Catchment recession analysis for environmental impacts on storage-discharge dynamics

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April 28, 2020

Abstract

The complex interaction of climate change and human activities has led to significant changes in hydrological patterns, thus affecting the catchment hydrological processes around the world. This has resulted in increased water resource problems and conflicts between social development and environmental sustainability. Moreover, the groundwater resource is less concerned than others due to the challenges posed by groundwater and aquifer monitoring. Recession analysis is typically used to explore the groundwater-streamflow relationship with easily accessible streamflow data. The environmental impacts can be considered as a variable into the recession analysis to assess the changes in dynamic groundwater storage and storage-discharge relationships. Seventeen gauge stations in Southern Taiwan were selected as a case study to elucidate the spatial and temporal results under a comprehensive impact. In addition, the quantified environmental impacts and changes in vegetation coverage were compared to assess whether these changes were consistent and their effect on the catchment drainage processes. The results showed that the regional differences in low-flow recession characteristics and the dynamic storage indicated the local differences in the aquifer properties. Decreasing dynamic storage and increasing storage-discharge sensitivities in most catchments indicated a consistent change with quantified environmental impacts. This demonstrated that the environmental change led to more groundwater loss and a lower streamflow with a reduced flow variation. This study attempted to explore the storage-discharge dynamics caused by the overall environmental impact, and the quantified impact can help us to realize whether the groundwater storage and the susceptibility to baseflow increase or decrease in the catchment drainage behaviors. This provides a simple way to explain comprehensive effect on storage-discharge processes under the environmental co-evolution.

1. Introduction

Recession analysis proposed by Brutsaert and Nieber (1977) is usually used to explore the relationship between groundwater storage and streamflow. With the function between streamflow and flow variation, the process of groundwater discharge from the aquifer to the river channel can be characterized (Brutsaert, 2008). Due to the availability of hydrological data, this method has generally been used to evaluate the drainage behavior (Thomas et al., 2013; Lin and Yeh, 2017; Parra et al., 2019) and dynamic storage (Buttle, 2016, 2018; Dralle, Karst, Charalampous, Veenstra, & Thompson, 2018; Meriö et al., 2019; Lin et al., 2020) that is sensitive to streamflow at the basin/catchment scale. The main focus of this method includes analyzing the basin hydrological conditions, spatial distribution of aquifer properties, and geomorphology as well as channel networks of basins (Roques, Rupp, & Selker, 2017).

It is widely used for various applications, including groundwater hydraulic characteristics estimation (Mendoza, Steenhuis, Walter, & Parlange, 2003; Dewandel, Lachassagne, Bakalowicz, Weng, & Al-Malki, 2003; Oyarzún et al., 2014; Arumí, Troch, Maddock, Meixner, & Eastoe, 2016; Huang & Yeh, 2019), drought detection (Stoelzle, Stahl, & Weiler, 2013; Stoelzle, Stahl, Morhard, & Weiler, 2014), regional low-flow analysis (Van Dijk, 2010; Beck et al. 2013), basin topographic impact assessment, and basin river network dynamic analysis (Biswal & Marani, 2010; Biswal & Nagesh Kumar, 2013; Biswal & Nagesh Kumar, 2014; Ward et al., 2016; Li, Zhang, Long, & Feng, 2017). Previous studies have also shown that the impact of the co-evolution among soil, vegetation, atmosphere, and human activities on the hydrological cycle can help explain the effects on the basin hydrological processes. Related research has also shown that the regional differences in basins with different factors such as geology and land coverage can be elucidated by the recession characteristics. (Bogaart, Van Der Velde, Lyon, & Dekker, 2016).

Savenije, Hoekstra, and Van der Zaag (2014) suggested that human activities have direct impacts such as river separation, reservoir and hydraulic structure formation, pumping and return flow, in addition to indirect impacts such as afforestation or deforestation, land use change, and climate change on a basin hydrological system. Combining the various influencing factors mentioned above, we can appreciate the importance of understanding the hydrological cycle change regime and elucidating the hydrological processes under environmental change. Some researchers have attempted to retained or added relevant hydrological variables in recession analysis based on the effects of the related environmental impacts. Szilagyi, Gribovszki, and Kalicz (2007) used a non-linear reservoir model to evaluate catchment evapotranspiration during the flow recession period through the lumped water balance model, comparing with the monthly estimation evapotranspiration measured by a two-dimensional finite element numerical model. Wang and Cai (2009, 2010a, 2010b) and Wang (2011) included groundwater pumping, return flow of agricultural irrigation, and bedrock leakage as variables in the recession process in agricultural and highly-urban basins. The results showed that the streamflow data provides an excellent explanation of the direct impacts on the catchment drainage behaviors. Thomas, Vogel, Kroll, and Famiglietti (2013) analyzed the importance of the baseflow recession model by incorporating human withdrawals and explored the deviations between catchment recession characteristics with and without human withdrawals. Cheng et al. (2017) used the paired-catchment approach and recession analysis considering changes in the vegetation coverage, thereby quantifying the impact of vegetation change on groundwater discharge regime. The results improved the predictability of the impact of vegetation change on catchment hydrological process. Recently, Ploum, Lyon, Teuling, Laudon, and van der Velde (2019) explored the effects of snowmelt caused by global warming on the runoff processes and flow paths through seasonal storage-discharge dynamics with linear and non-linear relationships.

In recent years, due to climate change, wet and dry years alternate more frequently in Taiwan. These changes in climate pattern include an increase in rainfall gap, rainfall intensity, temperature, and extreme events. The Water Resources Agency (2016) analyzed the rainfall trend in Taiwan using five general circulation models (GCM), evaluating the worst rainfall. The results showed that future rainfall and streamflow will gradually decrease in Taiwan basins, especially in Southern Taiwan. The main risk associated with this pattern are rising temperature, reduction of surface water resources, decline of reservoir water storage capacity, and increase in agricultural water demand. Groundwater is a relatively stable water resource due to the faster runoff with higher terrain and reservoir sedimentation in Taiwan. However, groundwater resource management has received less attention due to monitoring challenges. It is often neglected in developing countries, which leads to the excessive use of groundwater having various environment affects (Famiglietti, 2014). In Taiwan, groundwater pumping accounts for one-fifth of the available water resources (Water Resources Agency, 2014). A portion of the groundwater also provides streamflow during no-rainfall periods to maintain ecological habitats within the basin. However, most researchers have focused on surface hydrology such as runoff and evapotranspiration in different climate scenarios to explore the geological structural characteristics and rainfall infiltration regime in the basin. As a result, groundwater affected by climate change and human activities is less frequently discussed (Zhang, Brutsaert, Crosbie, & Potter, 2014; IPCC, 2014).

With industrial development and increase in population, the environment in Taiwan has undergone many changes. Land use in flat lands has been saturated, and urbanization has significantly increased areas with impermeable surfaces. Improper development of hillslopes coupled with the effects of earthquake and typhoons has resulted in increasing soil and water conservation problems. In addition, groundwater depletion in coastal areas that results from the over-pumping of groundwater by aquaculture and agriculture, has led to land subsidence with permanent aquifer shrinkage. Due to the complex interaction of different environmental impacts affecting groundwater–runoff process, it is difficult to assess the impact of varying environmental changes. Following Yeh and Huang's (2019) research, we focused on the catchments of Southern Taiwan by adding more available stations in order to discuss regional differences. The objectives of this study were (1) using low-flow recession analysis to evaluate the temporal and spatial changes in recession characteristics by considering environmental impacts, (2) exploring relationship between catchment storage-discharge dynamics and quantified impact, and (3) comparing the impact with change in vegetation cover as a simple land use to understand how the external factors affect catchment drainage process.

2. Study Area

Southern Taiwan covers an area of approximately 10,002 km^2, representing 28% of the total area of Taiwan, as shown in Figure 1. The climate is classified as a subtropical monsoon climate with distinct wet and dry seasons. As a result of the plum rain and typhoon season, rainfall is concentrated during summer and autumn (May to September). During winter and spring (October to April), the north-south Central Range blocks the northeast monsoon, resulting in relatively less rainfall. According to historical reports (Water Resources Agency, 2015), the average annual rainfall in Southern Taiwan is 2,527 mm with the ratio of the rainfall between dry and wet season is 1:9; the average streamflow is about 17.5 billion m^3/year across all regions in Taiwan.

With the Kaoping River basin serve as a boundary, Southern Taiwan can be divided into the Chianan Plain and the Pingtung Plain (including the Kaoping river basin). As a result of the Chianan Plain geological structure, different conditions exist between the northern and southern region with the Yanshui River as a boundary. The northern region is a sedimentary basin that contains marine and continental deposit cross-bedding with great lateral aquifer connectivity formed by past sea level changes. As a consequence of tectonic movements, the southern region contains different types of sedimentary basins, with several basement areas composed of marine mudstones which divide the region into several independent zones with poor lateral aquifer connectivity. The upstream catchment area of the Pingtung Plain is mainly composed of interbedded sandstone and shale with lower permeability. The middle and downstream river beds, formed on a platform of modern alluvial deposits with gravel and sand, are highly permeable. The thick aquifer in the Pingtung Plain covers the entire area with an aquifuge that is significantly smaller than aquifer in the southern region (Central Geological Survey, 2012; Water Resources Agency, 2017).

An overview of water use in Southern Taiwan showed that only 20% of the available water resources generated by rainfall (about 19.57 billion tons/year) can be used as a water supply source including 9% from reservoir storage, 5% from river intake, and 6% from groundwater pumping. Steep slopes and flash streams cause water to quickly discharge into the ocean while evapotranspiration also accelerates water losses. Total water consumption is comprised of 20% domestic, 12% industrial, and 68% agricultural uses. The efficiency of water use in the region is low due to its fragile geological structure leading to lower available water resources stemming from rainfall and the difficulty in reservoir construction. According to the results in the report, water resource shortages in Southern Taiwan will become increasingly severe in the worst-case scenario of future rainfall predictions. (Water Resources Agency, 2016).

This study selected 17 hydrological stations (Table 1, seven of which were used the same as Yeh and Huang (2019)) in Southern Taiwan in order to analyze catchment storage-discharge dynamics under environmental change. According to Lu, Cho, Lee, Lee, and Lin (2012) and Wu et al. (2010), temperature and rainfall trends from 1911-2009 indicate the emergence of a different climate pattern around the year 2000. After 2000, the decadal oscillation fluctuation reduced while changes in the tropical cyclone tracks resulted in an increase in the occurrence of typhoons in Taiwan. Liu, Chen, and Chu (2008) analyzed the long-term changes in rainfall from 1961-2005 and found that, compared with the 1960s, rainfall after 2000 increased significantly (by 200%) while the number of rain days with varying rainfall levels decreased. In light of these findings, this study collected streamflow data from 1986 to 2015. The data was divided into two time periods 1986 – 2000 and 2001 – 2015. The periods were used to explore spatial and temporal changes in low-flow characteristics, dynamic groundwater storage and groundwater flux under environmental change before and after 2000.

3. Methodology

3.1 Low-flow recession analysis under environmental impact

Brutsaert and Nieber (1977) proposed a low-flow recession analysis that characterizes catchment storage-discharge relationship, based on the assumption that streamflow is significantly greater than rainfall and evapotranspiration. This method suggests a power law relationship between daily streamflow(Q) and its time derivative (dQ/dt , flow variation).

$$-\frac{\mathrm{dQ}}{\mathrm{dt}} = -\mathrm{a_e Q^{b_e}} \quad (1)$$

The coefficient a_e and the exponent b_e (also known as the baseflow coefficients) can be derived using linear regression at log-log scale. The b_e value varies during the early to later recession state, where a_e represents a function of the hydraulic characteristics controlled by factors including slope, topography, drainage system density (Zecharias & Brutsaert, 1988), aquifer thickness (Dewandel, Lachassagne, Bakalowicz, Weng, & Al-Malki, 2003), and hydraulic characteristics (Biswal & Marani, 2010), and others. The recession constant above can be also expressed in the form of the baseflow coefficients a_e and b_e ($c = 1/[a_e$ (2-b_e)],d= 2-b_e). Related studies also made note of the correlation between coefficient a_e and catchment drainage networks (Biswal & Marani, 2014; Shaw, 2016) and antecedent groundwater storage (Patnaik, Biswal, Kumar, & Sivakumar, 2015; Bart & Hope, 2014). Previous studies indicated recession parameters can represent the physical characteristics of the resulting aquifers and the structure of the river network and characterized catchment drainage behaviors (i.e. drainage characteristic timescale and flow recession rate (Brutsaert, 2008; Zhang, Chen, Hickel, & Shao, 2009; Troch et al., 2013; van Tol & Lorentz, 2018; Dwivedi et al., 2019). It also used to estimate hydraulic conductivity, drainable porosity, aquifer thickness, and length of stream channels (Oyarzún et al., 2014; Arumí, Troch, Maddock, Meixner, & Eastoe, 2016; Li, Zhang, Long, & Feng, 2017; Huang & Yeh, 2019). To the purpose of this study, we regarded the results as low-flow characteristics rather than defined the correlations with related physical characteristics.

The recession process may also be affected by land cover (i.e. vegetation coverage, vegetation types) and human activities (artificial pumping, agricultural return flow, etc.). Therefore, the water balance can be added an environmental impact during the recession period (Cheng et al., 2017):

$$-\frac{\mathrm{dS}}{\mathrm{dt}} = \mathrm{Q + x} \quad (2)$$

where x represents the groundwater storage flux under environmental change [$\mathrm{mm^{-1}}$], named the 'impact parameter'. An increase in x indicates that the groundwater rapidly decreased, and a decrease in x indicated a slower groundwater decrease, as shown in Figure 2.

Groundwater discharge into the river channel during the recession period can be expressed as a function of catchment groundwater storage (Sugita & Brutsaert, 2009):

$$\mathrm{S = cQ^d} \quad (3)$$

where c and d are recession constants depending on the catchment physical characteristics. In the storage-discharge relationship, $d = 1$ indicates a linear reservoir; otherwise, the reservoir is nonlinear when d [?]1. They can also be expressed in the form of the baseflow coefficients a_e and b_e ($c = 1/[a_e$ (2-b_e)], d= 2-b_e).

Combining equations (2) and (3), the relationship between the streamflow and flow variation affected by environmental changes can be derived as follows:

$$-\frac{\mathrm{dQ}}{\mathrm{dt}} = \mathrm{aQ^{b-1}(Q+x)} \quad (4)$$

where a and b are the reformed parameters from the baseflow coefficient after parameter x is added. Therefore, quantifying x can show the overall environmental effect on the recession curve. Based on specific effects (e.g. evapotranspiration, bedrock leakage, groundwater pumping, return flow, vegetation cover and snowmelt), the similar approaches can describe the influence on groundwater-runoff process (Szilagyi, Gribovszki, & Kalicz, 2007; Wang, 2011; Thomas, Vogel, Kroll, & Famiglietti, 2013; Cheng et al., 2017; Ploum, Lyon, Teuling, Laudon, & van der Velde, 2019).

3.2 Recession fitting method

At first, the previous master recession curve method (Barnes, 1939) was replaced by overlapping individual recession events. It can avoid to ignore the variability of groundwater storage depletion and interference caused by the transition points between direct runoff and low-flow (Anderson & Burt, 1980). However, the filtered data points had a discontinuous time series due to the strict criteria for excluding the influence of precipitation and evapotranspiration. Therefore, to reduce the uncertainty for the definition of the initial time, the widely-used method is to plot the relationship between the flow variation ($-dQ/dt$) and the streamflow (Q) function to reveal the average recession behavior without the need for continuous data.

When Brutsaert and Nieber (1977) initially developed the analysis method, it was noted that evapotranspiration largely accelerated the flow variation during the recession process. In addition, the groundwater storage discharges from the aquifer had a lower flow variation than the other components of the observed streamflow, such as surface runoff and interflow. This indicates that the minimum flow variation dQ/dt corresponding to the given streamflow Q, that is, the lower envelope for the data points, can reduce the evapotranspiration influence and ensure that the streamflow value is only low-flow. In previous studies, the position of the lower envelope was manually fitted. To avoid observation and calculation errors, the fitting line placed 5% of the data points below the lower envelope (Brutsaert, 2008), however the precise location of the fitting line has been continuously debated because of the subjectivity and uncertainty (Ajami, Troch, Maddock, Meixner, & Eastoe, 2011; Stoelzle, Stahl, & Weiler, 2013). In addition to the lower envelope, many other fitting methods have been proposed since the development of the low-flow recession analysis. For example, Brutsaert (2005) proposed that soil heterogeneity may eliminate the evaporative effect in basins with large areas and hillslopes, so it is recommended that the fitting line should pass through the entire data point cloud instead of the lower envelope. Kirchner (2009) proposed a transformation method to reduce the noise and error of the original data by binning the threshold value of the streamflow and then calculating the average recession behavior. In this study, to reduce the disparity in the range of flow variation corresponding to a given streamflow, Kirchner's (2009) binning method was used. The method bins the screened data points into at least a 1% logarithmic range of the streamflow and then calculates the mean and standard deviation for each bin. Bins which were one-half of the mean flow variation higher than the flow variation of the standard deviation were selected. Finally, weighted regression analysis was performed using the inverse variance of the selected bins. Through this method, data points with high uncertainty have a lesser influence and data noise which reduces accuracy can be avoided to ensure the fitting result is more representative of the recession parameters at the overall catchment. A schematic diagram of the relationship between the streamflow and flow variation is presented in Figure 3.

3.3 Filtering criteria of the recession flow

To effectively improve the filtered results as low-flow, the filtered data must meet certain criteria. Cheng, Zhang, and Brutsaert (2016) evaluated the sensitivity between the recession index and each filtering criterion. The results indicated that the criteria for the number of data points before and after the recession events and those affected by the major streamflow event can be reduced in a relatively smaller basin due to the faster hydrological response after the rainfall event. According to the small catchments used here, this study used and revised the filtering criteria based on Brutsaert (2008) as follow:

1. Eliminate the data where the flow variation is equal to or larger than zero.
2. Eliminate the one data point before and two data points after each data point that meets criterion (1).
3. Eliminate three data points after a major streamflow event defined from the flow duration curve (Kingsford, 2000).

4. Eliminate data points with singular values.

3.4 Dynamic storage properties

To explore the physical-based representative of impact parameter, this study estimated the change in dynamic storage and storage-discharge sensitivity as dynamic storage properties derived from recession analysis.

Based on Kirchner's (2009) storage-discharge sensitivity function, substituting equation (2) with environmental change can be expressed as follows:

$$\frac{dQ}{dS}=\frac{\frac{dQ}{dt}}{\frac{dS}{dt}}\approx-\left.\frac{dQ/dt}{Q+x}\right|_{Q\gg P,\ E} \quad (5)$$

Integrating the above function with the groundwater storage change, the storage that generates the streamflow can be estimated through the following equation:

$$\int dS=\int dQ\frac{dS}{dQ}=\int-\frac{(Q+x)}{dQ/dt}dQ=\int\frac{1}{a}\frac{1}{Q^{b-1}}dQ \quad (6)$$

Because the above equation can't determine absolute groundwater storage, it is assumed that S at mean Q during the period is zero so as to calculate the relative groundwater storage S . Dynamic storage S_d is estimated as the difference between maximum and minimum S responding to the mean annual maximum and minimum Q (Kirchner, 2009):

$$S_d=S_{max}-S_{min}=f^{-1}(Q_{max})-f^{-1}(Q_{min})=\int_{Q_{min}}^{Q_{max}}\frac{dS}{dQ}dQ \quad (7)$$

The storage-discharge sensitivity (ε_S) represents the catchment storage-discharge relationship and can be defined as the instantaneous standardized flow variation divided by instantaneous groundwater storage variation (Berghuijs, Hartmann, & Woods, 2016):

$$\varepsilon_S=\frac{\frac{dQ}{Q}}{dS} \quad (8)$$

where ε_S (mm^{-1}) represents a certain proportion change in the streamflow when the groundwater storage per unit increases. Substituting equations (4) and (5), the storage-discharge sensitivity can be formulated as follows:

$$\varepsilon_S=-\frac{dQ/dt}{Q+x}\frac{1}{Q}=a\bullet Q^{b-2} \quad (9)$$

4. Results

4.1 Recession characteristics and impact parameter

Spatiotemporal changes in parameters a and b represent regional differences and changes in catchment drainage behaviors after environmental changes. According to a previous study that suggested that b represents the main recession regime (Santos, Fernandes, Moura, Pereira, & Pacheco, 2014; Sánchez-Murillo, Brooks, Elliot, Gazel, & Boll, 2015), here we analyzed b with all data as a constant for each period. Therefore, changes in a can show differences in hydrological behavior caused by environmental changes. The results are presented in Table 2. The a_{pre} ranged from 0.04 to 0.23, a_{post} ranged from 0.03 to 0.16, and b ranged from 0.53 to 1.44. There are 10 catchments showing decreasing a after 2000. In addition, the recession constants c

and d were estimated from the reformed parameter. In most catchments, the d value was close to 1˜1.5, while the c values had a greater variability. The results showed that a lower a value corresponding to higher c values indicates the discharge contributed from a relatively large groundwater storage when the recession constants d were fixed.

Impact parameter x represents the groundwater flux caused by external factor (e.g. evapotranspiration, land cover change, etc.), mainly affecting the recession curve in the portion of the lower streamflow. An increase in x means that a decrease in groundwater storage which contributes to streamflow and a higher flow variation. Otherwise, a decreasing x indicates increasing groundwater storage with lower flow variation. Therefore, the change in $x(\Delta x\ )$ can be explored to further understand its influence on catchment dynamic storage properties. Table 3 and Figure 4a show the results of x and its change. There is no obvious regional difference in all catchments, indicating that the environmental impact on each catchment varies greatly. The factors that affect Δx by altering or interfering with the hydrological process could be attributed to climate change, groundwater pumping, return flow of agricultural irrigation, change in land use/cover and vegetation coverage, topography, soil type, among others.

4.2 Dynamic storage

Dynamic storage S_d represents the maximum range of groundwater storage that discharges into the river channel.S_d ranges from 2.82 to 139.96 mm in the pre-period, and from 3.75 to 101.61 mm in the post-period. Most catchments have an increasing S_d , and only Chang-Pan Bridge, Chu-Kou, Tso-Chen, and Chao-Chou have a decreasingS_d , as shown in Figure 4b. To link with the aquifer properties for S_d , we performed a Spearman rank correlation analysis between the $S_d$and BFI (baseflow index that represents the ratio of baseflow to total streamflow) in the pre-period as BFI represents the integral state with the catchment streamflow type and aquifer properties (Eckhardt, 2005, 2008). Baseflow were calculated using Wittenberg's (2003) baseflow separation that inverting the recession curve equation for the nonlinear reservoir. Figure 5 shows a significantly strong correlation with BFI, indicating the relevance between S_d and regional geological structures. In addition, the significant groundwater storage variations mean that the groundwater–runoff process in these regions is more susceptible to environmental impact due to the presence of aquifers with greater permeability and connectivity.

4.3 Storage–discharge (S–Q) relationship

Storage-discharge sensitivity (ϵ) indicates whether the catchment storage-discharge behavior is susceptible to environmental impacts (e. g., climate change, human activities). Following Yeh and Huang's (2019) analysis for storage-discharge sensitivity in basins of Taiwan, we reproduced and focused on Southern Taiwan over two periods. The results showed that the S -Q sensitivities in southern Taiwan ranged from 0.026 to 4.048 mm^{-1} during the pre-period and from 0.032 to 2.053 mm^{-1} during the post-period. Regarding the large variability in the streamflow ranges among the catchments and the main influence on low streamflow, this study chose low flow Q_{85} (Q_i , $i$is the percentage of exceedance probability) as representative, and the corresponding ϵ were divided into five orders. The regional distribution of the sensitivities in the pre- and post-period were shown in Figure 6. In the first order (ϵ = 1-10 mm^{-1}), there are Chun-Huei Bridge, Tso-Chen, Chung-Te Bridge, Liu-Kwei, and San-Ti-Men in the pre-period and only AL in both periods. The catchments with higher sensitivities were evenly distributed, and most of the catchments declined during the post-period (Figure 4c). There was also no expected increase or decrease in the sensitivities from upstream to downstream in the basins. However, numerically, the higher sensitivities were mainly concentrated in the Liu-Kwei and San-Ti-Men, Tso-Chen, Yu-Tien, A-Lien and Chung-Te Bridge.

5. Discussion

5.1 Physical properties of recession characteristics

In order to understand whether the reformed parameters a and$b$ are still relevant to catchments characteristics, this study also analyzed their Spearman's rank correlation. The catchments characteristics (Table 4) include catchment area, elevation, mean catchment slope, length of main channel, the mean channel slope, and BFI (baseflow index, which represents the ratio of baseflow to total streamflow). The correlation between reformed parameters and catchments characteristics are shown in Figure 7. The parameter b only had a moderate correlation with the mean channel slope, indicating that the inclination of the aquifers has an effect on the catchment drainage process. These are also consistent with the previous study (Vannier et al., 2014; Santos et al., 2014; Sánchez-Murillo et al., 2015) that assumed the baseflow coefficient b_e change with the aquifer slope. The parameter a had a strongly negative correlation with the BFI, a moderately positive correlation with the length of main the channel and main channel slope. Biswal and Marani (2014) and Shaw (2016) mentioned the catchment drainage networks shrink with change in the coefficient a_e . In BFI, its representative of the catchment drainage condition and ability demonstrated the antecedent wet condition controls the initial streamflow condition before recession occur and the recession rate (Patnaik et al., 2015; Bart and Hope, 2014).

Here, this study also plotted a vs b to explore the regional differences in the catchment recession regimes (Figure 8). The overall result showed that parameters a and b are inversely proportional. The variability of b in the Chianan Plain was higher than in the Pingtung Plain. In the northern and southern subareas of the Chianan Plain, there was greater variability in the southern subarea. The results indicated that the variabilities may be related to the geological structure in Southern Taiwan. In addition, a more developed aquifer exists above the Pingtung Plain as compared to the Chianan Plain. The presence of marine mudstones reduces lateral aquifer connectivity in the southern subarea of the Chianan Plain. Therefore, the aquifer properties and structure can be regarded as one of the main factors causing differences in parameter b in each catchment.

Based on the above results, we can understand the reformed parameters still retained their physical properties after the impact parameter$x$ had been added. Assuming the geological properties were unchanged, the change in a between the pre- and post-period will mainly affected by the external factors including land cover change, land use condition, climate change, etc., which were quantified to the impact parameter x . Therefore, the recession regime influenced by the overall environmental change should focus on the dynamic storage and storage-discharge relationship.

5.2 Environmental impact on dynamic storage properties

Compared dynamic storage with Δx , most of the catchments have consistent changes except Shin-Ying, Tso-Chen, and Liu-Kwei. This indicates that groundwater storage variation increases when parameter$x$ increases, also indicating that parameter x would capture the original groundwater storage variation by inversely estimating from Q . Interestingly, more dynamic storage and temporal changes were mainly concentrated in the Pingtung Plain (Liu-Kwei, San-Ti-Men, Chao-Chou and Hsin-Pei) and the Bazhang River Basin (Chu-Kou and Chang-Pan Bridge). As mentioned in Sections 2 and 5.1, northern Chianan Plain and Pingtung Plain have great lateral aquifer connectivity and a more developed aquifer. The hydrogeological parameters estimated by Huang and Yeh (2019) also showed this significant regional difference.

In S -Q relationships, in addition to indicating that the catchment S -Q relationships become less susceptible to environmental changes, it also can be considered as the dimensionless$S$-Q relationship to compare regional difference. Higher sensitivities concentrated in the central region of Southern Taiwan and the decreasing change are similar to our previous work. However, the spatial distribution was different from larger dynamic storage with the higher susceptibility due to difference in the range of streamflow contribution. Relative to the storage capacity and the drainage characteristics formed by subsurface structures and hydrogeological properties, the vertical flow process (infiltration rate, groundwater evaporation, vegetation transpiration, etc.) also cause regional differences in the recession regime with different geomorphology or climatic conditions (Brooks, Chorover, Fan, Godsey, Maxwell, McNamara, & Tague, 2015; Tashie, Scaife, & Band, 2019). In addition, our results provided the perspective for quantified environmental impact and change in sensitivities. As Cheng et al. (2017) mentioned, the increasing parameter x indicates that the environmental change caused more groundwater storage loss thereby reducing groundwater discharge. Most catchments had the decreasing S -Q sensitivity with an increase in parameter x , showing the groundwater storage loss and lower baseflow are the crisis under the environmental change. It may lead to an increase in drought events, a change in ecological habitat, and even prompt people to consume more groundwater resources.

5.3 δμπαρινγ τηε χυαντιφιεδ ιμπαςτ Δξ ωιτη λανδ υσε ςηανγε

To understand the correlation between parameter x and land use change, we calculated the Normalized Difference Vegetation Index (NDVI) as a simple land use change so as to realize the related response mechanism. The NDVI is a numerical indicator used for assessing vegetation coverage in a target area through the reflection of red and near-infrared. Here we selected Landsat-5 satellite imagery from November to April in three periods (1988-1989, 2000-2001, and 2008-2009), as shown in Figure 9. Most of Δx in Southern Taiwan increased after 2000 which was consistent with changes in vegetation except for Chu-Kou, Chang-Pan Bridge, Hsin-Shih, and Liu-Kwei. Although the changes may actually contain various factors, the impact on groundwater storage and streamflow can be clearly identified. High consumption rate of water use showed urbanization reduces low flow and increase the flow variation through groundwater pumping (Wang & Cai, 2009,2010). Large bedrock leakage from storage to deep groundwater caused the dynamic storage loss (Wang, 2011). Cheng et al. (2017) demonstrated the increasing parameter x which indicates that the increase in vegetation cover results in lower groundwater storage as a result of strong canopy interception and transpiration. Ploum, Lyon, Adriaan, Laudon, and van der Velde (2019) suggested that more snowmelt infiltration lead to nonlinear S-Q relationship which is similar to the effect on the recession curve when parameter x decreases. This exhibits that catchments in Southern Taiwan mostly have increasing groundwater loss and decreasing baseflow owing to environmental changes. Due to the importance of baseflow, the problems of water resources allocation and management in these regions require attention under the environmental change.

The inconsistent results with Δx can be explained by the local land use which may affect the catchment drainage process. According to the previous reports, fruit trees and agriculture lands are present along the upstream bank of the Bazhang River (Chu-Kou and Chang-Pan Bridge). Therefore, groundwater drainage from the aquifer of the river bank may increase groundwater storage due to the return flow of agricultural irrigation ($\Delta x < 0$). There are fewer human activities upstream of the Laonong River (Liu-Kwei), however the large surface area exposure caused by erosion or collapse with high-intensity rainfall events (such as typhoons) on agricultural and forestry slope areas may result in an increase in rainfall infiltration ($\Delta x< 0$). Upstream of the Yanshui River (Hsin-Shih), the agricultural areas with better permeability were gradually replaced with dense industrial and residential areas that reduced the groundwater storage with the lower rainfall infiltration ($\Delta x > 0$) (Water Resources Agency, 1986, 2000b, 2007). However, there is still a critical issue regarding how to separate the environmental change impacts into unnatural (e.g. human activities, land use change) and natural (e.g. climate change) factors. It is necessary to identify whether the effects of climate change and human activities on catchment hydrological processes overlap or are offsetting. We suggest that future work of the study should improve or incorporate relevant researches to solve related problems inherent for more exploration in detail.

6. Conclusion

This study considered the environmental impact in low-flow recession analysis, exploring the changes in low-flow characteristics, dynamic storage, and storage-discharge relationships in order to understand the effect of groundwater loss or gain on the catchment recession regime. The results showed decreased low-flow characteristics in most catchments which represent the lower flow variation owing to environmental change. In addition, the regional distribution of low-flow characteristics and dynamic storage showed regional differences in aquifer properties, which is consistent with previous work. The majority of the dynamic storage increased in the post-period, indicating that environmental change ultimately led to increased groundwater consumption by increased vegetation cover, groundwater pumping or other possible factors. It also causes a decrease in storage-discharge sensitivities with lower streamflow. This highlighted a critical problem where frequent drought events may occur during dry periods due to a lower streamflow generated from groundwater. To understand whether the quantifying environmental change is consistent with changes in land use, this study calculated the NDVI changes for comparison. As expected, both changes were the same, and only a few catchments were inconsistent. These inconsistent cases can be explained by the possible impact factors (including return flow of agricultural irrigation, increase in industrial land use, surface erosion by natural hazards, and others) from local land use. In conclusion, this study demonstrated that quantifying environmental impacts through the recession method can help to clarify current changes in groundwater and related processes from environmental co-evolution. Different from our previous research that focused on S-Qsensitivity and its change, this study can compare regional differences and its changes over time by quantified environmental impact. Future challenges lie in the development of methods or modeling for assessing an impact of specific factor with a physics-based description.

Acknowledgments

The authors are grateful for the support from the Research Project of the Ministry of Science and Technology (MOST 108-2221-E-006-017-MY2).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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