Chapter 2

Spatiotemporal Analysis of Groundwater Recharge Trends and Variability in Northern Taiwan

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/63508

Abstract

In this study, the base flow estimation method was used to assess long-term changes of groundwater recharge in Northern Taiwan. The Mann-Kendall test was used to examine the characteristics of the trends. This was followed by trend slope calculation and change-point analysis. The annual groundwater recharge was found to exhibit a significant upward trend for the Fushan and Hengxi stations (Tamsui river basin). On the other hand, the Ximen Bridge station (Lanyang river basin) recorded a significant downward trend. Calculations showed that the rate of change for the Fengshan and Touqian river basins was small (less than 10%). However, that for the following stations was greater than 30%: Fushan, Hengxi, Ximen Bridge, and Niudou (also in the Lanyang river basin). The results of the change-point analysis further indicated a significant change-point for the annual recharge at Fushan, Hengxi, and Ximen Bridge stations in 1999, 1983, and 2001, respectively. The findings can be used for regional hydrological studies and as reference for water resource planning.

Keywords: groundwater recharge, base flow, Mann-Kendall test, Northern Taiwan

1. Introduction

The annual average precipitation in Taiwan is 2500 mm, 2.6 times higher than the global average values. In spite of the high precipitation per unit area, the annual precipitation per person is only 1/7 of the global average, due to both small land area and large population [1]. Analysis of environmental sustainability indicators revealed that Taiwan ranked 18th among 146 countries experiencing water shortages, with the average available water per person in

Taiwan being 1740 m^3/year [2]. Climate changes and increasing temperature experienced in recent decades caused the precipitation in Taiwan to increase during the rainy season, while decreasing in the dry season, resulting in a drier dry season and a wetter wet season [3]. Consequently, stream flow in both dry and wet seasons varied significantly. Thus, it is urgent to assess and discuss groundwater recharge characteristics, toward effective water resource management in Taiwan.

When analyzing the hydrogeological model and groundwater system of a region, the study on recharging groundwater through precipitation is a very important but complex issue. Meteorological factors (e.g., intensity and delay of precipitation, temperature, humidity, and wind speed), thickness of the soil layer, prevailing groundwater level, topographical conditions on the surface, vegetation cover, and land uses, all have direct relationships with the system and must be considered [4–10]. It is very easy to measure precipitation and run-off amounts when analyzing water balance, but it is very difficult to quantify the recharging process. Its evaluation requires not only precipitation data, but also other factors, such as prevailing climatic conditions, soil type, soil moisture status, vegetation cover, and evapotranspiration conditions [11, 12]. The infiltration of precipitation into the soil leads to the recharging process and is an important factor determining circulation of the groundwater system and its recharge volume.

Groundwater recharge can be quantitatively estimated using two methods. The first is the water balance model [13–16], which is applicable for humid regions; the second is for arid regions and involves the use of tensiometers, tracers, infiltrometers, and other instruments on site to observe the movement of water in the unsaturated zone, before estimating the groundwater recharge for that area [17–19]. However, it is generally more difficult to implement the second method because of high costs and the need for long-term monitoring on site. The existing methods for estimating groundwater recharge at the regional level using the water balance model are further divided into two types: (i) precipitation, infiltration, run-off, evapotranspiration, and groundwater recharge are treated as components of an interrelated system, with the soil moisture status being that of an ever-changing soil water balance model [7, 20, 21]; and (ii) the hydrograph of a stream flow is used to estimate its base flow, with the latter being treated as the groundwater recharge (based on the assumption that the heterogeneous hydrogeological conditions within the catchment area are ignored) [22–26].

In this study, the base flow estimation method was used to determine groundwater recharge and the evapotranspiration from the unsaturated zone was not considered. The calculation method to determine the effective recharge is simple, and it neither requires any complicated hydrogeological models, nor factors such as weather conditions and soil types. In this study, the calculation method was used to assess long-term changes of groundwater recharge in Northern Taiwan, and the findings can serve as reference for the management of water resources.

http://dx.doi.org/10.5772/63508

2. Methodology

2.1. Base flow model

Based on the concept of water balance and the data from stream flow gauging stations in the main river basins of the catchment area, this study employed the stream flow PARTitioning (PART) program (a base flow analysis method) developed by the US Geological Survey [27]. This method utilized the stream flow data to separate the base flow, which is regarded as the groundwater recharge. However, for rainy and humid regions and steep mountainous areas, if the estimation of groundwater recharge is based solely on base flow separation, it will often lead to overestimation of the base flow during the wet season [7, 28]. Therefore, the calculation of a steady base flow separation is required. In this study, a method for steady base flow analysis was adopted for this calculation to subsequently estimate a reasonable groundwater recharge.

Using Grey theory, the steady base flow analysis obtains data trends with reference to the rearrangement and accumulation of data. The steady base flow analysis uses trends for a low-flow period, a steady base flow period, and an overestimated base flow period, as shown in **Figure 1**. These are obtained after the rearrangement and accumulation of the separated base flows, and then, the steady base flow period is linearly extrapolated to achieve the steady base flow.

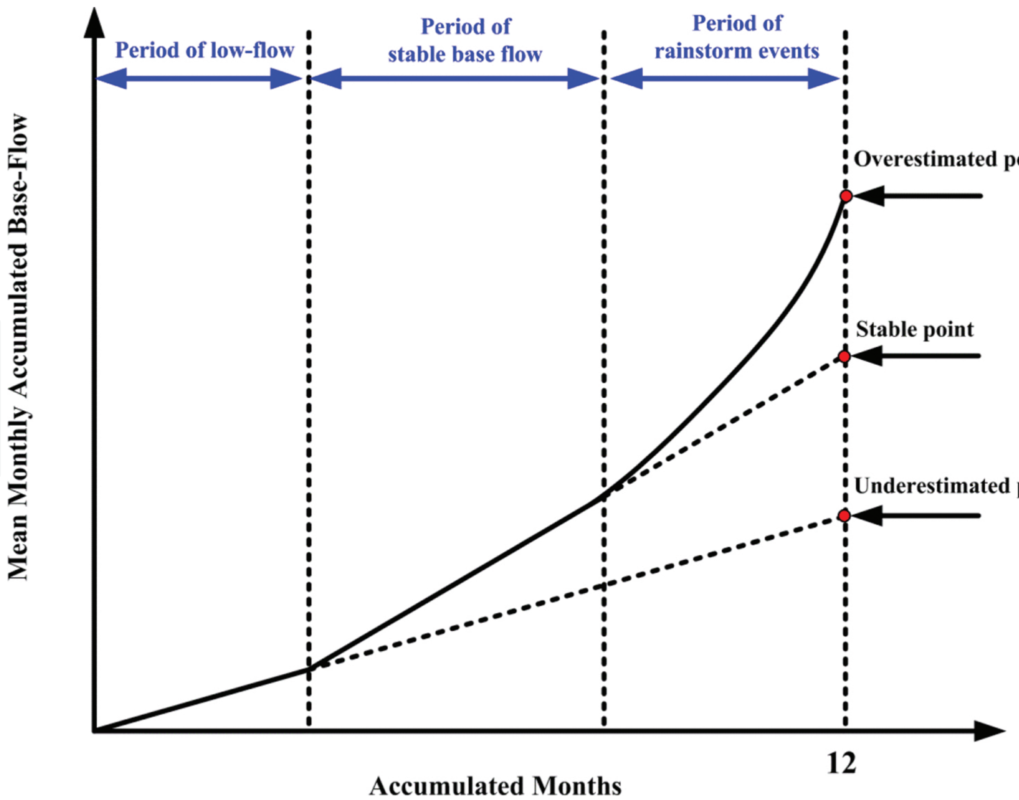

Figure 1. The diagram of the stable base flow analysis.

The steps in the analytical process are as follows:

1. Obtain the base flow of each month by base flow separation.

2. Sum the base flow per month over several years and then average the sum to achieve the long-term mean base flow on a month-by-month basis.

3. Sort the long-term mean base flow of each month in descending order and accumulate them to obtain the base flow accumulated per month and the trend of such base flows.

4. Determine the rising point of the base flow by the trend line of the accumulated base flow and obtain the steady base flow period.

5. Obtain the annual base flow, namely the annual groundwater recharge, by the extrapolation of the linear regression equation.

2.2. Mann-Kendall test

Mann-Kendall (MK) [29, 30] test is a nonparametric method developed from Kendall's tau (τ). It can be used to test the relationship between two sets of data. The advantages of this method is that extreme values and missing data problems will not seriously affect the certification value. The MK test assesses the trend in a series via comparing the value of the series before and after to determine whether the series exhibits a specific degree of trend. The null hypothesis given that if there is not significant trend in the series, test statistic S is defined as follows:

$$Sign\,(X_j - X_i) = \begin{cases} +1\,, & X_j - X_i > 0 \\ 0\,, & X_j - X_i = 0 \\ -1\,, & X_j - X_i < 0 \end{cases} \quad , \; S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sign\,(X_j - X_i) \tag{1}$$

where $\{X_1, X_2 X_3, \ldots, X_n\}$ is stream flow data which is arranged in accordance with time $\{T_1, T_2 T_3, \ldots, T_n\}$. n is the number of data. When n is close to infinity, the probability of the S distribution curve will present as a normal distribution with a mean of 0. In addition, when n is more than 10, the variance of S can be substituted into the following approximate solution:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{2}$$

In this study, long-term stream flow data are likely to be repeated in the data series; thus, Kendall modified the approximated solution Eq. (2) to Eq. (3).

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$$\sigma^2 = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{u=1} u(u-1)(2u+5) \right] \tag{3}$$

where u is the duplicate value number of the data series.

Finally, the normalized statistical test S values becomes the Z value, as follows:

$$Z = \begin{cases} \frac{S-1}{\sigma} & , S>0 \\ 0 & , S=0 \\ \frac{S+1}{\sigma} & , S<0 \end{cases} \tag{4}$$

When Z is a positive value, this indicates that the series is exhibiting an increasing trend; in contrast, when the value is negative, it indicates that the series has decreased. At this time, the obtained Z value should be tested by a significance test to assess whether the series is significant. Assuming a significance level of α, if $|Z| \geqq Z_{\alpha}$, the null hypothesis is rejected, which represents that the series has a significant trend, otherwise the series has no significant trend. In the study, the significance level is set as α=0.05. When $|Z| \geqq 1.96$, the series has a significant trend. When it is below this level, there is no significant trend.

2.3. Theil-Sen slope

The Theil-Sen slope [31] is used to estimate the magnitude of the trend slope. The Theil-Sen slope estimation method is different from the slope values calculated using a linear regression, because it selects the median value, and therefore, the properties are less affected by extreme values. Thus, it is often used with the MK test. Slope β is defined as follows:

$$\beta = Median\left(\frac{X_j - X_i}{j - i} \right), \ for \ all \ i < j \tag{5}$$

$$\begin{aligned} X(t) &= \beta t + C \\ X(t) &= X_1 \sim X_n, t = 1 \sim n \end{aligned} \tag{6}$$

2.4. Mann-Whitney-Pettit test

The Mann-Whitney-Pettit (MWP) test [32] can be used to search for significant change points in a data series. The definition of a change point is when a data series $\{X_1, X_2,\ldots, X_n\}$ has a change point X_t, Order $\{X_1, X_2,\ldots, X_t\}$ is $F_1(X)$ and $\{X_{t+1}, X_{t+2}, \ldots, X_n\}$ is $F_2(X)$, then $F_1(X)\neq F_2(X)$. The definition of is as shown in Eq. (7) shown. If there is not a change point in the data series, $|U_{t,n}|$ on the function of time, t will continue to rise, and there will be no turning point. On the contrary, if there is a change point, $|U_{t,n}|$ on the function of time t, there will be a decreasing turning point. In the same data series, the turning point may occur several times on behalf of this data series, and there may be more than one change point.

$$Sign\,(X_i - X_j) = \begin{cases} +1, X_i - X_j > 0 \\ 0\,, X_i - X_j = 0 \\ -1, X_i - X_j < 0 \end{cases} \quad , \quad U_{t,n} = \sum_{i=1}^{t} \sum_{j=t+1}^{n} Sign\,(X_i - X_j) \tag{7}$$

$$K_n = Max\left|U_{t,n}\right|,\ 1 \le t < n \tag{8}$$

To confirm that change points exist, Eq. (8) is used to calculate the extreme value of $|U_{t,n}|$ that is turning point as $K_{n>}$. Equation (9) is used to calculate the probability of a change point. In this study, $P = 0.95$ is set the as confidence level, where $P > 0.95$ judges that the time is a significant changing point.

$$P = 1 - \exp\left(\frac{-6K_n^{\ 2}}{n^2 + n^3}\right) \tag{9}$$

However, in some data series, a change point may not exist by itself; thus, Eq. (10) is used to calculate each year's $P(t)$ value. The $P(t)$ value is identified when it is greater than the confidence level.

$$P(t) = 1 - \exp\left(\frac{-6\left|U_{t,n}\right|^2}{n^2 + n^3}\right) \tag{10}$$

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3. Study area

The northern region of Taiwan includes several administrative districts, namely Yilan County, Keelung City, New Taipei City, Taipei City, Taoyuan County, and Hsinchu City. There are five types of terrains in this region: plains (mainly distributed in the Taoyuan Alluvial Fan and the Hsinchu Plain in the west, as well as the Yilan River Delta in the east); hills (mainly the Chutung Hill in Keelung); tablelands (the Linkou Plateau); basins (the Taipei Basin); and mountainous areas (the Tatun Mountain range in the north and the Central Mountain range). With these varied topographic features, this region ranges significantly in height from the <100 m above mean sea level (AMSL) plain areas to the <500 m AMSL hilly areas and to the >1000 m AMSL mountainous areas. The main rivers in the region are the Tamsui River, Lanyang River, Fengshan River, and Touqian River, with drainage areas of 2726, 978, 250.1, and 565.9 km^2, respectively. The annual average overall stream flow in the region is less than 15.1 billion m^3, which is less than that of the central, southern, and eastern regions. The data for the past several years indicate that the stream flow of the northern region during the dry season is different from that of the wet season. The total stream flow of the dry season (from November to April) is approximately 5.62 billion m^3; while during the wet season (from May to October), it is 9.48 billion m^3 [33].

The long-term data on stream flow in Northern Taiwan were collected from the Water Resources Agency, Ministry of Economic Affairs. We selected stream flow stations that are not affected by artificial irrigation facilities and for which recorded data go as far back as 30 years. The eight gauging stations studied were Niudou and Ximen Bridge (Lanyang river basin); Fushan, Gaoyi, and Hengxi (Tamsui river basin); Xinpu (Fengshan river basin); and Neiwan and Shangping (Touqian river basin). Detailed information and geographical location of the various stations are shown in **Table 1** and **Figure 2**, respectively.

Basin	Station	Area (km^2)	X-coordinate (TWD67[a])	Y-coordinate (TWD67[a])	Record years
Lanyang River	Niu-Dou	446.7	306388.4	2726321	1979-2013
	Ximen Bridge	101.4	324454.8	2739377	1984-2013
Danshui River	Fu-Shan	160.4	298991.3	2742949.3	1953-2012
	Gaoyi	542.0	286029.3	2734394.2	1957-2002
	Hengchi	52.9	289452.4	2758619.3	1958-2012
Fengshan River	Hsin-Pu	208.1	255810.3	2746676	1970-2012
Touqian River	Nei-Wan	139.1	267503.3	2733084	1971-2012
	Shang-Ping	221.7	260738.5	2729330	1971-2012

Note: [a] is Taiwan triangulation points' coordinates.

Table 1. Information on gauging stations in Northern Taiwan.

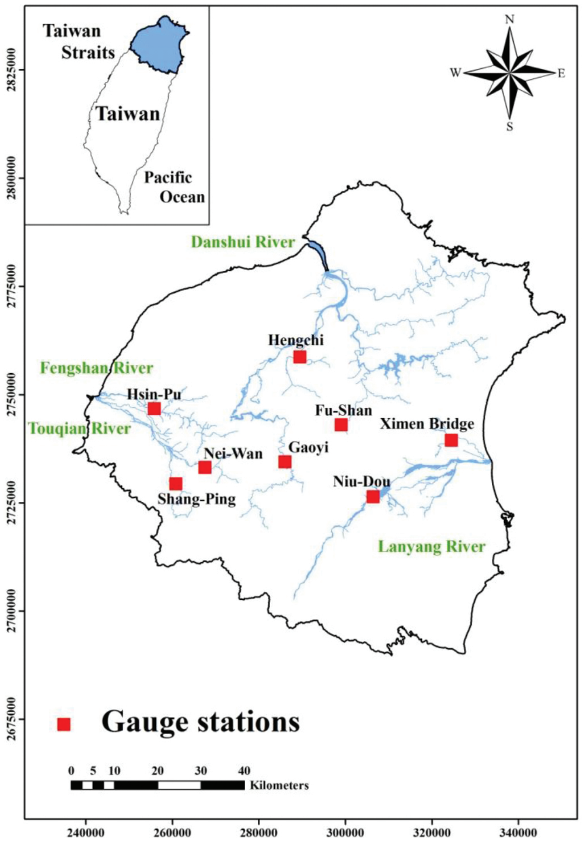

Figure 2. Spatial distribution of gauging stations in Northern Taiwan.

4. Results and discussion

4.1. Results of base flow separation

After collecting the annual stream flow data of the stations, the PART program developed by the United States Geological Survey (USGS) was used for analysis and to calculate the base flow of each station. The results showed that the trends of the base flow and stream flow were consistent, with the former ranging from 60.9 to 284.9 cm/year. Since Taiwan is located in a subtropical humid zone with perennial precipitation, during the steady base flow period, the recharge derived from base flow separation might still be greater than the groundwater recharge and discharge situations reflected by stream flow.

From a short-term perspective, base flow is affected by the amount of precipitation for that year. However, the amount of water discharged from the groundwater system should be a constant value over the long-term. Hence, stable base flow analysis was used to examine and estimate the groundwater recharge. Lee et al. [7] pointed out that the calculated base flow is likely to be overestimated when the base flow estimation method is used to assess stream flow data. This will in turn affect the calculations of the groundwater recharge. After estimating the base flow for all eight stations, evaluation was made using stable base flow analysis. This provided the depth of annual groundwater recharge for each station. The results are shown

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in **Table 2**. The depth of annual groundwater recharge for the northern region was 15.6–160.65 cm/year. The maximum and minimum values were recorded at the Fushan and Niudou stations, respectively.

Basin	Station	Record years	Recharge depth (cm/year)
Lanyang River	Niu-Dou	1979-2010	15.60
	Ximen Bridge	1983-2012	142.89
Danshui River	Fu-Shan	1953-2012	160.65
	Gaoyi	1957-2002	144.07
	Hengchi	1958-2012	50.55
Fengshan River	Hsin-Pu	1970-2012	20.56
Touqian River	Nei-Wan	1971-2012	52.23
	Shang-Ping	1971-2012	55.83

Table 2. Results of the depth of annual groundwater recharge in Northern Taiwan.

4.2. Analysis of groundwater recharge

After calculating the depth of groundwater recharge for the respective stations using stable base flow analysis, the results were multiplied by the area of the water catchment. This gave the annual groundwater recharge for each station and the long-term average amount (**Table 3**). Annual groundwater recharge for the northern region worked out to be between 2.67×10^7 and 7.81×10^8 m^3/year. Both largest and smallest volumes were found in the Tamsui river basin, at the Gaoyi and Hengxi stations, respectively.

Basin	Station	Record years	area (km^2)	Recharge Depth (cm/year)	annual recharge (m^3/year)
Lanyang River	Niu-Dou	1979-2010	446.7	15.60	6.97×10^7
	Ximen Bridge	1983-2012	101.4	142.89	1.45×10^8
Danshui River	Fu-Shan	1953-2012	160.4	160.65	2.58×10^8
	Gaoyi	1957-2002	542.0	144.07	7.81×10^8
	Hengchi	1958-2012	52.9	50.55	2.67×10^7
Fengshan River	Hsin-Pu	1970-2012	208.1	20.56	4.28×10^7
Touqian River	Nei-Wan	1971-2012	139.1	52.23	7.26×10^7
	Shang-Ping	1971-2012	221.7	55.83	1.24×10^8

Table 3. Results of annual groundwater recharge in Northern Taiwan.

4.3. Analysis of trends in groundwater recharge

The Mann-Kendall test was used to analyze the characteristics of the long-term annual recharge trends for Northern Taiwan and to examine the distribution of significant trends. The test results are shown in **Table 4**. The significant level $\alpha = 5\%$ was adopted as the standard, meaning that $|Z_{\alpha/2}| = 1.96$ was used to verify that a trend was of significance. Three river flow stations were found to exhibit significant trends, namely Fushan, Hengxi, and Ximen Bridge stations. It was a significant upward trend for the first two stations, but a significant downward trend for the third station (**Table 4**). Overall, among the eight stations within the study area, only two exhibited downward trends: Gaoyi station at upstream Tamsui River and Ximen Bridge at downstream Lanyang River. The spatial distribution of trends for the various stations is shown in **Figure 3**. In addition, the Theil-Sen estimation method was used to calculate the trend slope. An upward and downward trend is indicated by a value larger and smaller than zero, respectively. The trend line can also be calculated using the trend slope values and annual recharge volume for the individual years. **Equation (10)** was then used to calculate the rate of change and the results are shown in **Figure 4**.

Basin	Station	Record years	Mann-Kendall test result	Slope estimator	Relative change
Lanyang River	Niu-Dou	1979-2010	1.768	0.155	30.9%
	Ximen Bridge	1983-2012	-3.604	-5.254	-106.6%
Danshui River	Fu-Shan	1953-2012	2.991	1.198	44.0%
	Gaoyi	1957-2002	-0.095	-0.026	-0.8%
	Hengchi	1958-2012	2.195	0.363	33.7%
Fengshan River	Hsin-Pu	1970-2012	0.415	0.049	10.0%
Touqian River	Nei-Wan	1971-2012	0.398	0.087	7.0%
	Shang-Ping	1971-2012	0.356	0.105	7.9%

Note: *indicates the significant trends. The positive values represent increasing trends, and the negative ones represent decreasing trends.

Table 4. Results of significant trend, slope, and relative change in Northern Taiwan.

It was observed that the rate of change for the annual recharge was small at the Fengshan and Touqian river basins: that for the Xinpu, Neiwan, and Shangping stations was all less than 10%. For the Tamsui river basin, with the exception of Gaoyi, the rate of change for the other stations was greater than 30%. In particular, the increases for Fushan and Hengxi stations were 44.0 and 33.7%, respectively. The rate of change was also greater than 30% for the Niudou and Ximen Bridge stations. However, it was an increase of 30.9% for the former, but a decrease of 106.6% for the latter. The slopes of the significant trends in stream flow are shown in **Figure 4**.

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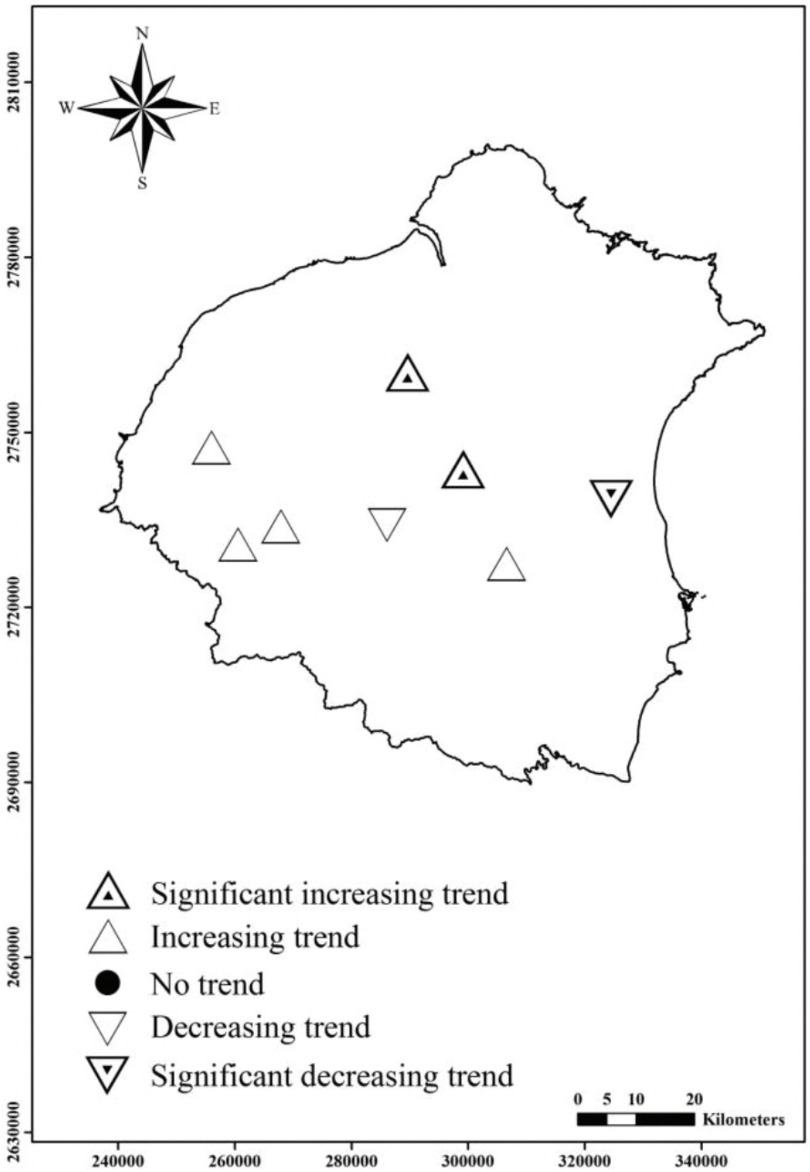

Figure 3. Map showing spatial variation in trends in annual recharge in Northern Taiwan.

The change-point analysis results revealed that change points occurred at three gauging stations: Fushan, Hengxi, and Ximen Bridge (**Table 5** and **Figure 5**). The change point for the Fushan station occurred in 1999. The average annual groundwater recharge before and after the change point was 23.1 × 10^2 and 35.2 × 10^7 m^3/year, respectively. The amount exhibited an upward trend post-1999, and the rate of increase was 46.9%. For the Hengxi station, the change point occurred in 1983, with the before and after volume being 2.2 × 107 and 3.3 × 10^7 m^3year, respectively. There was an overall upward trend as well, and the rate of increase was 41.7%. The change point for the Ximen Bridge station occurred in 2001. The before and after volumes there were 19.6 × 10^7 and 6.7 × 10^7 m^3/year, respectively. The overall trend after the change point declined by as much as 89.4%. Among the three aforementioned gauging stations, the magnitude of change at the Ximen Bridge station was the largest.

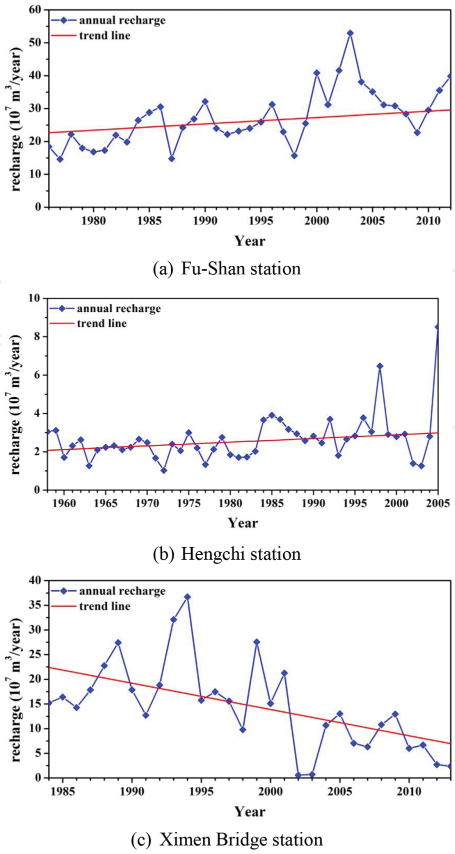

Figure 4. The significant trend line of gauging stations in Northern Taiwan. (a). Fu-Shan station, (b) Hengchi station, (c) Ximen Bridge station

Basin	Station	Change point (year)	P (Mann-Whitney-Pettitt)	Mean recharge (107 m^3/year)		Relative change at the change point
				before change point	after change point	
Lanyang River	Niu-Dou	-	0.8423	-	-	-
	Ximen Bridge	2001	0.9999	19.6	6.7	-89.4%
Danshui River	Fu-Shan	1999	0.9995	23.1	35.2	46.9%
	Gaoyi	-	0.8553	-	-	-
	Hengchi	1983	0.9990	2.2	3.3	41.7%
Fengshan River	Hsin-Pu	-	1.0660	-	-	-
Touqian River	Nei-Wan	-	0.8012	-	-	-
	Shang-Ping	-	0.7013	-	-	-

Note: The number in bold indicates a statistically significant difference.

Table 5. Results of change points using cumulative deviations and Mann-Whitney-Pettitt test.

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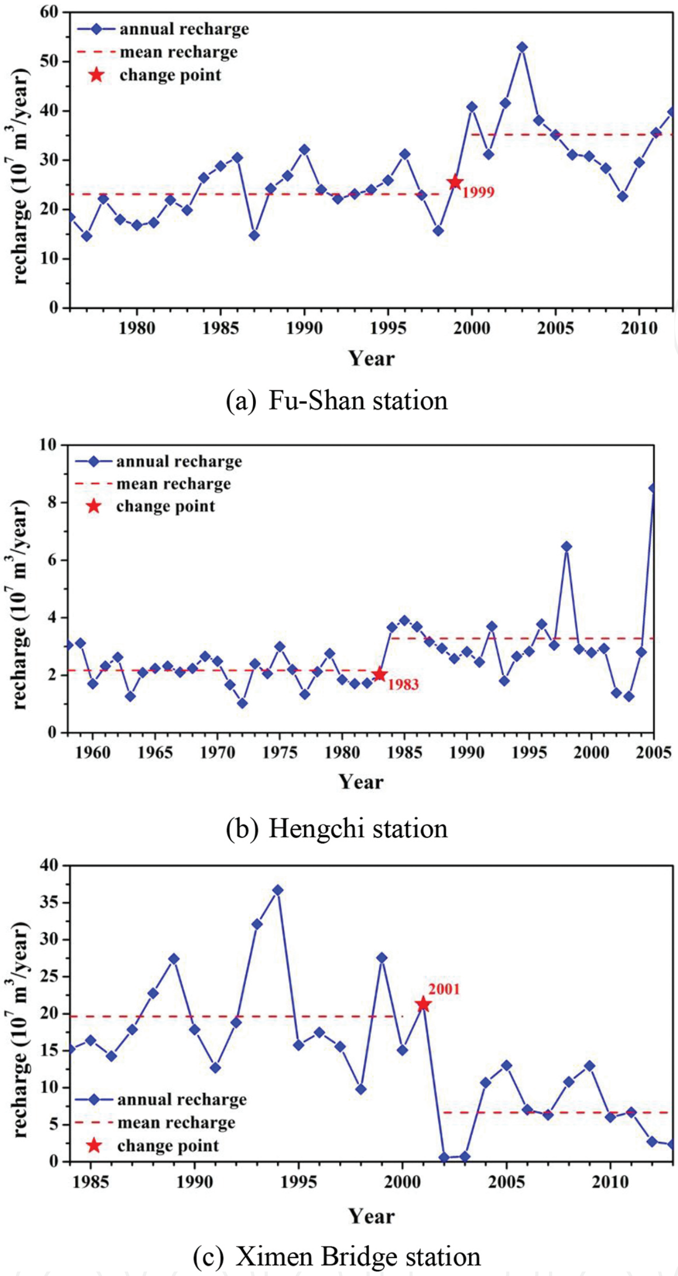

Figure 5. The results of change points of significant trend stations. (a)Fu-Shan station, (b) Hengchi station, (c)Ximen Bridge station

5. Conclusions

In this study, the base flow estimation method and stable base flow analysis were used to evaluate the long-term stream flow data of eight stations in Northern Taiwan. The range was between 2.67×10^7 and 7.81×10^8 m^3/year based on the cumulative annual recharge. The characteristics of the trends were examined using the Mann-Kendall test. Further, trend slope calculation and change-point analysis were carried out. The results provided an understanding of the trends for the eight stations and indicated that only two had downward trends: Gaoyi station at the upstream of the Tamsui River and Ximen Bridge at the downstream of the Lanyang River. The rate of change for the Fengshan and Touqian river basins was relatively small. Separately, the rate of change for the annual groundwater recharge was greater than 30% for all stations in the Lanyang river basin, while Gaoyi station was the only exception in the Tamsui river basin. The results of the change-point analysis showed that the change point for the Fushan, Hengxi, and Ximen Bridge stations occurred in 1999, 1983, and 2001, respectively. The average annual groundwater recharge for the first two stations exhibited an upward trend before and after the change point (46.9 and 41.7%, respectively), while that for the last station decreased by as much as 89.4%. The findings can be used for regional hydrological studies and as reference for water resources planning.

Acknowledgements

The authors are grateful for the support of the Research Project of the Ministry of Science and Technology (MOST 103-2221-E-006-205-MY2).

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