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# Estimation of groundwater recharge using water balance coupled with base-flow-record estimation and stable-base-flow analysis

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**Abstract** In this paper, the long-term mean annual groundwater recharge of Taiwan is estimated with the help of a water-balance approach coupled with the base-flow-record estimation and stable-base-flow analysis. Long-term mean annual groundwater recharge was derived by determining the product of estimated long-term mean annual runoff (the difference between precipitation and evapotranspiration) and the base-flow index (BFI). The BFI was calculated from daily streamflow data obtained from streamflow gauging stations in Taiwan. Mapping was achieved by using geographic information systems (GIS) and geostatistics. The presented approach does not require complex hydrogeologic modeling or detailed knowledge of soil characteristics, vegetation cover, or land-use practices. Contours of the resulting long-term mean annual *P*, BFI, runoff, groundwater recharge, and recharge rates fields are well matched with the topographical distribution of Taiwan, which extends from mountain range toward the alluvial plains of the island. The total groundwater recharge of Taiwan obtained by the employed method is about 18 billion tons per year.

**Keywords** Groundwater recharge · Water balance · Base-flow-record estimation · Stable-base-flow analysis · Base-flow index

## Introduction

Estimating groundwater recharge is an important issue in hydrogeologic studies. In most cases, recharge is estimated by multiplying the magnitude of water-level fluctuations in wells by the specific yield of the aquifer material or by applying the water budget model or using the water-balance method. While other parts of the water-balance equation, such as precipitation and runoff, are relatively easy to measure, recharge remains an elusive process to quantify. This is especially so because it depends not only on precipitation but also on meteorological conditions, as well as on soil type, soil–moisture status, vegetation cover and condition, slope, cultivation practices, and most of all, on evapotranspiration, which is a function of the previously noted factors.

Currently, standard techniques of estimating regional recharge most often involve (1) applying a water-balance model, where the moisture content of the soil is tracked through time (Finch 1998; Simmons and Meyer 2000; Chen et al. 2005), or (2) parameter-value adjustment of groundwater flow models (Lee et al. 2000; Jyrkama et al. 2002; McDonald and Harbaugh 2003). Application of the first approach, while generally less intensive computationally, requires knowledge of the vegetation and soil types within the study area, in addition to a number of basic meteorological variables such as air temperature and precipitation. The second approach is more taxing of computer resources because a potentially complex groundwater flow model may have to be run repeatedly in search of a multidimensional parameter-value optimum.

With the purpose of inspecting recharge, estimating the groundwater component of streamflow has been a research focus for more than a century. Following the work of Boussinesq (1877), numerous studies (Bevans 1986; Moore 1992; Rutledge 1992; Rutledge and Daniel 1994; Mau and Winter 1997; Chen and Lee 2003) have investigated the recession of streamflow, particularly baseflow, and have estimated the contribution of groundwater to streamflow. In some cases, the value of baseflow is assumed to be equal to groundwater recharge. The primary purpose of most researches is to determine the groundwater component of streamflow. Nevertheless, only a handful of researchers, including Meyboom (1961), Rorabaugh (1964), and Rutledge (1992), have focused on groundwater recharge through analyzing the streamflow data. Rutledge (2005) further summarizes constraints involved with the application of the Rorabaugh model for estimating groundwater recharge. Mau and Winter (1997) have provided the instantaneous recharge method and the constant recharge method of hydrograph analysis to estimate recharge.

Although several methods have been used to estimate the groundwater discharge and recharge from streamflow records, the most commonly used are the techniques of baseflow separation. These methods aim at estimating a continuous or daily record of baseflow under the streamflow hydrograph. In other words, it requires an extended period of recording efforts in estimating the long-term groundwater discharge, as well as the exercise of a variety of manual methods (Horton 1933; Barnes 1939; Olmsted and Hely 1962; Dzhamalov 1973; Zektser 1977) or a rapid analysis and that introduces some elements of subjectivity in the research for the base-flow-record estimation (Rutledge 1992; Mau and Winter 1997). One study employed a water-balance approach and digital filter method to estimate base recharge to groundwater in Nebraska (Szilagyi et al. 2003).

To increase the speed of analysis and reduce the subjectivity inherent in manual analysis, Rutledge (1993) proposes several computer programs: RECESS, RORA, and PART, and newer versions have been proposed (Rutledge 1998, 2000). The research of this paper is accomplished using an automated analysis procedure by the programs described above.

To prevent overestimation caused by rainstorm events, several studies (Rutledge 1993, 1998, 2000; Zektser 2002; Chen and Lee 2003) indicate that the baseflow in the dry season should be chosen to be the average value of the year. For this purpose, the stable-base-flow analysis is developed in this study to obtain a more reliable result.

Based on our previous research (Chen and Lee 2003), the proposed approach in this paper offers an estimate of total recharge for regions where groundwater evaporation is negligible, i.e., for areas where the water table is not so close to the surface that the vegetation can use it through its root system. The approach combines the water-balance model, base-flow-record estimation, and stable-base-flow analysis. It is computationally simple, requires minimal optimization, and does not need information on vegetation and soil types. The technique is mainly a collection of existing methods which, to the best knowledge of the authors, have not yet been combined in a similar fashion for recharge estimation. It is expected to be most practical for regional-scale studies where the long-term mean annual value of the spatially variable recharge is of interest. The approach was applied using data from Taiwan to demonstrate the utility of the technique.

## Methodology

The water balance of a geographic region can, in general, be written as

$$P = \mathrm{ET} + q_{\mathrm{s}} + q_{\mathrm{b}} + q_{\mathrm{N}} + \Delta S, \tag{1}$$

where $P$ is the precipitation ($\mathrm{LT}^{-1}$); ET is the evapotranspiration ($\mathrm{LT}^{-1}$); $q_{\mathrm{s}}$ is the surface runoff ($\mathrm{LT}^{-1}$); $q_{\mathrm{b}}$ is the groundwater contribution to runoff ($\mathrm{LT}^{-1}$), which is the definition of baseflow; $q_{\mathrm{N}}$ is the net flux ($\mathrm{LT}^{-1}$) of any water entering or leaving the region other than precipitation (e.g., water diversions, groundwater flux across the basin boundaries, and irrigation); and $\Delta S$ is the change in stored water ($\mathrm{LT}^{-1}$) within the area. Generally, evapotranspiration is by far the largest loss term in Eq. 1, amounting to 70% of precipitation (including evaporation from open water surfaces) on a global basis (Brutsaert 1982). Long-term ET measurements are practically nonexistent, and the available ET estimation methods may differ by as much as 10–20% on an annual basis (Vorosmarty et al. 1998). In light of these uncertainties, the general assumption that $\Delta S$ is negligible in most cases on a long-term basis may be well justified. For our purposes, this assumption is employed, acknowledging that for some watersheds where hydraulic heads have changed significantly in the past, it may lead to biased recharge estimates. It is further assumed that $q_{\mathrm{N}}$ in Eq. 1 can be neglected as well, at least on a regional scale.

With regard to the stated assumptions, Eq. 1 simplifies to

$$P - E = q_{\mathrm{s}} + q_{\mathrm{b}} \tag{2}$$

which states that the difference between precipitation and ET emerges as surface runoff and baseflow. If the change in the stored water volume is negligible, as was assumed, then on a long-term basis, baseflow must represent a lower bound to groundwater recharge within a given watershed. By quantifying $q_b$, one obtains an estimate of recharge, provided that the portion of the areal ET originating from the groundwater is negligible when compared to the total ET of the watershed.

Flow as completely groundwater discharge (while the surface runoff is negligible) can be based on the antecedent recession. Linsley et al. (1982) proposed the empirical relation that

$$N = A^{0.2}. \tag{3}$$

This relation gives the time base of surface runoff ($N$ [$d$]) as a function of the drainage area ($A$) upstream from a streamflow-gauging station, in square miles. The time base of surface runoff is the number of days after a peak in the hydrograph of streamflow while the component of flow attributed to surface runoff (including the bulk of interflow) is considered negligible. A part of the streamflow hydrograph may thus be considered completely groundwater discharge, if it is preceded by a period of recession equal to or greater than $N$.

Various techniques have been used to estimate a record of groundwater discharge under the streamflow hydrograph. The base-flow-record estimation employed here is a form of streamflow partitioning. Rutledge (1992) developed this method first based on the antecedent streamflow recession. The principles of this method are as follows: (1) Daily data of streamflow are required. (2) Linear interpolation is used to estimate groundwater discharge during the period of surface runoff.

Figure 1 shows a flow diagram of the steps analyzed by the method of base-flow-record estimation. The requirement of the antecedent recession is met for the day in question if, for the part of the daily mean streamflow record that includes all days that precede the day in question by $N$ days or less, the streamflow on each of these days is greater than or equal to the streamflow on the day that follows where $N$ is the time base of surface runoff.

Steps of the base-flow-record estimation are as follows (see Fig. 1). First, a one-dimensional array of the daily mean streamflow data is filled. This array is searched for days that fit the requirement of the antecedent recession. On each of these days, groundwater discharge is designated equal to streamflow, as long as it is not followed by a daily decline of more than 0.1 log cycle. According to Barnes (1939), a daily decline more than 0.1 log cycle could indicate interflow (stormflow) or surface flow. The array is searched again, and it is determined by linear interpolation of the groundwater discharge on remaining days. For some streamflow records, this interpolation can cause the calculated groundwater discharge to exceed streamflow for a few days on the record. The last step of the procedure is to correct this error.

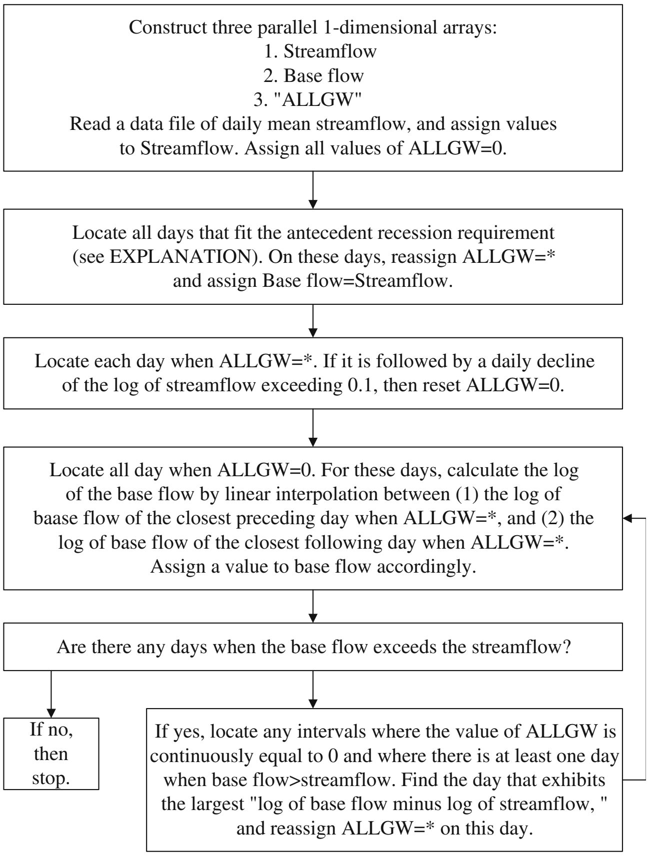


**Fig. 1** Flow diagram showing the procedure of streamflow partitioning [baseflow is considered to be groundwater discharge. Referenced from Rutledge (1993)]

To prevent overestimation caused by rainstorm events, Rutledge (1993, 1998, 2000) suggests that the wintertime recession data are chosen to represent the behavior of the recession characteristic. Zektser (2002) indicates that the lowest two monthly baseflows should be chosen to be the average value of the year in some cases. For this purpose, an alternative method, the stable-base-flow analysis, is developed in this study to obtain a more reliable result.

The diagram of the stable-base-flow analysis according to our previous study is shown in Fig. 2 (Chen and Lee 2003). The procedure of the stable-base-flow analysis is as follows:

1. Obtain monthly baseflow from the base-flow-record estimation.
2. Obtain long-term mean monthly baseflow.
3. Perform data processing by sorting and accumulating the long-term mean monthly baseflow, and then a new series of long-term mean monthly accumulated baseflows is obtained.
4. Choose the most stable (near-linear) segment and obtain the slope of the stable baseflow. To avoid

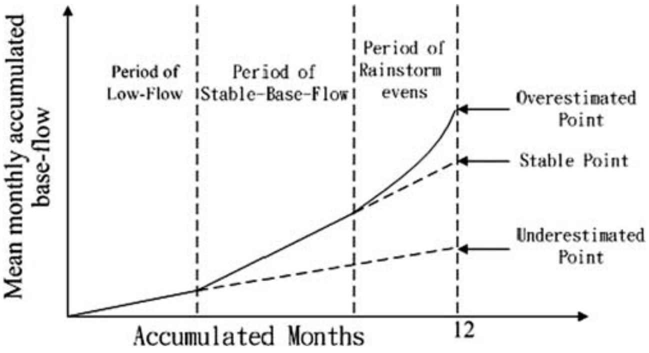


**Fig. 2** The diagram of the stable-base-flow analysis

overestimating the results, the largest several monthly values (minimally adjusted requirements for each gauging station) will not be chosen.

5. Use linear interpolation on the remaining months, and finally the mean annual baseflow is obtained.

Baseflow ($Q_b$) is obtained by employed the base-flow-record estimation and the stable-base-flow analysis. As a consequence, the drainage area value of the gauging station is used for the calculation of $N$, and Eq. 2 is employed through the introduction of the dimensionless base-flow index (BFI), which is the ratio of baseflow and total stream runoff ($Q = Q_b + Q_s$) over time:

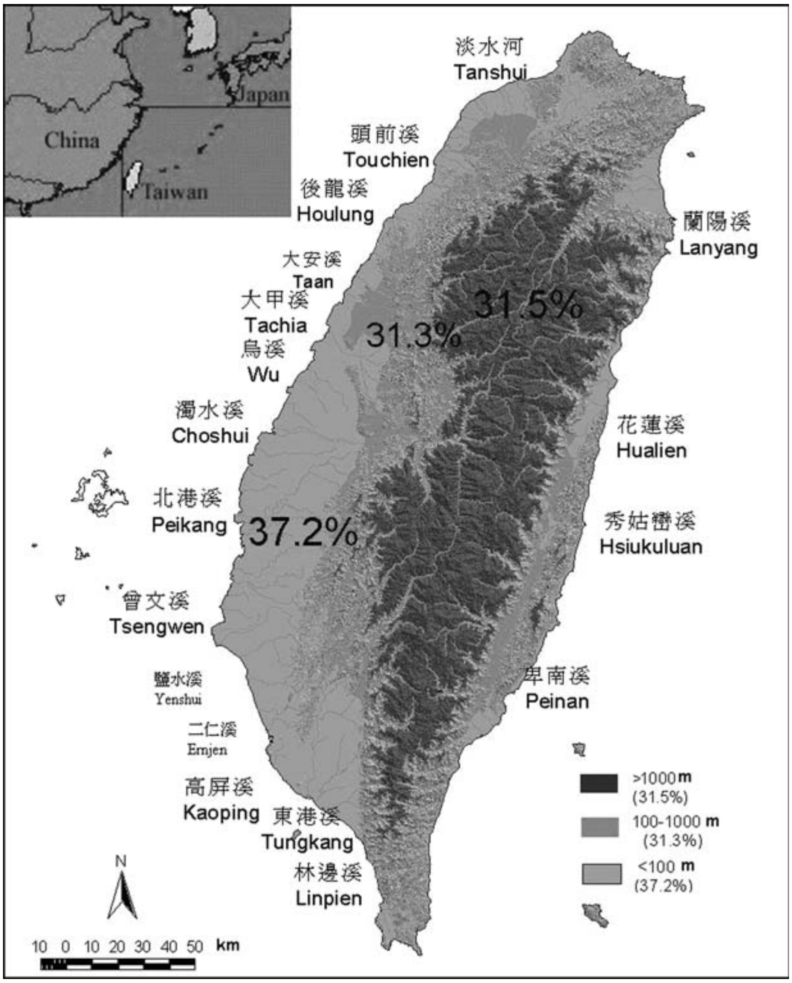
$$\mathrm{BFI} = \frac{Q_b}{Q_b + Q_s}. \tag{4}$$

Inserting Eq. 4 into Eq. 2 yields

$$\mathrm{BFI} \times (P - ET) = \mathrm{BFI} \times q = q_b \approx R, \tag{5}$$

where $R$ ($\mathrm{LT}^{-1}$) is the yet unknown groundwater recharge, and $q = Q/A_d$, with $A_d$ denoting the contributing drainage area. Note that the base-flow-record estimation and the stable-base-flow analysis are only used to calculate BFI, but neither $q$ nor $q_b$ were used in Eq. 5 because they require the extent of the contributing drainage area, $A_d$, whereas BFI does not. When the two

**Fig. 3** Topography of Taiwan



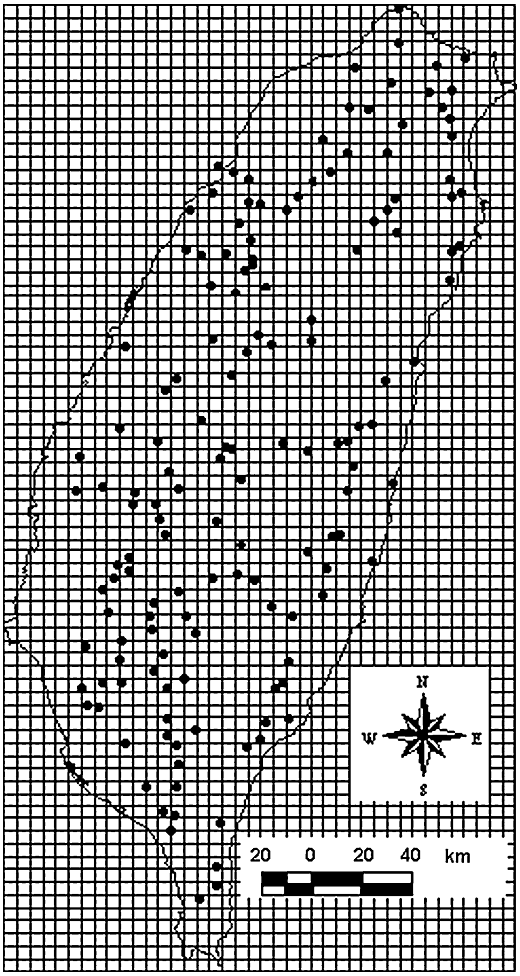


**Fig. 4** Distribution of the climatic stations in Taiwan with long-term daily precipitation records

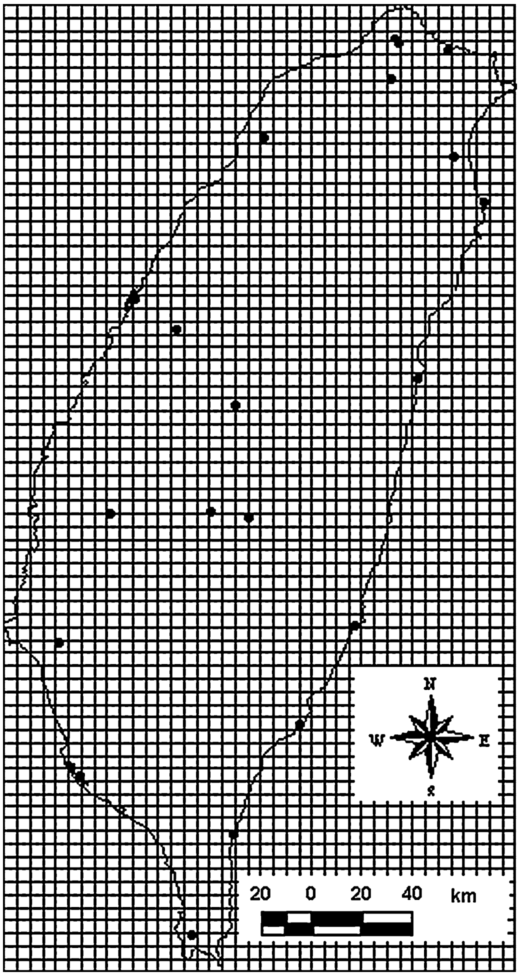


**Fig. 5** Distribution of the climatic stations in Taiwan with long-term daily evapotranspiration records

contributing areas for surface runoff and groundwater are known to be fairly close, then $q$ can be used in Eq. 5, eliminating the need for the $P$ and ET measurements.

## Results and discussion

The island of Taiwan is in the Western Pacific between Japan and the Philippines off the southeast coast of China, from which it is separated by the Taiwan Strait. With a total area of about 36,179 km$^2$, Taiwan is 394 km long and 144 km wide at its widest point.

High mountains over 1,000 m constitute about 31% of the island's land area; hills and terraces between 100 and 1,000 m above sea level make up 31%; and alluvial plains below 100 m in elevation, where most communities, farming activities, and industries are concentrated, account for the remaining 38%. Taiwan's most prominent geographic feature is its 270-km central mountain range, which has more than 200 peaks over 3,000 m high. Foothills from the central mountain range lead to tablelands and coastal plains in the west and south. The eastern shoreline is relatively steep, and mountains over 1,000 m high dominate the island in the north. The topography of Taiwan is shown in Fig. 3.

Taiwan is between the world's largest continent (Asia) and largest ocean (the Pacific). The Tropic of Cancer (23.5° N) running across its middle section divides the island into two climates, the tropical monsoon climate in the south and subtropical monsoon climate in the north. High temperature and humidity, massive rainfall, and tropical cyclones in summer characterize the climate of Taiwan. The latitude and topography, ocean currents, and monsoons are the main contributing factors. According to Köppen's climate classification, the four climate types in Taiwan are a monsoon and trade-wind coastal climate (Am) in the south, mild, humid climate (Cfa) in the north, wet–dry tropical climate (Cwa) in the west, and temperate rainy climate with dry winter (Cw) in mountain areas.

Figures 4 and 5 show the distribution of the climatic stations with long-term daily precipitation and evapotranspiration values used respectively in the study. From the long-term mean annual values of the point measurements of *P* and ET, surfaces were generated using universal kriging with a linear drift. Contours of the resulting long-term mean annual *P* and ET fields are shown in Figs. 6 and 7, respectively.

The main stream of the northward-moving Kuroshio Current passes up the eastern coast of Taiwan, thus bringing in warm and moist air. Summer and winter monsoons also bring intermittent rainfall to Taiwan's hills and central mountains. As a result, more than 2,300 mm of rain fall every year. The northeastern corner is the rainiest place in Taiwan, receiving 4,000–5,000 mm of rain per year. The coast of the western plain of the island is the driest spot, with less than 1,000 mm per year. Some characteristics of Taiwan's rainfall are as follows. (1) Spatial distribution of rain: More rain falls in the mountains than in the plains, on the east coast than the west coast, and at the windward side of hills than the leeward (sheltered) side. (2) Seasonal distribution of rain: The north has rain all year round while the south is rainy in summer and dry in winter. In winter, when the northeastern monsoon system is active, the north is constantly visited by drizzle while the south remains dry. However, in summer when the southwestern monsoon comes in force, afternoon thunderstorms and typhoons carry heavy rain to central and southern Taiwan. This intensive and concentrated summer rainfall, which constitutes up to 80% of annual precipitation, often causes flooding and landslides. (3) Variability of rainfall: As northern Taiwan has more rainy days than the south, the variability of rainfall increases as we move toward the south.

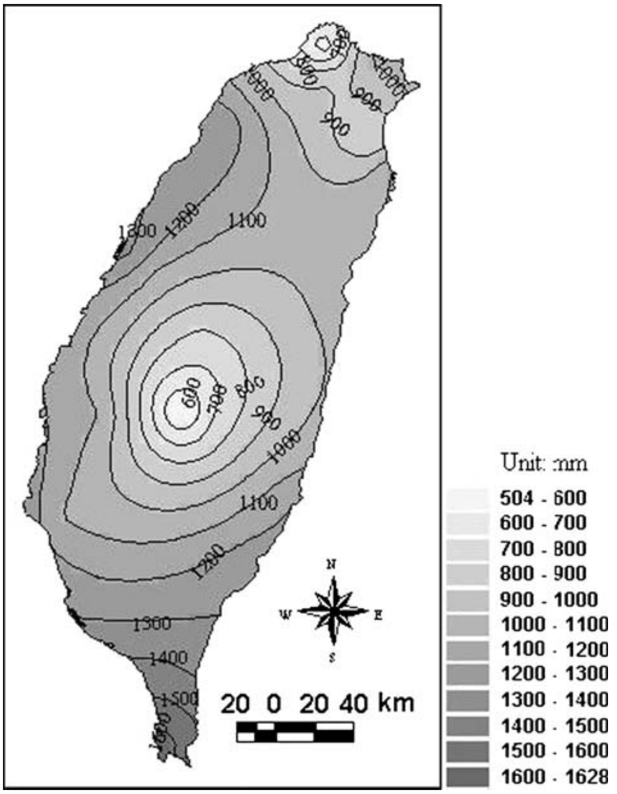


**Fig. 7** Long-term mean annual evapotranspiration (mm) in Taiwan. The contour interval is 100 mm

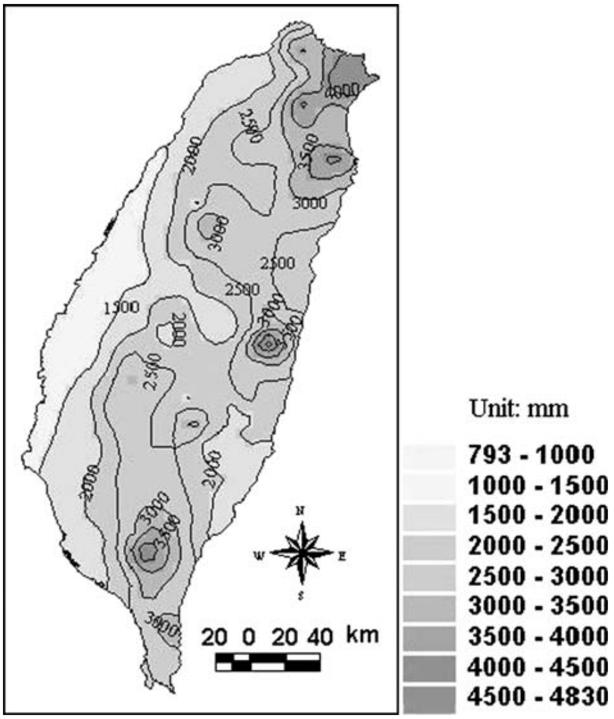


**Fig. 6** Long-term mean annual precipitation (mm) in Taiwan. The contour interval is 50 mm

The evaporative behavior is mainly related to sunshine in Taiwan. The number of hours of sunshine has an inverse relationship with the degree of cloudiness. That is, the accumulation of clouds shortens the daylight. Less sunshine is seen in the mountains than on the plains, and less on the east coast than the west. While rainy days prevent the northeastern corner from getting much sunshine, the western and southern areas of Taiwan enjoy more hours of sunshine a year.

The spatial distribution (Fig. 8) of long-term mean annual runoff is obtained by subtracting the ET map values from those of the precipitation map, in accordance with Eq. 5. Runoff is about 0–1,000 mm in the western area, and above 3,000 mm in the northeastern corner. This significant difference in runoff is mostly due to the general distribution in annual precipitation and

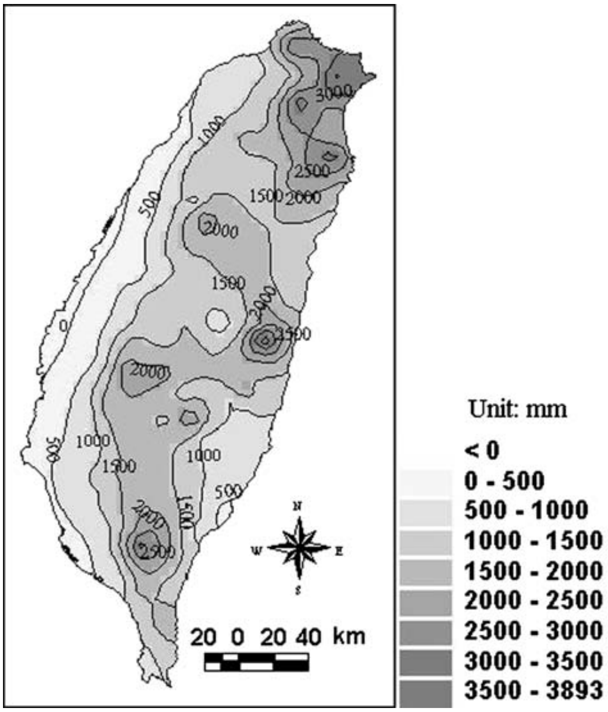


**Fig. 8** Estimated long-term mean annual runoff (mm) in Taiwan, estimated as the difference between precipitation and evaportranspiration. The contour interval is 500 mm

the aridity of the environment around the island. The degree of aridity can expressed as the ratio of ET and precipitation (Fig. 9). The closer the value to unity (i.e., 100%), the more arid the environment. Note the extremely high aridity value of the western edge of Taiwan. A long-term mean runoff ratio of 55.5% for Taiwan can be obtained by dividing the spatial mean (1,304 mm/year) of the runoff values of Fig. 8 by the long-term mean precipitation (2,348 mm/year, from Fig. 6) of the island.

There are 129 rivers in Taiwan, most of which flow toward the east or west. Because of the major watershed, the drainage area of western Taiwan is larger than that in the east. Taiwan's rivers have the following characteristics: (1) They are fast flowing due to their short length and steep grade. Even Taiwan's longest river, the Choshui River, is only 186 km long but its degree of steepness of slope is 1/55. (2) They have a limited water flow in dry seasons, and they even became wildbachs unsuitable for sailing. (3) Their peak flow is enormous; a catchment area of 2,000–3,000 km$^2$ often receives peak flows of up to 10,000 m$^3$/s.

According to the watershed division of the Water Resource Agency, Ministry of Economic Affairs, Taiwan, can be divided into 61 catchments in total. The first step is to collect and establish a complete daily streamflow database, and the streamflow gauging stations collected in this paper, total 191. The distribution of the daily streamflow gauging stations used in this study is shown in Fig. 10.

The daily streamflow of each gauging station is used to calculate BFI by employing the base-flow-record estimation and the stable-base-flow analysis. To avoid overestimating results due to rainstorm events which mostly occur in the typhoon season, the largest three monthly values (minimally adjusted requirements for each gauging station) will not be chosen when the stable-base-flow analysis is employed. From the long-term mean annual values of the estimations of BFI, surfaces were generated using ordinary kriging where no apparent spatial drift in the values could be detected. The contour of the resulting long-term mean annual BFI field is shown in Fig. 11.

Finally, the spatial distribution of the naturally occurring long-term mean annual groundwater recharge (Fig. 12) is obtained by multiplying the runoff map values (Fig. 8) with those of the BFI map (Fig. 11). The highest rates (> 1,000 mm/year) occur in the northeastern part and the central-eastern part of Taiwan, primarily due to more abundant precipitation and a less severe aridity index. High mountain areas (over 1,000 m) express a rate of 800–2,000 mm/year annually, the areas of hills and terraces (between 100

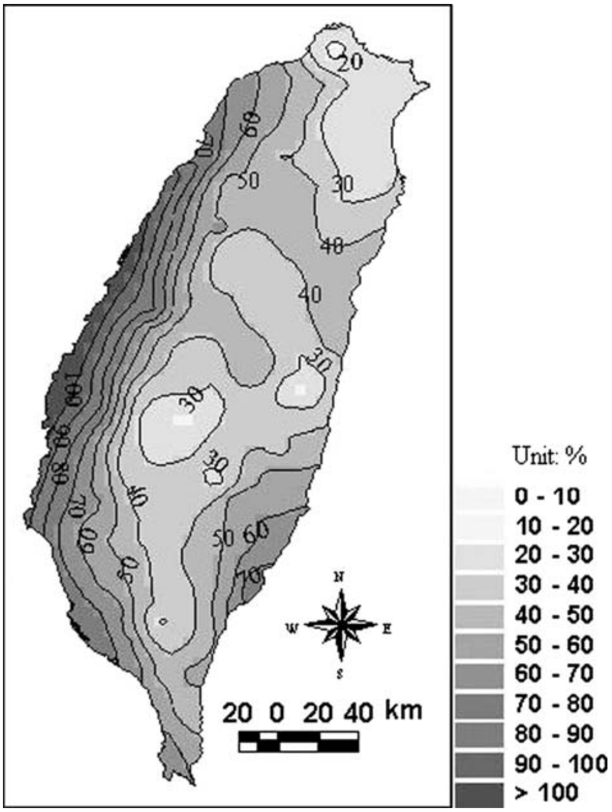


**Fig. 9** Aridity (%) of the environment in Taiwan. The closer the value to 100%, the more arid the environment becomes

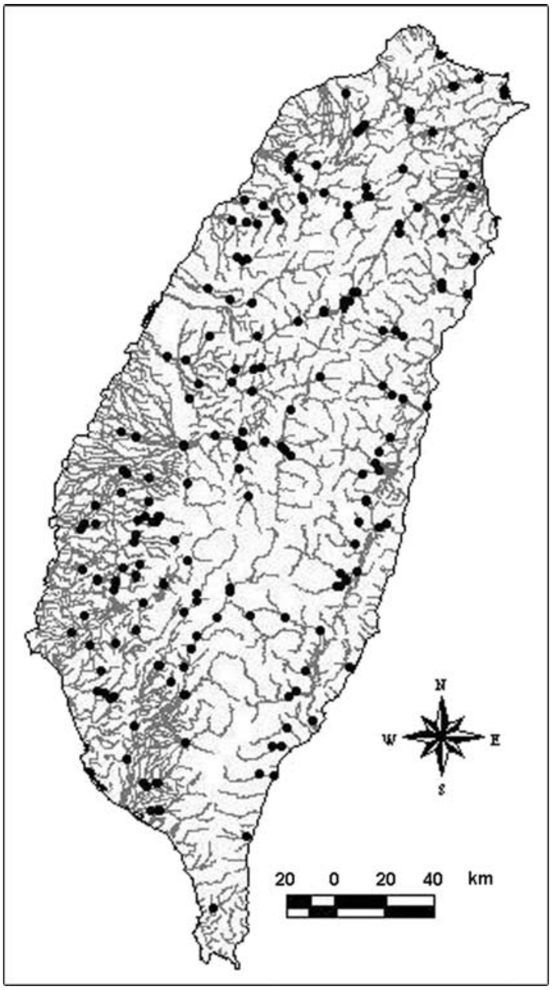


**Fig. 10** Distribution of the gauging stations in Taiwan, used in the study

and 1,000 m above sea level) express a rate of 200–600 mm/year annually, and the areas of alluvial plains (below 100 m in elevation) receive an annual groundwater recharge of 0–200 mm. Note that the mean annual groundwater recharge is below 0 mm at the western edge of Taiwan, which is the most serious land subsidence area in Taiwan. The total groundwater recharge of Taiwan is obtained by multiplying the long-term mean annual groundwater recharge map values by the area of each grid. The total groundwater recharge of Taiwan is about 18 billion tons per year. The value compares well with the long-term mean groundwater recharge provided by the Water Resource Agency (2003). They obtained a long-term mean annual groundwater recharge of 17.3 billion tons for Taiwan.

The central mountain range of Taiwan has long been considered the main recharge area for groundwater due to the region's highly permeable gravelly/sandy aquifers. The high recharge rates are reflected in the high values of the BFI map (Fig. 11) and in the increased recharge rates in Fig. 12 when compared to the areas of hills, terraces, and alluvial plains. Because aridity increases and precipitation decreases from the mountain range toward its alluvial plains, groundwater recharge decreases as well. Note that at the western edge of Taiwan below 0% of the long-term mean annual precipitation recharges the groundwater (Fig. 13), while this recharge is larger than 20% of the annual precipitation in the mountain range of the island. This mainly due to greater precipitation and a less arid climate in the mountain range of Taiwan.

## Conclusions

Naturally occurring long-term mean annual groundwater recharge on a regional scale can be estimated using a water-balance approach coupled with an automated baseflow separation technique and a procedure of adjustment. The water balance uses meteorological and discharge measurements. Geostatistics are used to generate surfaces of variables from point measurements. An objective automated baseflow separation technique (the base-flow-record estimation) and a procedure of adjustment (the stable-base-flow analysis) are applied to estimate the BFI. Finally, geographic information

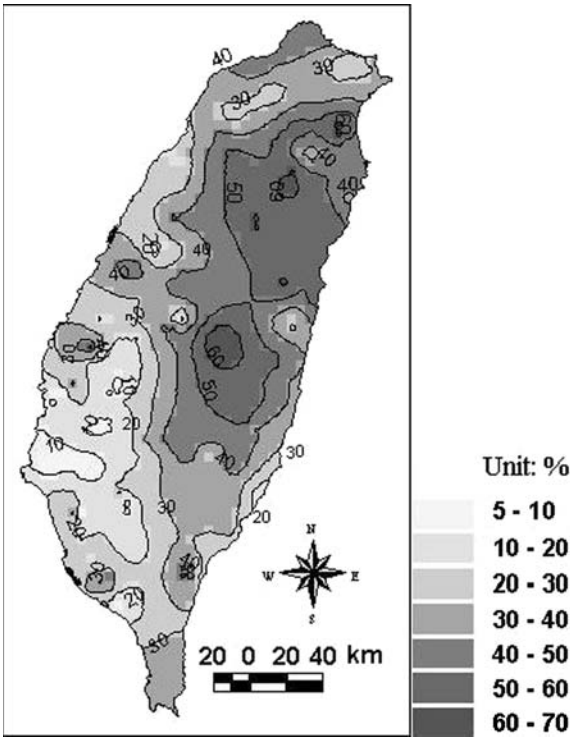


**Fig. 11** Estimated long-term mean annual baseflow index, BFI (%) in Taiwan

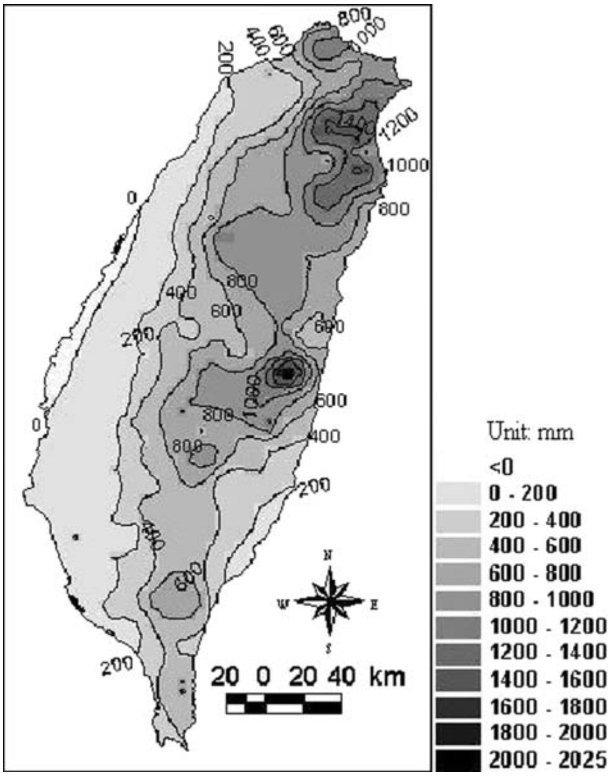


**Fig. 12** Estimated long-term mean annual groundwater recharge (mm) in Taiwan. The contour interval is 200 mm

system (GIS) is used to manipulate the maps of the different variables in the water balance.

Contours of the resulting long-term mean annual *P*, BFI, runoff, groundwater recharge, and recharge rates fields are well matched with the topographical distribution of Taiwan, which spans from the mountain range toward the alluvial plains of the island. Note that the mean annual groundwater recharge is below 0 mm at the western edge of Taiwan, which is the most serious land subsidence area due to overdrawing groundwater in Taiwan. The total groundwater recharge of Taiwan is about 18 billion tons per year as obtained by the employed method. The value compares well with long-term mean groundwater recharge estimates from related research.

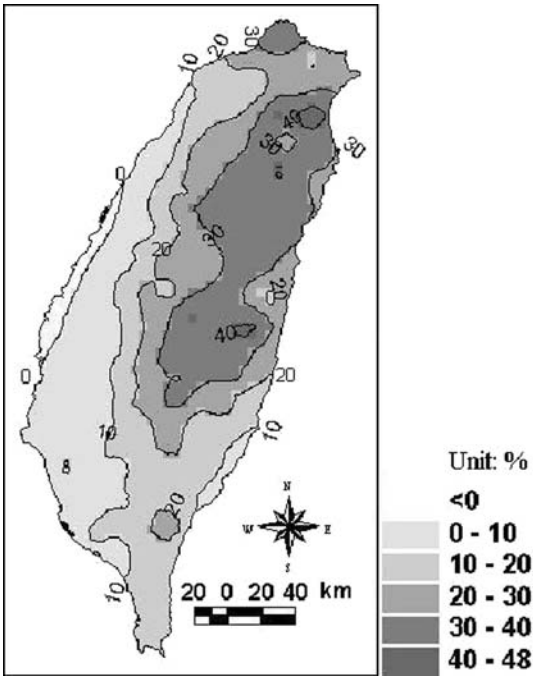


**Fig. 13** Estimated long-term mean annual groundwater recharge as a percentage of long-term mean annual precipitation in Taiwan

The techniques used are easy to implement, widely available and do not require complex hydrogeologic modeling or detailed knowledge of soil characteristics, vegetation cover, or land-use practices. The technique can also provide input to complex groundwater flow models or validate their recharge estimates obtained through parameter optimization.

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