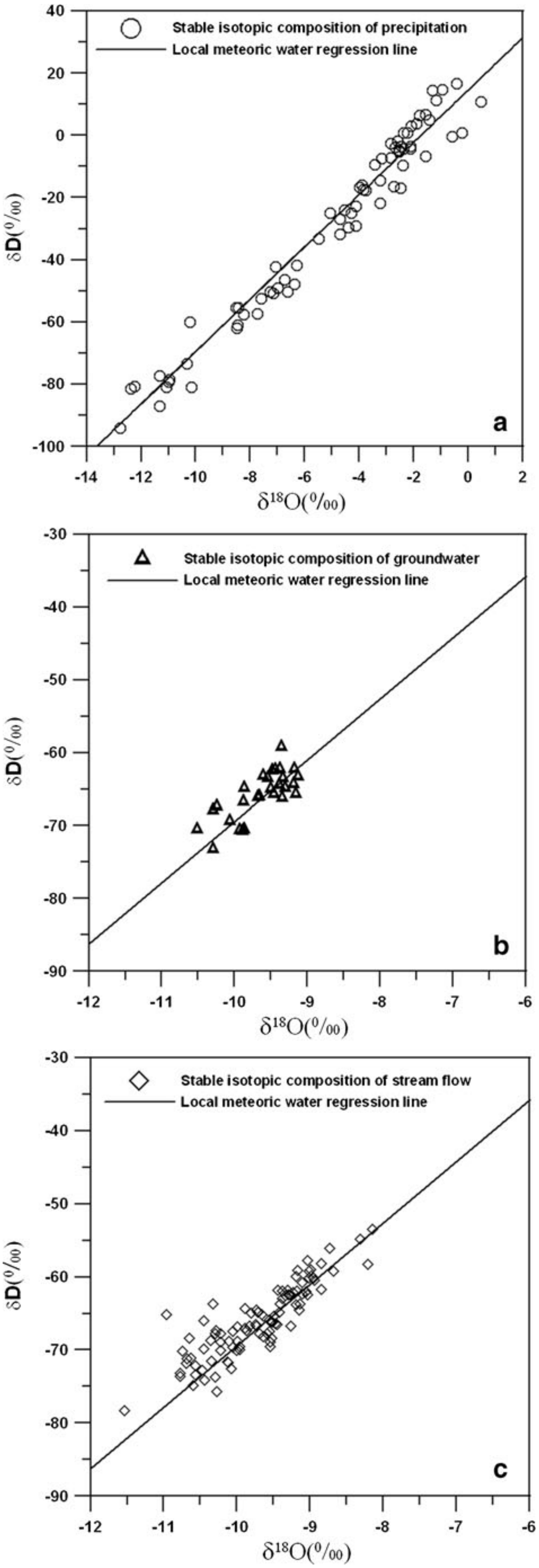

Fig. 6 Stable-isotope data for **a** precipitation, **b** groundwater, and **c** stream flow, for the Chih-Ben watershed

with part of it recharging the groundwater. Therefore, the index of effective infiltration directly reflects the maximum amount of infiltration. For a basin with a constant infiltration rate, α is zero. When the intensity of precipitation increases with time, the field soil may have limited capacity to transmit rainfall (via infiltration) and will then generate more surface runoff. The surface runoff can be related to precipitation through the overland-flow model, which is described by the kinematical wave equation for flow over a plane (Eagleson 1970; Woolhiser and Goodrich 1988) as:

$$\frac{\partial h}{\partial t} + \frac{\partial a h^m}{\partial x} = r_i(t) - f_i(t) \qquad (2)$$

where h [L] is the average depth of the overland flow per unit area averaged over some characteristic area; t is the time; x is the distance down along the slope; $r_i(t)$ [L/T] is the rainfall rate; and $f_i(t)$ [L/T] is the infiltration rate. If flow resistance is approximated by the Manning law, the parameter $a = S^{1/2}/n$, where S is the slope of the plane, m=5/3, and n is the Manning coefficient. Equation (2) shows that a precipitation event with stronger rainfall intensity contributes more to surface runoff. This result was demonstrated by a numerical study by Wooding (1965). In such a case, more surface runoff is generated with a negative α in Eq. (1). When the precipitation is more uniform with a smaller intensity in time, the field soil is able to transmit rainfall adequately, generating less overland flow, and α becomes positive.

A fixed infiltration rate (i.e., α=0) was tested first. The monthly precipitation data for the study period (1988–2007) shown in Fig. 5, and β values of 100, 150, 200, 250, and 300 mm were applied. The infiltrated water I is estimated based on:

$$I = \begin{cases} P & \text{for } P \prec \omega \\ \omega & \text{for } P \geq \omega \end{cases} \qquad (3)$$

where P [L] is the precipitation.

To evaluate the effectiveness of the index model, the degree of correlation between infiltrated water and groundwater level was determined for the various indices. It was found that indices above 150 mm have correlation coefficients higher than 0.6. An index of 200 mm showed the highest linear correlation, with a coefficient of 0.666. Preliminary groundwater modeling using an index of infiltrated water of 200 mm showed that the groundwater level was being underestimated and overestimated before and after 2005, respectively, which indicates the underestimation and overestimation of infiltrated water before and after 2005, respectively.

To improve the effectiveness of the index method, the increasing tendency in rainfall intensity and the decreasing trend of the groundwater level shown in Fig. 4 were considered. As a result, an index of effective infiltration that decreases with time was chosen (i.e., $\alpha \prec 0$). The oblique-cut method was developed and applied to the index of effective infiltration to give it a decreasing trend, as shown in Fig. 7, based on a rate of change of –13.26 mm/year and an effective infiltration of 200 mm for 2005. The portion below the index refers to infiltration, whereas that above the index refers to excess rainfall that contributes to overland flow and stream flow.

Time-series for infiltration (derived from the oblique-cut method) and groundwater level from the Chih-Ben station for 20 years (1988–2007) are plotted in Fig. 8. The infiltration and groundwater level data show similar patterns and the correlation coefficient between them is up to 0.82, supporting the use of the oblique-cut method. The infiltration is directly transformed to land recharge by multiplication factors of 0.2 and 0.35 for areas above and below an elevation of 400 m asl, respectively. These factors were chosen so that the total recharge (the sum of land recharge and streambed recharge as described in the next section) would be 26% of the total precipitation, which matches the reported recharge rate from the mass-balance analysis (Water Resource Agency 2009), as shown in section Basin-scale groundwater response to precipitation variation and anthropogenic pumping. The rest of the infiltration serves as the inter-flow and part of evapotranspiration. It was added back to the excess rainfall to obtain the total excess rainfall. If the index of effective infiltration is appropriate, the total excess rainfall should be closely related to the surface runoff, i.e., the stream flow. The regression of stream flow with respect to the total excess rainfall is shown in Fig. 9, with a goodness of fit of 0.657. This supports the use of the index of effective infiltration.

Lumped model for river recharge

The interaction between the stream and the aquifer leads to flow exchange between groundwater (or the hyporheic zone) and surface water (Harvey and Bencala 1993). The dynamics of stream-aquifer interactions are relatively poorly understood (Sophocleous 2002; Kalbus et al. 2006). A detailed investigation of the geometry of the streambed and the related permeability distribution is needed, but it is often unattainable on a large spatial scale. A simpler approach was adopted for this study. Since the streambed recharge is physically related to the stream flow, which is correlated to the total excess rainfall with a goodness of fit of 0.657 (as shown in Fig. 9), the total excess rainfall was used as the basis for estimating the streambed recharge. The total excess rainfall includes the streambed recharge, evapotranspiration, and surface runoff. Considering the decreasing trend in the ratio of groundwater level to the stream flow as shown in Fig. 5, the oblique-cut method was applied to the total excess rainfall in order to estimate the streambed recharge, as shown in Fig. 10. The total excess rainfall below the oblique cut is related to the streambed recharge. Correlations were calculated for the groundwater level and the portion of excess rainfall below the oblique cut. Change rates of 0, –1, –2, –3, and –4 mm/month were used for the oblique-cut method. A rate of change of –2 mm/month had the highest correlation coefficient (0.29). The low value of cross-correlation was not unexpected, due to the nonlinear and dynamic watershed response (Jain and Kumar 2009); it was considered sufficient for the lumped model of streambed recharge and was applied in this study.

The total excess rainfall is the sum of surface runoff, evapotranspiration, and streambed recharge. The total excess rainfall below the oblique cut was first related to

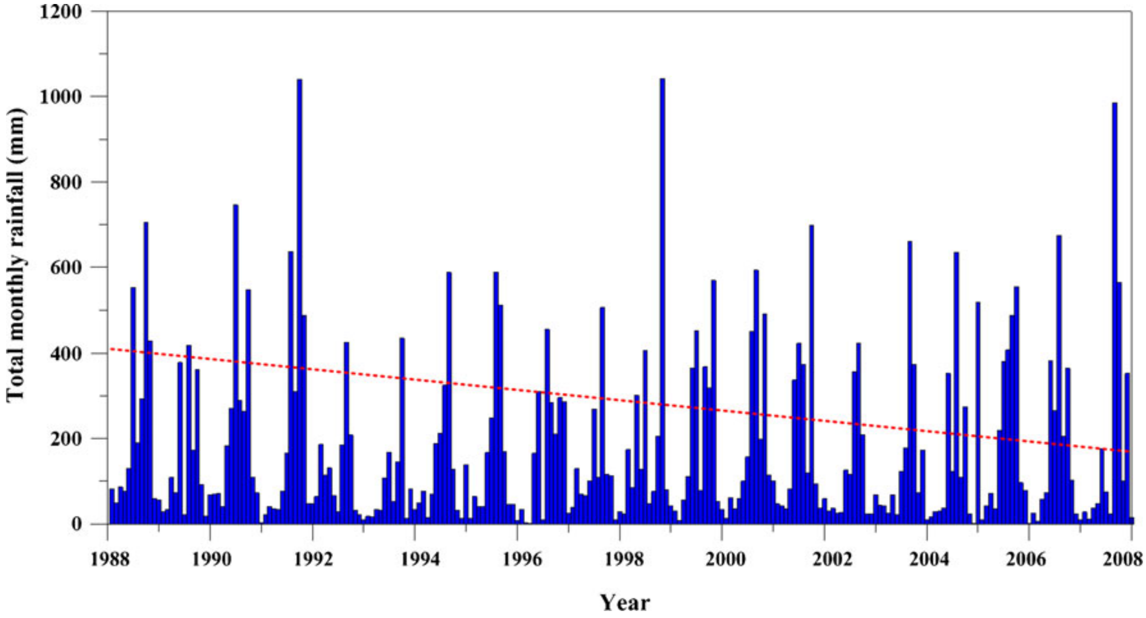

Fig. 7 Oblique-cut method applied to precipitation. The *red dashed line* shows the trend in the index of effective precipitation. Precipitation below the oblique cut is the water for infiltration. Precipitation above the oblique cut contributes to surface runoff

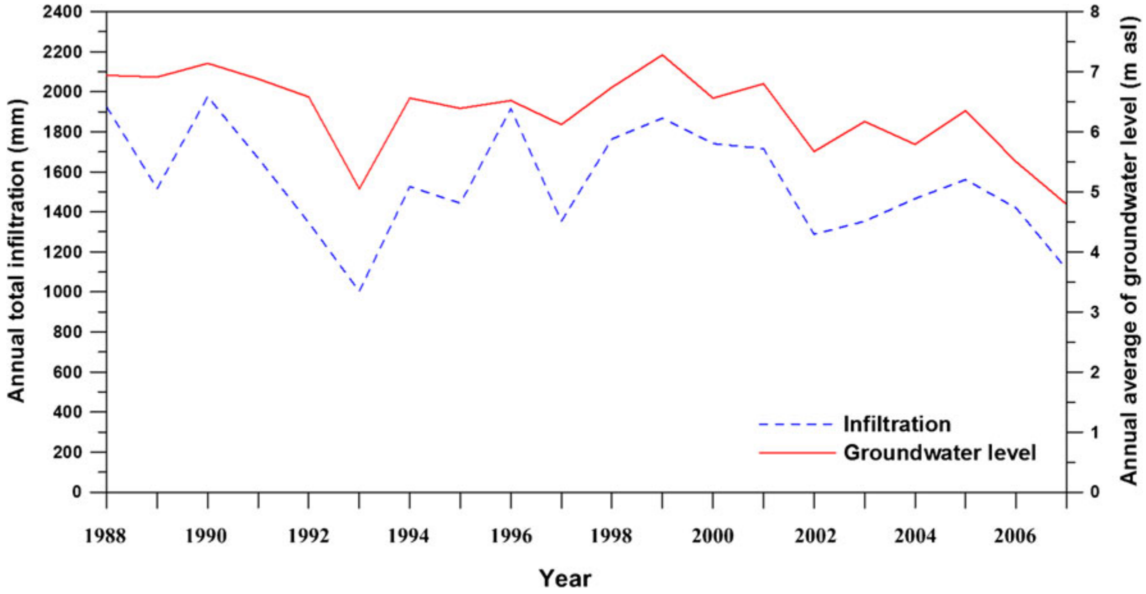

Fig. 8 Comparison between total infiltration water (derived from the oblique-cut method) and groundwater level for Chih-Ben station, showing similar behavior, with a correlation coefficient of 0.82

the stream flow through the regression line in Fig. 9. Then, the stream flow was related to the stream water level using the rating curve from the stream gauge station. The stream water level was used to represent the monthly average value, which is directly related to the groundwater level variation. The stream water level was used in the river package of the distributed groundwater model. The stream water level from the measured stream flow was not applied to the groundwater model due to its high fluctuation (the monthly representative stream level for streambed recharge is difficult to define). The streambed recharge can be calculated from the modeling results. With the land recharge, the total recharge is close to the reported recharge rate of the Chih-Ben watershed as shown in section Basin-scale groundwater response to precipitation variation and anthropogenic pumping.

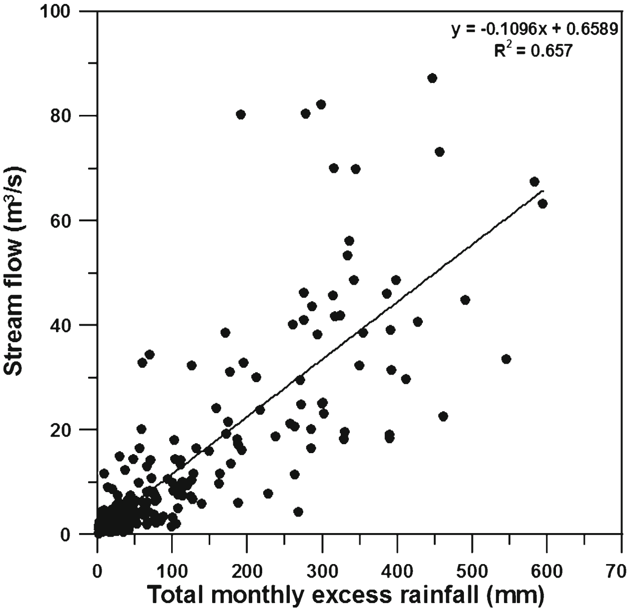

Fig. 9 Comparison between total excess rainfall and stream flow (goodness of fit = 0.657); the regression line and equation are also shown

Distributed groundwater model

To understand the basin-scale groundwater spatial-temporal response to precipitation variation and anthropogenic pumping, a distributed groundwater model is needed. A hydrogeological model was constructed for the Chih-Ben watershed based on information about geology, hydrogeology, and physiography. A distributed numerical model was used to simulate the groundwater response.

Hydrogeological model

The aim of establishing a conceptual hydrogeological model is to simplify field conditions, integrate geological data, and reasonably analyze the groundwater system. Conceptualizing the initially complicated geological situation is an extremely important step. For this purpose, based on the geological features of the study area and spatial extent of the aquifer, the hydrogeological structure and conceptual model of groundwater were constructed as a foundation for the numerical groundwater model. The groundwater flow in the study area was then evaluated using numerical simulation.

The hydrogeological model follows the concept of piedmont modeling (Daniel and Dahlen 2002). Eighteen drilling data-sets are available for obtaining lithological information in the downstream region of the Chih-Ben watershed (Water Resource Agency 2009). Five of the cores are about 500 m long and the rest are in the range of 13.6–150 m. Two electrical resistance measurements were performed along the streambed (Water Resource Agency

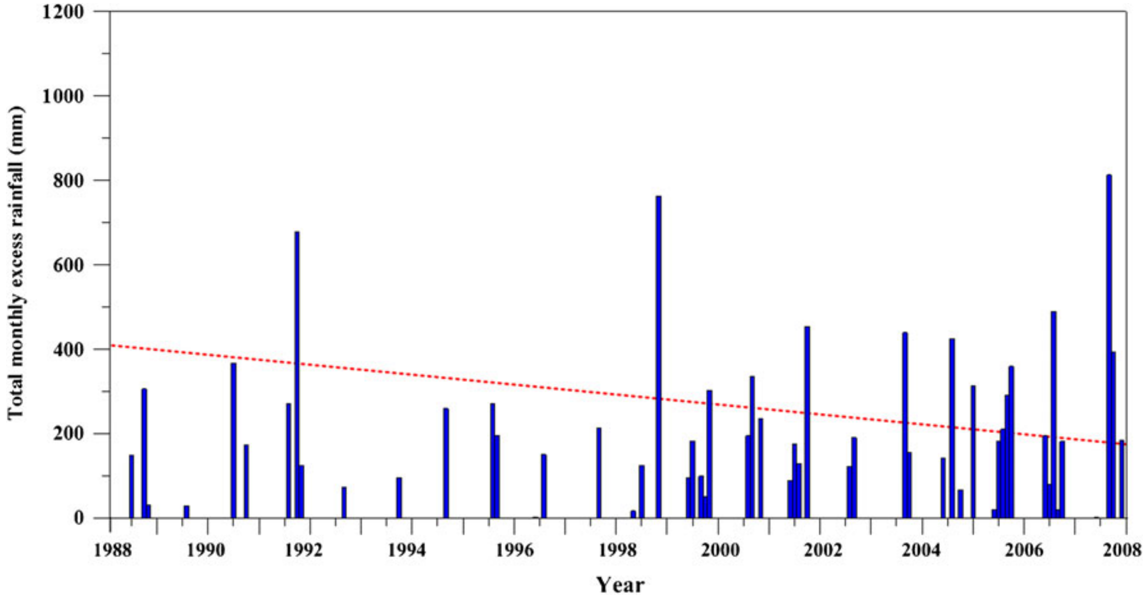

Fig. 10 Oblique-cut method applied to the excess rainfall for the period 1988–2007. The *red dashed line* shows the oblique cut. The total excess rainfall below the oblique cut is related to the streambed recharge

2009). The conceptual hydrogeological model of the Chih-Ben watershed was constructed based on the field drilling data, lithology distribution, and electrical-resistivity tomography using four layers, representing (from top to bottom) saprolite, weathered-bedrock layer, and two unweathered-bedrock layers, as shown in Fig. 11.

Numerical model

A distributed model using the finite-difference numerical software MODFLOW-SURFACT (Hydrogeologic Inc. 1996) was constructed to model the 1988–2007 groundwater response of the Chih-Ben watershed. The study area was subdivided into uniform rectangular grids of 63 rows

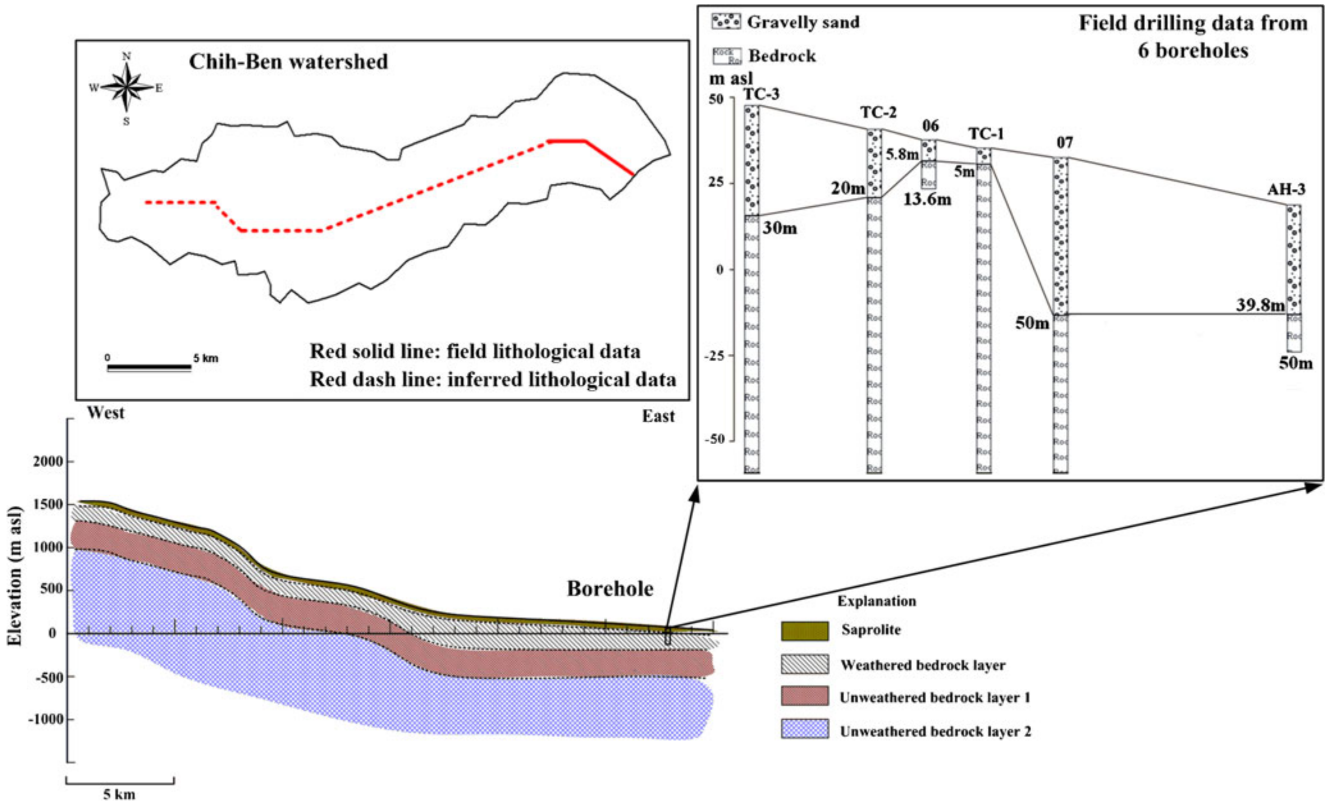

Fig. 11 Hydrogeological conceptual model for the Chih-Ben watershed. The system of four layers was constructed based on field drilling data (shown in the inset figure), lithological information, and data from electrical resistivity tomography

and 27 columns, with four layers, as shown in Fig. 12. The cell size was set to 500 m×500 m. The height of each layer increases from downstream towards upstream to match the topography. The River package was applied to simulate the interaction of the stream and the groundwater aquifer. The model time-step was in months.

Hydrogeological parameters

Initial values of hydraulic conductivity were assigned to layers based on the lithology data using textbook values (Domenico and Schwartz 1998; de Marsily 1986). The values of hydraulic conductivity in the aquifers range from 10^{-3} to 10^{-5} m/s. Field double-ring infiltration tests confirmed the values of saturated hydraulic conductivity to be 10^{-2}–10^{-4} m/s for alluvium. The hydraulic conductivity of the unweathered rock layer is 10^{-9}–10^{-13} m/s. The Chih-Ben fault was modeled by unweathered rock. The values of specific storage range from 10^{-7} to 10^{-2} m^{-1} and those for specific yield range from 0.01 to 0.3.

Initial groundwater level

Due to the lack of spatially distributed groundwater observation data, the study used ground surface elevation as the initial groundwater level for a steady-state simulation, using the precipitation of January 1988. Then, the results were used as the initial condition of the following 20-year transient simulation to reduce the influence of initial hydraulic head on the simulation results.

Pumping

The amount of extracted groundwater plays a critical role in the modeling. Groundwater is mainly extracted by the municipal wells of the local water supply company. The 2003–2007 pumping rates were applied in the modeling, as only data for that period were available. The average pumping rate was calculated and applied to the period 1988–2002.

Boundary conditions

The ridges of Kadala, Jueifen, and Shemagan mountains were identified as the northern boundary. The ridge of Wu-Tau mountain was identified as the western boundary. The ridges of Gueina, Taimali, and Chichuan mountains were identified as the southern boundary. The ridges serve as groundwater divides and were therefore defined as zero-flow boundaries. The Pacific Ocean was identified as

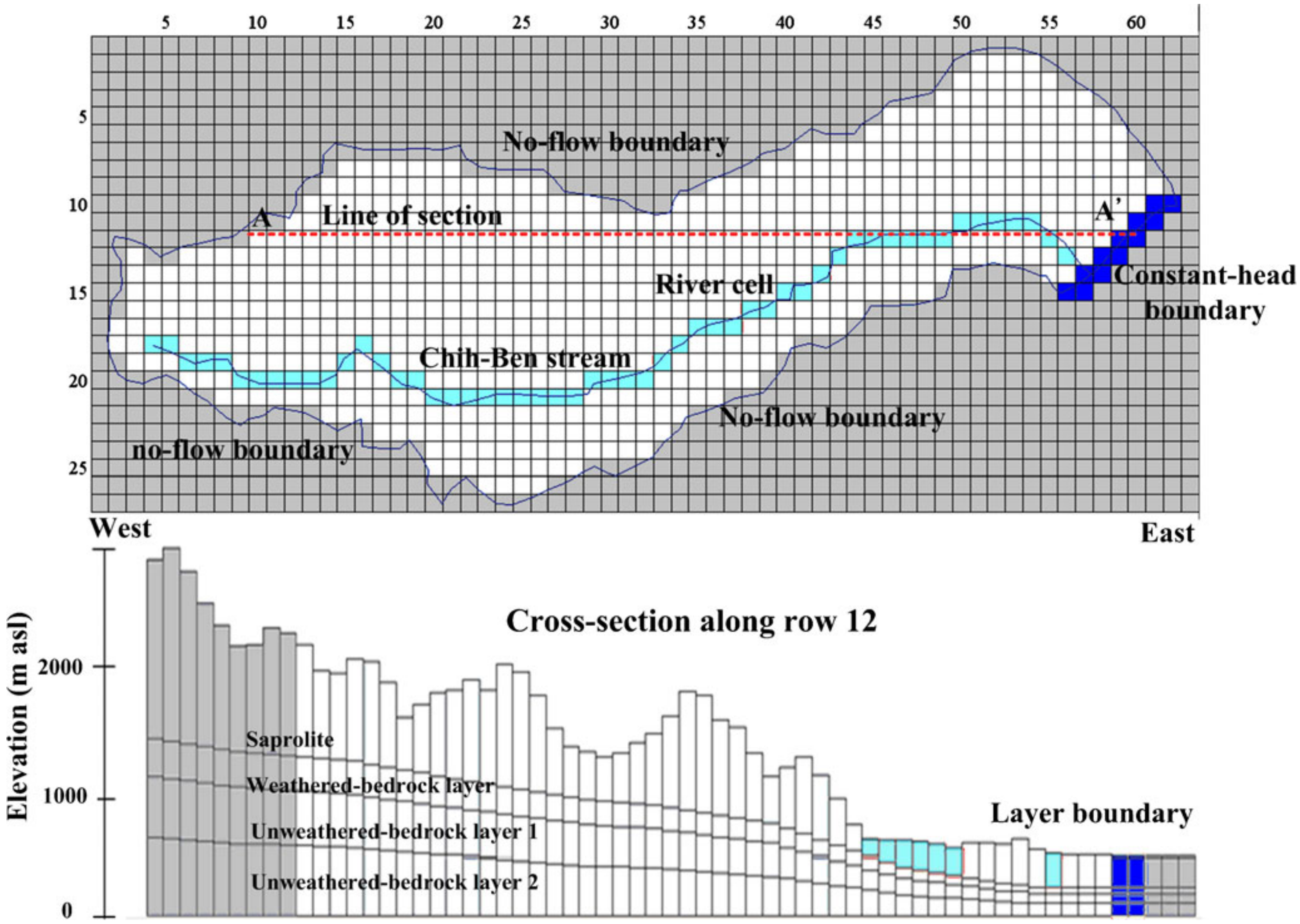

Fig. 12 Numerical model of the Chih-Ben watershed, showing model grid and boundary types

the eastern boundary, with the coastline being defined as a prescribed-head boundary. Although the seawater level is affected by the tide, it was regarded as having a constant water level of zero from a long-term perspective, and thus was set as a constant-head boundary.

The upper boundaries are land recharge and streambed recharge. The river is distributed along the main reach of the Chih-Ben stream, modeled as a prescribed-head boundary. The interaction of the stream and the groundwater was modeled by the River package. The stream stage was provided by the lumped streambed-recharge model. For the stream reach below an elevation of 400 m asl, the stream depth was assumed to be the same as that calculated at the gauge station, while for the stream reach above an elevation of 400 m asl, it was assumed to be half that value. If the stream stage is higher than the surrounding groundwater level, the stream recharges the aquifer; otherwise, the aquifer recharges the stream. The recharge extent for the land recharge covers the entire Chih-Ben watershed, with its recharge value provided by the lumped land-recharge model. The bottom boundary of the domain was set as a no-flow boundary due to the expected deep, dense, and unfractured bedrock.

Basin-scale groundwater response to precipitation variation and anthropogenic pumping

The basin-scale groundwater response to precipitation variation and anthropogenic pumping was modeled by the distributed groundwater model. The lumped recharge models link precipitation and groundwater to provide the recharge from the ground surface and the streambed. The 20-year (1988–2007) monthly groundwater-level data from the Chih-Ben and Jiann-Heh groundwater monitoring wells were used for the Chih-Ben watershed modeling. Observed 1988–2002 groundwater-level data and isotope analyses of oxygen were first used for model calibration, to obtain patterns of groundwater flow by gradually adjusting modeling parameters; data from 2003–2007 were used for model verification. Model calibration was achieved using a trial-and-error procedure by matching simulated heads with observed heads and by matching the proportion of flow paths from the mountain area above an elevation of 471 m asl that reach the municipal wells with the reported ratio.

The calibration results indicate that the average error between simulated and observed water levels in the Chih-Ben well is –0.56 m, and that the root mean square (RMS) error is 1.13 m. The average error between the simulated and observed water level in the Jiann-Heh well is –0.62 m, and the RMS error is 1.64 m. The results are regarded as favorable when compared to the groundwater fluctuation of up to 10 m in the two monitoring wells.

Particle tracking incorporates infinitesimally small imaginary particles in the groundwater flow system to track the route or flow-line of the transport of fluid particles. The velocity range is calculated and the transport route of particles is tracked using the head range resulting from the groundwater flow model. This method is often deployed to visualize the groundwater flow and route track of contaminants. In the present study, numerical simulations utilizing the groundwater flow software MODFLOW-SURFACT were used to initiate particle-tracking simulations using MODPATH (Pollock 1994). Stable-isotopic data analysis shows that 68% of the groundwater is recharged from the mountains at an elevation of above 470 m asl, and that 32% is from plain precipitation (Water Resource Agency 2009). Therefore, the major recharge source of groundwater in the watershed is the mountains; the ratio of water from mountain recharge to plain precipitation (from isotope analysis) is 14:6. Using the particle-tracking technique offered by MODPATH, 40 particles were released from the cells of the two municipal wells in the transient numerical modeling, for the inverse calculation of particle paths. Results show that ratios of groundwater from the mountains to groundwater from plain precipitation were 14:6 and 15:5 for the two wells, respectively. The results are compatible with the data from the isotope analysis and confirm the suitability of the model parameters.

For the model verification, the 2003–2007 monthly groundwater-level data were utilized. The results show that the observed groundwater levels fit the simulated levels. The average error of the simulated and observed levels for the Chih-Ben well is –0.16 m with an RMS error of 1.04 m, and that for the Jiann-Heh well is –0.43 m with an RMS error of 1.64 m.

The water budget shows that during the modeling period, the average total recharge was 1.06×10^{8} m^3/year the average pumping rate was 5.11×10^{5} m^3/year, the discharge to sea was 4.45×10^{7} m^3/year, and the discharge to streams was 6.84×10^{7} m^3/year. There is a decrease of 7.41×10^{6} m^3/year in the storage of the groundwater system. The total recharge rate, including land recharge and streambed recharge, is about 26% of the total precipitation, which is close to the reported value of 27% (Water Resource Agency 2009).

The distributed numerical model also provides the detailed spatial-temporal groundwater dynamic responses of the Chih-Ben watershed to precipitation variation for 1988–2007. Two observation points were assigned in the numerical model as imaged wells, MW-1 and MW-2, in the midstream and upstream areas, respectively, to obverse the impacts of precipitation variation and anthropogenic pumping, as shown in Fig. 13. Imaged wells MW-1 and MW-2 show significant drawdowns of up to 28.76 and 28.01 m, respectively, during the modeling period (1988–2007). The drawdowns at the Chih-Ben well and the Jiann-Heh well were only 1.52 and 2.71 m, respectively. The results show that under current precipitation variation and pumping activity, there is a minor groundwater decrease in the downstream region but a significant groundwater drawdown in the mountain areas. The information provided by the basin-scale modeling enables an evaluation to be made of the sustainability of groundwater use, based on the whole watershed rather than just local water use at the wells.

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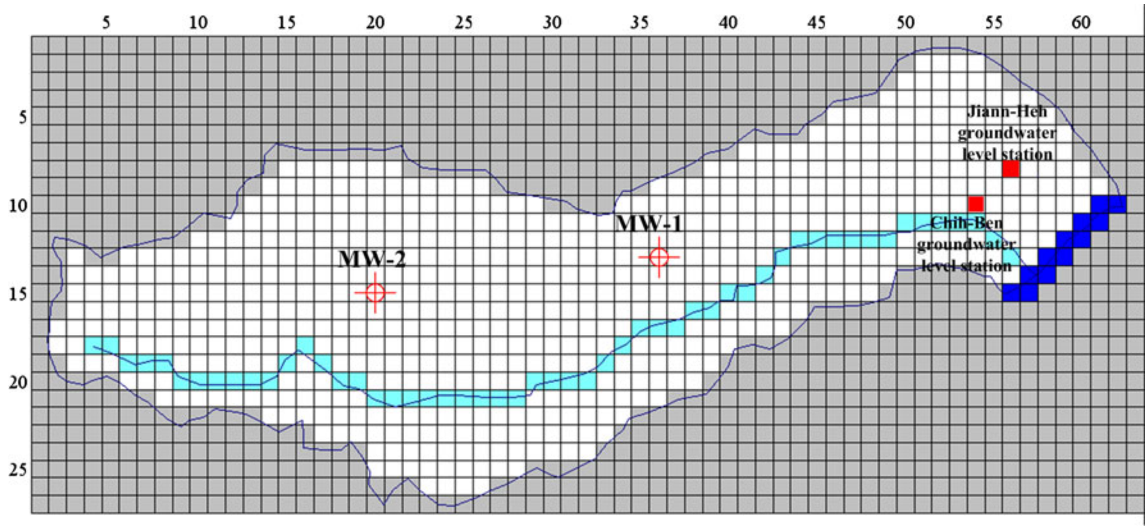

Fig. 13 Location of imaged wells (*MW-1* and *MW-2*) and municipal wells in the numerical model (see the legend from Fig. 12 for the meaning of other symbols)

Safe yield and sustainable water resources

Safe yield is commonly used to determine the quantity of water that can be regularly extracted over the long term without dangerously depleting storage resources (Lee 1915). The Hill method (Todd 1959) plots simulated pumping rate against drawdown, with the safe yield determined as the groundwater pumping rate that causes zero drawdown. Historically, for the Chih-Ben watershed, the lowest annual precipitation (1,500 mm) and the highest annual precipitation (3,000 mm,) are 0.7 and 1.4 times the average value (2,200 mm), respectively. The lowest, average, and highest precipitation were used in the modeling to represent dry, normal, and wet precipitation scenarios, respectively. To obtain the safe yield, the precipitation for each scenario was first run for the steady state. Three pumping rates were run consecutively following the steady state, and the groundwater change was calculated for each year. The groundwater change and pumping rate were plotted for each precipitation scenario. Safe yield was determined as the pumping rate associated with zero groundwater-level change (Sophocleous 1998).

Figures 14, 15, and 16 show the derivation of safe yields at the municipal wells for dry, wet, and normal precipitation scenarios, respectively. Three data pairs of average annual groundwater level change versus pumping rate are plotted for each scenario. The safe yield is derived as the pumping rate at the point of zero groundwater-level change of the regression line. The safe yields for dry, wet, and normal precipitation scenarios are 0.77, 2.09, and 1.25 million m^3/year, respectively. The safe yields for dry and wet climate scenarios are 0.6 and 1.7 times the safe yield

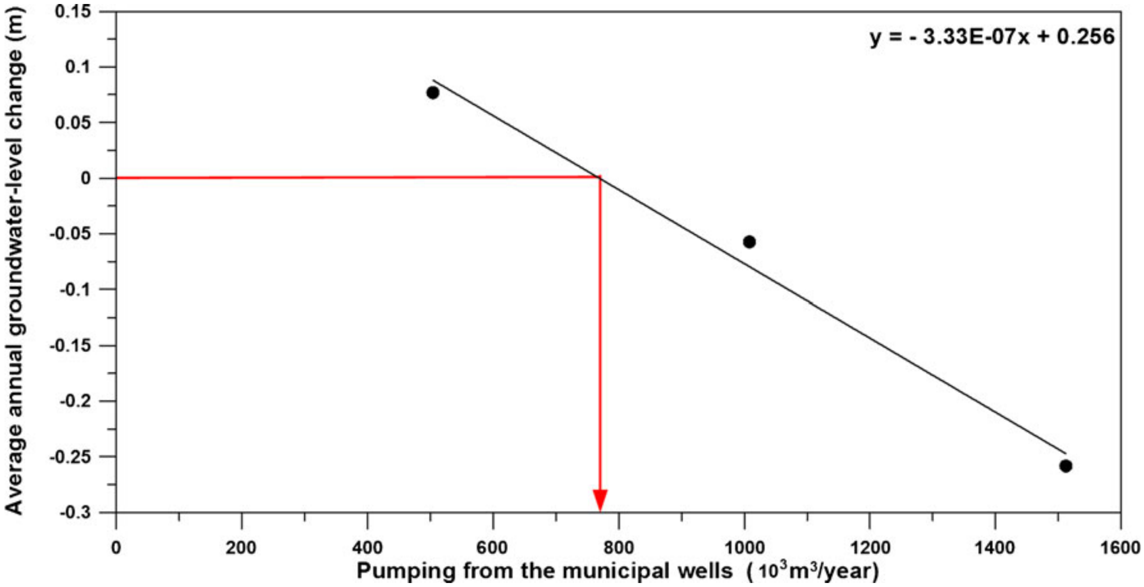

Fig. 14 Derivation of safe yield for dry climate scenario (annual rainfall of 1,500 mm); the regression line and equation are also shown

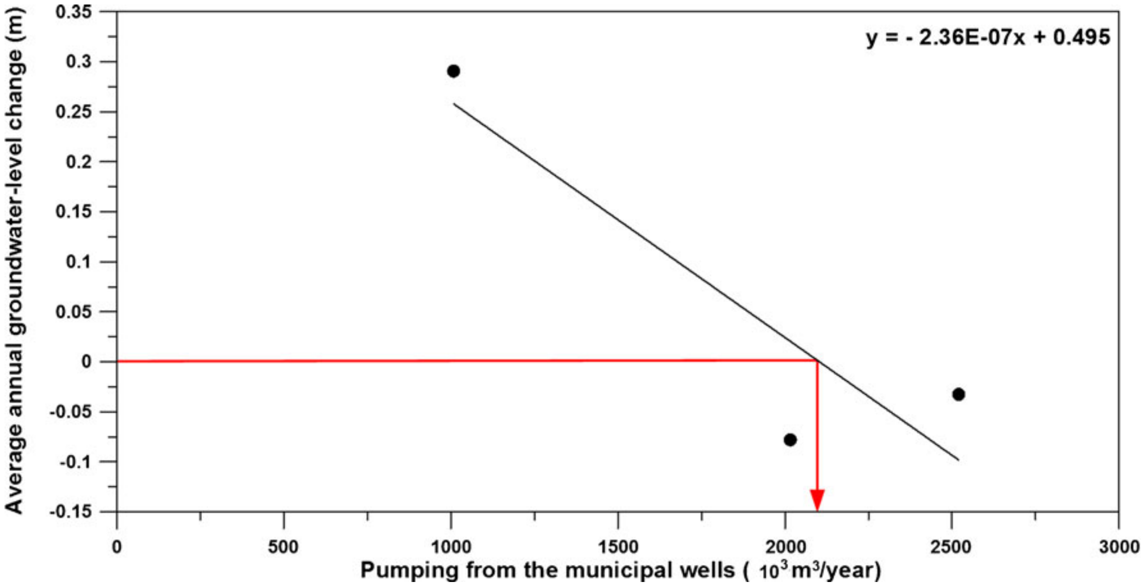

Fig. 15 Derivation of safe yield for wet climate scenario (annual rainfall of 3,000 mm); the regression line and equation are also shown

of the normal climate scenario, respectively. The results indicate that for years with precipitation below the average value, the corresponding safe yields decrease more than the decreasing rate of rainfall, and for years with rainfall above the average rainfall, the corresponding safe yields increase more than the increasing rate of rainfall. These characteristics should be considered in water-resources management.

Figure 17 shows the safe yield versus annual precipitation for three precipitation scenarios. The safe yield is not a constant; it is sensitive to precipitation variation. The safe yield decreases with decreasing precipitation. Considering the significantly decreasing trend of annual precipitation in the Chih-Ben watershed, a lower safe yield is expected in the future. Long-term conjunctive operation of the surface water and groundwater may mitigate the stress of water demand in dry years.

The model was used to simulate groundwater-level changes in the mountain areas caused by pumping at the safe yield in the downstream region. Using data from the two imaged wells, MW-1 and MW-2, in the mid and upper reaches, respectively, the anthropogenic impact on the groundwater system was evaluated. Safe yield for the normal precipitation scenarios was applied to the municipal wells as the pumping rates under the historical 20-year (1988–2007) precipitation condition. The results show that despite a quite stable water table in the alluvium in the downstream region, continuously decreasing groundwater levels appear in the mountain area, as shown in Fig. 18. The falls in groundwater level were 33.12 and

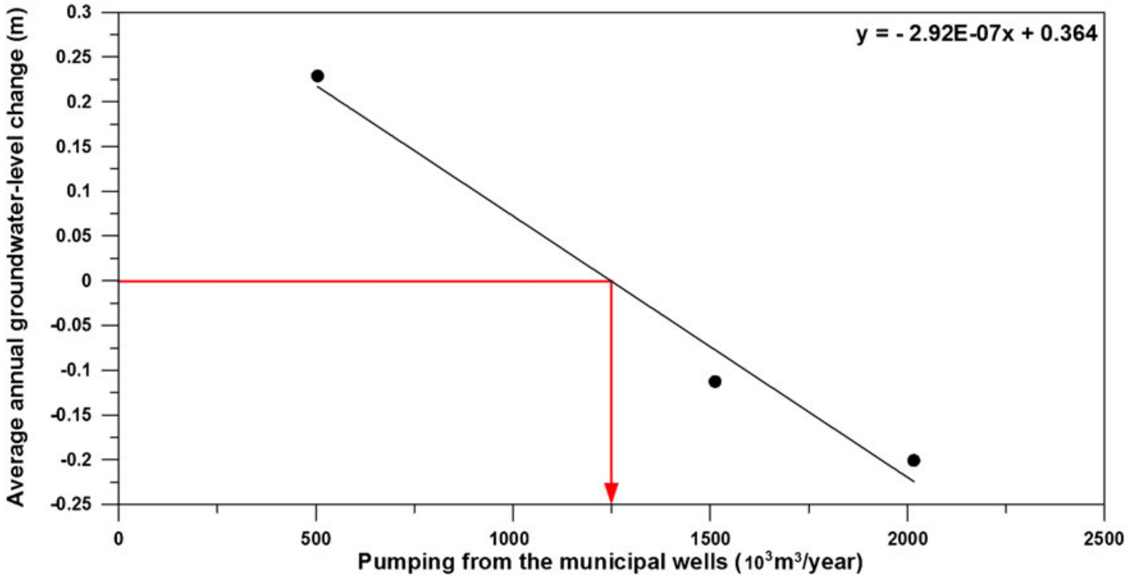

Fig. 16 Derivation of safe yield for average climate scenario (annual rainfall of 2,200 mm); the regression line and equation are also shown

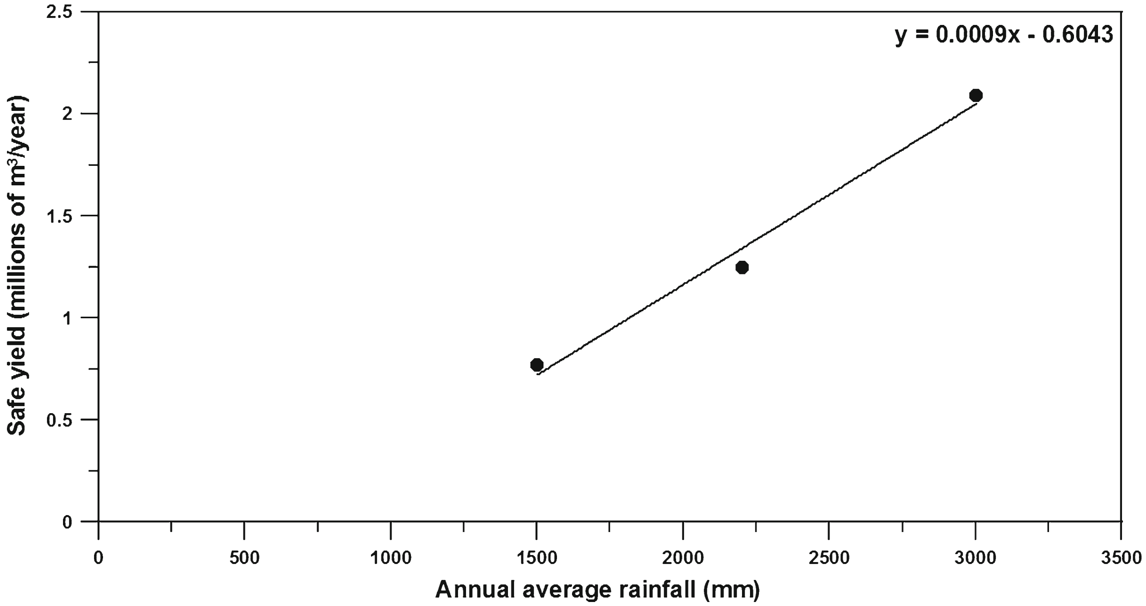

Fig. 17 Relationship between rainfall and safe yield in the Chih-Ben watershed; the regression line and equation are also shown

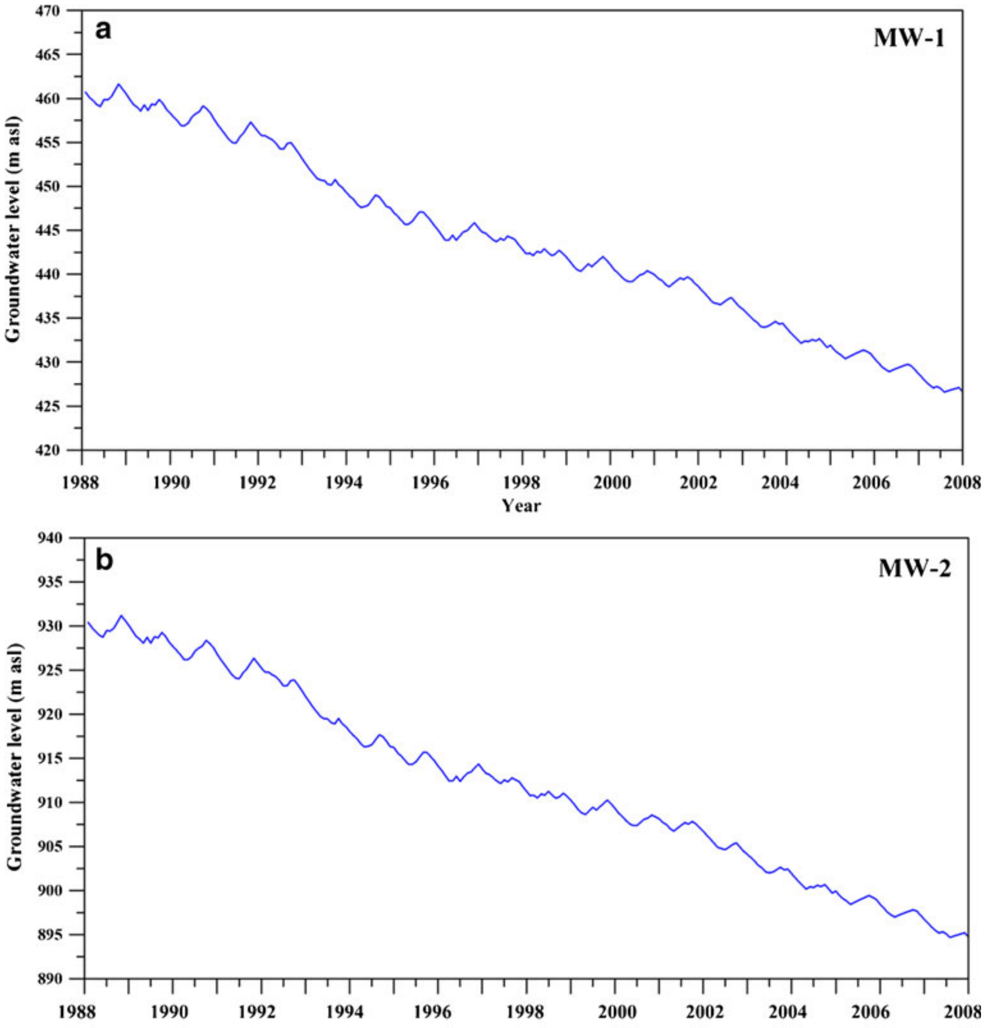

Fig. 18 Groundwater levels at **a** MW-1 and **b** MW-2 for 1988–2007 historical precipitation using the safe yield of the normal scenario

34.63 m for imaged wells MW-1 (midstream) and MW-2 (upstream), respectively.

Although the groundwater level in the downstream region is unchanged or only slightly changed using the safe yield as the pumping rate, the groundwater level decreases dramatically in the midstream and upstream areas. The decline of the groundwater level in mountain areas directly leads to greater difficulty accessing groundwater, and a reduction in the base flow in the mountain area. Lower groundwater levels in the mountain areas will also lead to a decrease of soil water content and deterioration of the ecosystem. The groundwater in the midstream and upstream areas of the basin is more vulnerable to precipitation variation and anthropogenic pumping than that in the downstream area. Since the mountain area is the main recharge area of the watershed (Wiegandt 2008), the decrease of groundwater level indicates a possible shortage of fresh groundwater sources. Sustainable water resources should, therefore, be evaluated on the basin scale instead of relying on the concept of safe yield for human consumption.

Assumptions and limitations

As with any hydrologic model, the integrated modeling applied in this study is subject to a number of assumptions and approximations. The integrated model could use more complex distributed surface and surface-flow software such as HydroGeoSphere (Therrien et al. 2007), if data were sufficient. The model calibration could be improved by using small-scale spatial-temporal hydrological knowledge when data are available. The oblique-cut method for land and streambed recharge used in this study could be improved by using more complicated models. The linear oblique cut provides the possible trend of future precipitation changes and is suitable for conservative water-resources management. Other lumped models such as Topmodel (Beven 1997) and PRMS (Leavesley et al. 1983) could be applied in a future investigation to determine their applicability. Risk and uncertainty assessments of sustainable groundwater resources need to be performed through stochastic analyses such as Monte Carlo simulation. Although the integrated model results require further verification and evaluation, the methodology developed in this study provides a practical and useful way of generating a physically based evaluation of basin-scale groundwater dynamic response to anthropogenic activity and precipitation variation for data-poor watersheds.

Conclusions

The basin-scale groundwater dynamic response to precipitation variation was studied using an integrated model that comprises lumped models for land and streambed recharge and a distributed model for groundwater. The integrated model was applied to the Chih-Ben watershed in Taiwan for a recent 20-year period (1988–2007). The Chih-Ben watershed has a decreasing amount and increasing intensity of precipitation with time. A reduction in recharge and an increase in surface runoff were observed, resulting in a complicated groundwater dynamic response.

Based on the observed decreasing trends in precipitation and groundwater level, and an increasing trend in stream flow, an oblique-cut method was applied to separate precipitation data into infiltration water and excess rainfall, to take into account temporal precipitation variation. The land recharge is proportional to the infiltration water and the stream recharge is related to the total excess rainfall. The oblique-cut method was applied to the total excess rainfall to assess the streambed recharge. These lumped models provide the recharge required for the distributed groundwater model.

A distributed groundwater model was constructed for the Chih-Ben watershed based on information about geology, hydrogeology, and physiography. The model was used to simulate the basin-scale groundwater dynamic response to the 1988–2007 precipitation variation.

The 1988–2002 groundwater-level data were used for model calibration. Besides 2003–2007 groundwater-level data, information about water sources was derived from isotope data. The groundwater level represents the potential energy of the flow field and the isotope data contain information about the groundwater flow paths. Both types of data were used to calibrate the constructed groundwater model. It was found that under current precipitation variation and anthropogenic pumping, the groundwater level in the mountain area decreased by over 20 m, which affects the ecosystem of the Chih-Ben watershed.

Safe yields for municipal wells in the Chih-Ben watershed were estimated using the Hill method for dry, wet, and normal precipitation scenarios. The safe yield was found to be sensitive to precipitation variation; it decreased with decreasing precipitation. Simulation results show that a small drawdown in the downstream region may cause a significant decrease of groundwater levels in the mountain areas. Extracting groundwater for human consumption at the safe yield may lead to unsustainable usage of groundwater resources when considered at the basin-scale, and therefore to the deterioration of the ecosystem. Since mountain areas are important for biodiversity and serve as the major recharge source for groundwater, water resources for human consumption should be surveyed at a basin scale rather than only in the alluvium.

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References

Alley WM, Leake SA (2004) The journey from safe yield to sustainability. Ground Water 42(1):12–16

Alley WM, Reilly TE, Franke OL (1999) Sustainability of groundwater resources. US Geol Surv Circ 1186:79

Alley RB, Marotzke J, Nordhaus WD, Overoect JT, Peteet DM Jr, Pielke RA, Pierrehumbert RT, Rhines PB, Stocker TF, Talley LD, Wallace JM (2003) Abrupt climate changes. Science 299 (5615):2005–2010

Anderson MS, Acworth RI (2009) Stream-aquifer interactions in the Maules Creek catchment, Namoi Valley, New South Wales, Australia. Hydrogeol J 17(8):2005–2021

Bai LT (2007) Application of satellite imagery to assess landslide and landscape indicators of eastern Hualien and Taitung debris disaster watershed areas. Bachelor Thesis, National Pingtung University of Science and Technology, Pingtung, Taiwan

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate change and water: technical paper VI of the Intergovernmental Panel on Climate Change (IPCC). IPCC Secretariat, Geneva, 210 pp

Beven K (1997) TOPMODEL: a critique. Hydrol 11:1069–1085

Bredehoeft JD (1997) Safe yield and the water budget myth. Ground Water 35(6):929

Brutsaert W (2005) Hydrology: an introduction. Cambridge University Press, New York, 605 pp

Daniel CC III; Dahlen PR (2002) Preliminary hydrogeologic assessment and study plan for a regional Ground-Water resource investigation of the blue ridge and piedmont provinces of North Carolina. UUS Geol Surv Tech Water Resour Invest Rep 02-4105

Danyar S, Yudong S, Jumakeld M (2004) Influence of groundwater level change on vegetation coverage and their spatial variation in arid regions. J Geogr Sci 14(3):323–329

Davis JC (2002) Statistics and data analysis in geology. Wiley, New York

de Marsily G (1986) Quantitative hydrology: groundwater hydrology for engineers. Academic Press, San Diego, 440 pp

Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology. Wiley, New York

Eagleson PS (1970) Dynamic hydrology. McGraw-Hill, New York

Ferguson IM, Maxwell RM (2010) Role of groundwater in watershed response and land surface feedbacks under climate change. Water Resour Res 46:W00F02

Gat JG (1980) The isotopes of hydrogen and oxygen in precipitation. In: Frita P, Fontes JCh (eds) Handbook of environmental isotope geochemistry. Elsevier, New York, pp 21–74

Gleick PH (2006) The world's water 2006–2007: the biennial report on freshwater resources. Island Press, Washington, DC

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: impacts of climate change on groundwater. J Hydrol. doi:10.1016/j.jhydrol.2011.05.002

Gurdak JJ, Hanson RT, Green TR (2009) Effects of climate variability and change on groundwater resources of the United States, USGS Fact Sheet 2009-3074. http://pubs.usgs.gov/fs/2009/3074/. Cited 18 January 2012

Harvey JW, Bencala KE (1993) The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resour Res 29(1):89–98

Hsu KC, Li ST (2010) Clustering spatial-temporal precipitation data using wavelet transform and self-organizing map neural network. Adv Water Resour 33(2):190–200

Hydrogeologic Inc (1996) MODFLOW-SURFACT software. version 2.2. Hydrogeologic Inc, Hemdon, VA

Jain A, Kumar S (2009) Dissection of trained neural network hydrologic models for knowledge extraction. Water Resour Res 45:W07420

Kalbus E, Reinstorf F, Schirmer M (2006) Measuring methods for groundwater, surface water and their interactions: a review. Hydrol Earth Syst Sci Discuss 3:1809–1850

Kendall MG, Stuart A (1961) The advanced theory of statistics, vol 2. Hafner, New York

Krabbenhoft DP, Bowser CJ, Anderson MP, Valley JW (1990) Estimating groundwater exchange with lakes 1: the stable isotope mass balance method. Water Resour Res 26(10):2445–2453

Kundzewicz ZW (2007) Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change, Cambridge University Press, Cambridge, pp 173–210

Leavesley GH, Lichty RW, Troutman BM, Saindon LG (1983) Precipitation-runoff modeling system: user's manual. US Geol Surv Tech Water Resour Invest Rep 83-4238

Lee CH (1915) The determination of safe yield of underground reservoirs of the closed basin type. Trans Am Soc Civ Eng 78:148–151

Liu SC, Fu C, Shiu CJ, Chen JP, Wu F (2009) Temperature dependence of global precipitation extremes. Geophys Res Lett 36:L17702

Loucks DP (2000) Sustainable water resources management. Water Int 25(1):3–10

Meinzer OE (1923) Outline of ground-water hydrogeology with definitions. US Geol Surv Water Suppl Pap 494

Owor M, Taylor RG, Tindimugaya C, Mwesigwa D (2009) Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. Environ Res Lett 4(3):035009

Pollock DW (1994) User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model. US Geol Surv Open-File Re 94-464

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

Sophocleous M (1998) On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development in perspectives on sustainable development of water resources in Kansas. Kansas Geol Surv Bull 239

Sophocleous M (2000) From safe yield to sustainable development of water resources: the Kansas experience. J Hydrol 235:27–43

Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10:52–67

Stoll S, Hendricks Franssen HJ, Butts M, Kinzelbach W (2011) Analysis of the impact of climate change on groundwater related hydrological fluxes: a multi-model approach including different downscaling methods. Hydrol Earth Syst Sci 15:21–38

Therrien R, McLaren RG, Sudicky EA (2007) HydroGeoSpher: a three-dimensional numerical model describing gully-integrated subsurface and surface flow and solute transport. Groundwater Simulations Group, University of Waterloo, Waterloo, ON, Canada

Todd DK (1959) Groundwater hydrology. Wiley, New York

UNESCO Working Group M IV (1999) Sustainability criteria for water resource systems. Cambridge University Press, Cambridge, UK

Viessman W, Lewis GL (2003) Introduction to hydrology, 5th edn., Prentice Hall, Englewood Cliffs, NJ, 612 pp

Von Holle K (2008) AGU revises position statement on climate change. EOS Trans AGU 89(5):41

Wang JC (2005) The Investigation on the Biota of Tawushan Nature Preserve-Chihpenhsi Watershed. Report 92-13 of Forestry Bureau of Taiwan, Taipei

Water Resource Agency (2009) Investigation of groundwater resource in Chih-Ben and Jin-Lin creek basins, Report MOEA-WRA0950416, Water Resource Agency, Taipei

Wiegandt E (2008) Framing the study of mountain water resources: an introduction, in Mountains—sources of water, sources of knowledge. Springer, Heidelberg, Germany

Wilson, Gelhar (1974) Ground-water quality modeling. Ground Water 12(6):399–408

Wooding RA (1965) A hydraulic model for the catchment-stream problem: II numerical solutions. J Hydrol 3:268–282

Woolhiser DA, Goodrich DC (1988) Effect of storm rainfall intensity patterns on surface runoff. J Hydrol 102:335–354

Yeh HF, Chen JF, Chen WP, Chang KL, Lee CH (2006) Evaluation of pan coefficients for estimating reference evapotranspiration in southern Taiwan. American Geophysical Union Fall Meeting, San Francisco, December 2006

Yeh HF, Lee CH, Hsu KC, Chang PH, Wang CH (2009) Using stable isotopes for assessing the hydrological characteristics and sources of groundwater recharge. J Environ Eng Manage 19 (4):195–201

Zhou Y (2009) A critical review of groundwater budget myth, safe yield and sustainability. J Hydrol 370:207–213