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Evaluating the effect of partial contributing storage on storage–discharge function from recession analysis

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Abstract

Hydrograph recession during dry periods has been used to construct water storage–discharge relationship, and to quantify storage dynamics and evaporation when streamflow data is available. However, variable hydrologic connectivity among hillslope-riparian-stream zones may affect the lumped storage–discharge relationship, and as a result, affect the estimation of evaporation and storage change. Given observations of rainfall and runoff, and remote sensing-based observation of evaporation, the ratio (α) between estimated daily evaporation from recession analysis and observed evaporation, and the ratio (β) between estimated contributing storage and total watershed storage are computed for 9 watersheds located in different climate regions. Both evaporation and storage change estimation from recession analysis are underestimated due to the effect of partial contributing storage, particularly when the discharge is low. It was found that the values of α decrease significantly during individual recession events, while the values of β are relatively stable during a recession event. The values of β are negatively correlated with the water table depth, and vary significantly among recession events. The partial contributing storage effect is one possible cause for the multi-valued storage–discharge relationship.

1 Introduction

The physical control of climate, vegetation, soil, and topography on water balance is an important research question in watershed hydrology. A comprehensive understanding of water balance dynamics is a challenge partly due to the fact that evaporation and water storage data are limited in many watersheds. Evaporation is controlled by complex factors such as atmospheric condition, vegetation, and water availability. With the advancement of measurement technology, evaporation can be estimated by utilizing remote sensed data which covers large spatial scales with high resolution (Mu et al., 2007; Zhang et al., 2010). The difficulties involved in measurement of water storage

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are due to the spatial variability of soil moisture and groundwater storage. Terrestrial water storage changes can be identified by monitoring the variability in gravity field through Gravity Recovery and Climate Experiment (GRACE) satellite (Swenson et al., 2006). However, the spatial resolution of GRACE is too large to be applicable for watershed scale studies. Water storage changes can also be estimated by using point-based observations of groundwater level and soil moisture (Wang, 2012a) or water balance closure (Sayama et al., 2011; Wang and Alimohammadi, 2012). These methods are constrained by the data availability of soil moisture, groundwater and actual evaporation.

The conceptual storage–discharge function derived from base flow recession has been used to estimate storage changes (e.g., Kirchner, 2009; Teuling et al., 2010; Ajami et al., 2011; Krakauer and Temimi, 2011), evaporation (e.g., Szilagyi et al., 2007; Palmroth et al., 2010), and leakage from and to bedrock (Wang, 2011). The estimated evaporation and water storage dynamics from the lumped storage–discharge relationship are usually treated as the total values of the entire watershed. The underlying assumption is that all the subsurface storage in the watershed contributes to the streamflow observed at the outlet (Wang, 2012b). The violation of this assumption may affect the evaporation and storage change estimation significantly, especially in large watersheds with considerable spatial heterogeneity of soil water storage.

During dry periods, not all the landscape components (hillslope, riparian and stream zones) are hydrologically connected to the watershed outlet and further contribute to the observed base flow. In subsurface hydrology, spatial heterogeneity of hillslope-riparian-stream zones has been found to be important for water table response to precipitation (Vidon, 2012) and base flow recession behavior (Clark et al., 2009; Harman et al., 2009). Moreover, at the plot scale, the water table dynamics can be independent at the hillslope and riparian zones (Seibert et al., 2003; Vidon and Hill, 2004; Rodhe and Seibert, 2011). Due to this spatial heterogeneity, the flowing stream network expands to respond rainfall events and contracts during drought periods (Gregory, 1976; Day, 1978). Biswal and Marani (2010) demonstrated the linkage between base flow

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recession and the spatial organization of stream network with a focus on the contraction of active stream network. Even in the active stream network, the hydrologic connectivity of riparian and upland zones to channel may decrease during dry periods (Ocampo et al., 2006; Molenat et al., 2008). Some river reaches may even become entirely detached from the riparian zone at very low flows owing to obstruction of the channel by vegetation (Blyth and Rodda, 1973). Riparian zones are the interfaces between hillslope and stream, and the water table fluctuations in riparian zones are usually not significant (Jencso et al., 2009). Even within hillslope or riparian zones, bedrock depressions can be disconnected during low flow periods (McDonnell et al., 1998; Buttle et al., 2004; Tromp-van Meerveld and McDonnell, 2006a,b).

Since the hydrologic connectivity between hillslope, riparian, and stream zones varies with time, the storage–discharge function may also vary when total watershed storage is used in the lumped discharge model. The variable characteristic of storage–discharge function has been reported by several studies (e.g., Rupp et al., 2009). Using a linearized distributed model, Sloan (2000) found that total water storage and groundwater discharge is not a one-to-one relationship. Hysteresis relation between storage and streamflow has been reported due to the variable hydrologic connectivity of water storage (Spence et al., 2010). Clark et al. (2011) demonstrated that a multi-valued storage–discharge relationship could be replicated by a simple lumped conceptual model with two parallel stores representing the saturated zone. Krakauer and Temimi (2011) reported that storage change estimated from base flow recession is underestimated compared with GRACE based estimation.

The objective of this study is to evaluate the effect of partial contributing storage caused by variable subsurface hydrologic connectivity on the water storage–discharge relationship derived from recession analysis. In this paper, the estimation of evaporation and storage change using storage–discharge functions will be evaluated based on observed rainfall, streamflow, and observed evaporation from remote sensing data at 9 watersheds located in different climate regions. The ratio between estimated daily evaporation from recession analysis and observed evaporation, and the ratio between

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estimated contributing storage and total watershed storage are computed for the 9 study watersheds, and their temporal variability are discussed.

2 Methodology

2.1 Recession analysis

Hydrograph recession analysis is usually utilized to derive water storage–discharge functions at the watershed scale. The recession analysis method proposed by Brutsaert and Nieber (1977) is to plot recession slope ($-\mathrm{d}Q/\mathrm{d}t$) as a function of discharge (Q). This method facilitates the analysis on a collective of recession events, and the impact of recession starting time on parameter estimation is minimized. As proposed by Brutsaert and Nieber (1977), the relationship between recession slope and discharge can be modeled as a power function:

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = aQ^b \tag{1}$$

Exponent b is dimensionless and the unit of a depends on the value of b. Q (mm d^{-1}) is groundwater discharge per unit watershed area. The data pairs ($-\frac{\mathrm{d}Q}{\mathrm{d}t}$, Q) can be computed by the difference of discharges in consecutive days ($Q_t - Q_{t+1}$) and the average discharge (($Q_t - Q_{t+1})/2$), respectively (Brutsaert and Nieber, 1977). Recession periods were selected when there was no rainfall. As an example, the data pairs ($-\frac{\mathrm{d}Q}{\mathrm{d}t}$, Q) for the Spoon River watershed are plotted in Fig. 2.

Based on the plot of $-\frac{\mathrm{d}Q}{\mathrm{d}t}$ versus Q on log-log space, the function of $-\frac{\mathrm{d}Q}{\mathrm{d}t} = f(Q)$ and further the storage–discharge function can be constructed. Several methods have been used to estimate the parameters in the literature (Stoelzle et al., 2013). Vogel and Kroll (1992) estimated the parameter values in Eq. (1) by linear regressions. Kirchner (2009) proposed to use polynomial functions which fit the binned data points. Therefore, the

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power function in Eq. (1) was not assumed a priori. Since the recession rate of groundwater discharge is smaller than other storage components, Brutsaert and Nieber (1977) proposed to place the fitted line at the lower envelope of the data points. The effect of evaporation on recession parameter estimation is minimal at the lower envelope. In this study, the lower envelope method is used for estimating the recession parameters a and b.

When rainfall is zero and the net groundwater flux from outside the watershed is negligible, the water balance equation during recessions can be written as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -Q - E \tag{2}$$

where S (mm) is the depth of water storage per unit watershed area. S is the water storage contributed to observed base flow at the outlet but normalized over the entire watershed area. Therefore, E (mm) is also the depth of evaporation from the contributing storage but normalized by the watershed area. Both S and E are not the corresponding total values in the entire watershed. The storage–discharge function derived from hydrograph recession is a conceptual lumped model. The unsaturated and saturated zones are modeled by one storage term. Therefore, evaporation in Eq. (2) is assumed for the total value from unsaturated and saturated zones (Szilagyi et al., 2007; Kirchner, 2009; Palmroth et al., 2010). The recession parameters can be estimated at the lower envelope where the impact of evaporation is minimal (Fig. 2). Correspondingly, the storage–discharge relation is obtained:

$$\mathrm{d}S = \frac{1}{a} Q^{1-b} \mathrm{d}Q \tag{3}$$

Substituting dS into Eq. (2), evaporation can be estimated based on the observed recession slope and discharge (Palmroth et al., 2010):

$$E = \frac{-\mathrm{d}Q/\mathrm{d}t}{a} Q^{1-b} - Q \tag{4}$$

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The effect of evaporation on hydrograph recession has been reported in many watersheds (Federer, 1973; Daniel, 1976). The seasonal variability of recession rate is caused by seasonal pattern of evaporation (Wittenberg and Sivapalan, 1999).

During the late recession, the exponent b_2 is usually less than 2, and the contributing storage is obtained by integrating Eq. (3):

$$S = S_\mathrm{m} + \frac{Q^{2-b_2}}{a_2(2-b_2)} \tag{5a}$$

S_m is interpreted as the minimum storage for generating base flow. During the early recession, the exponent b_1 is usually larger than 2 and the contributing storage is computed as:

$$S = S_\mathrm{c} + \frac{Q^{2-b_1}}{a_1(2-b_1)} \tag{5b}$$

S_c is interpreted as the storage capacity (Kirchner, 2009). Storage and discharge functions by Eq. (5), which are estimated from recession analysis as shown in Fig. 2, are usually assumed to be one-to-one relationships.

Discharge at the transition point from early to late recessions is a function of recession parameters:

$$Q_0^* = \left(\frac{a_2}{a_1}\right)^{\frac{1}{b_1-b_2}} \tag{6}$$

For the parameters in Fig. 2, Q_0^* is 0.29 mm d^{-1} for the Spoon River watershed. If $Q > Q_0^*$, the recession is at the early stage. Otherwise, it is at the late stage. According to Eq. (5), the storage capacity can be computed given S_m and Q_0^*:

$$S_\mathrm{c} = S_\mathrm{m} + \frac{{Q_0^*}^{2-b_2}}{a_2(2-b_2)} - \frac{{Q_0^*}^{2-b_1}}{a_1(2-b_1)} \tag{7}$$

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Storages at the late and early recessions are computed by Eqs. (5a) and (5b), respectively.

As discussed earlier, due to the effect of partial contributing storage, S in these equations is the contributing storage normalized by the watershed area. The ratio of contributing storage to total storage is represented by β:

$$\beta = \frac{S}{\mathrm{TS}} \tag{8}$$

where TS (mm) is the total depth of water storage per unit watershed area. Similarly, the ratio of evaporation estimated by Eq. (4) to total evaporation is represented by:

$$\alpha = \frac{E}{\mathrm{TE}} \tag{9}$$

where TE (mm) is the total evaporation per unit watershed area. The variables α and β can be interpreted as the fraction of the watershed underlain by aquifers that contributes to streamflow (Brutsaert and Nieber, 1977). The values of α and β are indicators of hydrologic connectivity among hillslope-riparian-stream zones. The variability of β, such as seasonal variation, is one potential factor for variable storage–discharge functions, $\mathrm{TS} = f(Q)$, at the watershed scale.

2.2 Estimation of α and β

In order to explore the impact of the variable contributing storage on the storage–discharge relationship, the values of α and β are estimated in the study watersheds. At each individual recession event, α is estimated as the ratio between estimated daily E by Eq. (4) and observed daily evaporation (E^{obs}) based on remote sensing data at the watershed scale: $\alpha = E/E^{\mathrm{obs}}$. On the other hand, β is estimated as the ratio between estimated storage and total storage. For a recession segment, the value of β is estimated by the water balance described as follows. Storages at two consecutive

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days, $S(t_1)$ and $S(t_2)$, are computed by Eq. (5). The total watershed storage change is equal to discharge and total evaporation:

$$\mathrm{TS}(t_1) - \mathrm{TS}(t_2) = Q(t_2) + \mathrm{TE}(t_2) \tag{10}$$

Combining Eqs. (8) and (10), the contributing storage parameter at t_2 is computed by:

$$\beta(t_2) = \frac{S(t_2)}{\left[S(t_1)/\beta(t_1) - Q(t_2) - \mathrm{TE}(t_2)\right]} \tag{11}$$

At the onset of the recession event (t_1), the value of β is assumed to be equal to the average of α during the recession, since α and β are both majorly controlled by the variation of contributing storage in the watershed. This assumption is used to determining the initial value of β in a recession event. The uncertainty of the initial β does not affect the generalization of the findings.

2.3 Data selection and S_m

The analysis in this paper is based on recessions during the period from April to October in order to focus on the rainfall events. The following criteria are used to filter recession segments: (1) declining streamflow; (2) no rainfall during recession; (3) recession event is longer than 4 days. The recession rate computed by $\frac{Q(t)-Q(t+2)}{2}$ is used to compute $S(t+1)$ associated with discharge $Q(t+1)$. The estimated storage in Eq. (5) is affected by the minimal storage S_m, which is set to 0. However, the estimation of evaporation in Eq. (4) is unaffected by S_m.

3 Study watersheds and data

Table 1 shows the background information of 9 selected watersheds including watershed name, USGS gage station identification number, drainage area, and climate aridity index. The values of climate aridity index for the watersheds range from 0.38 to

1.34. Rainfall and runoff data during 1948–2003 were obtained from the Model Parameter Estimation Experiment (MOPEX) dataset (Duan et al., 2006). Daily actual evaporation during 1983–2006 was obtained from the dataset developed by Zhang et al. (2010). Weather stations-based observations and Normalized Difference Vegetation Index (NDVI) from remote sensing data are utilized for evaporation estimation at each pixel with a spatial resolution about 8 km. The grid-based values of daily evaporation are aggregated to the watershed level. The evaporation algorithm accuracy was evaluated by comparing the estimated evaporation with tower-measured meteorology results from totally 82 tower sites of the FLUXNET data archive (Zhang et al., 2010). Based on their results, the root mean square error (RMSE) of the estimated evaporation at the sites in America is 32 $\mathrm{W\,m^{-2}}$, which is around 1.20 $\mathrm{mm\,d^{-1}}$. Considering the availability of rainfall, runoff and evaporation data, this study is focused on the period from 1983 to 2003.

Among the 9 study watersheds, Spoon River watershed located in Illinois will be discussed with more emphasis (Fig. 1) because of the rich data availability. Soil moisture observation during 1981–2004 and groundwater level observation since 1960s are available (Changnon et al., 1988; Hollinger and Isard, 1994; Scott et al., 2010). These datasets can be used to explore the seasonal water storage changes directly (Wang, 2012a). The land cover in this watershed includes 85 % of agricultural land including corns and soybeans and others including forest, barren and urban lands (Demissie et al., 2007). The soil thickness of river riparian zone varies from 5 to 15 feet (IDNR, 1998).

4 Results and discussion

The values of α and β in the 9 case study watersheds shown in Table 1 are calculated using the method discussed above. The Spoon River watershed will be discussed with more details as mentioned before. As shown in Fig. 2, the recession parameters for the Spoon River watershed are $b_1 = 2.2$ and $a_1 = 0.035\ \mathrm{mm^{-2}\,d}$ for the early recession

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and $b_2 = 1.2$ and $a_2 = 0.01\,\mathrm{mm}^{-0.2}\,\mathrm{d}^{-0.8}$ for the late recession. The values of recession parameters for the other 8 watersheds are shown Table 1, and the corresponding plots of $-\mathrm{d}Q/\mathrm{d}t \sim Q$ can be found in the Supplement.

4.1 Underestimation of evaporation from base flow recession analysis

The estimated daily evaporation from the lumped storage–discharge relationship is compared with the one estimated from remote-sensing and weather stations-based data. For demonstration purpose, Table 2 shows two recession events from: (1) the Spoon River watershed during May 1994 in Table 2a; (2) and the Nodaway River watershed during May 1994 in Table 2b. The estimated E by Eq. (4) and E^{obs} from remote sensing data are shown in columns 6 and 7, respectively. As we can see in Table 2, the estimated evaporation from recession analysis is much smaller than E^{obs}. Figure 3 plots estimated E versus E^{obs} from all the 9 watersheds. Most of the estimated values of evaporation are smaller than the remote sensed ones, and 93 % of data points are below the 1 : 1 line in Fig. 3.

The mismatch between estimated E versus E^{obs} can be induced by two potential reasons. The values of E are underestimated, or the values of E^{obs} are overestimated. However, E^{obs} is not biased toward overestimating evaporation as discussed earlier, and the average RMSE of E^{obs} is $1.2\,\mathrm{mm\,d}^{-1}$. The detailed uncertainty assessment of E^{obs} is not discussed in this paper and referred to (Zhang et al., 2010). Even if $1.2\,\mathrm{mm\,d}^{-1}$ of overestimation in E^{obs} is assumed, the estimated E is still underestimated in most recession events. As shown in Table 2, the estimated E decreased from $1.72\,\mathrm{mm\,d}^{-1}$ to $0.92\,\mathrm{mm\,d}^{-1}$ during a recession event in May in the Spoon River watershed while E^{obs} remained at the level of $3.08\,\mathrm{mm\,d}^{-1}$ to $3.35\,\mathrm{mm\,d}^{-1}$. The underestimation of E is also supported by the fact that potential evaporation of the Spoon River watershed is $6.20\,\mathrm{mm\,d}^{-1}$ and the land use is dominated by agriculture including corns and soybeans (ISWS, 2010). It should be noted that the placement of lower

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envelope in Fig. 2 also affects the estimation of E. If the lower envelope in Fig. 2 was moved upward, the estimated evaporation will be even lower.

The underestimation of evaporation from hydrograph recession analysis can be explained by two major reasons: (1) the storage contributed to the observed base flow in the outlet is mainly from riparian groundwater during dry periods, and therefore the estimated evaporation by Eq. (4) only accounts for evaporation from the riparian zone; (2) the linkage between water storage in the unsaturated zone and base flow becomes weak while the groundwater table declining. As a result, evaporation from unsaturated zone is not included in the estimated E by recession analysis. Because of these two reasons, the value of estimated E by Eq. (4) will be underestimated, since the estimated E from riparian zone or contributing storage to base flow is normalized by the entire watershed area.

4.2 Temporal variability of α

The ratio between estimated E and E^{obs}, which is described as α, reflects the significance of bias in the estimated evaporation. As shown in Table 2a, the value of α decreases by 58 % from 0.656 to 0.274 during the recession event; and the value of α decreases by 28 % from 0.436 to 0.313 during the event in Table 2b. The value of α decreases with declining discharge during individual recession events in all the study watersheds. The value of α also varies with events and is dependent on the initial soil moisture and groundwater table. For example, the water table rises after a heavy rainfall and therefore more groundwater area contributes to the base flow, which is corresponding to a higher value of α. At the same time, higher discharge is corresponding to higher water table. Figure 4 plots the relation between estimated α and observed discharge from the Spoon River watershed. As it shows, the larger values of α correspond to higher discharges.

As a statistical summary on the underestimation of E, Fig. 5 shows the cumulative distribution function (CDF) curve of α, in which over 93.3 % of the α values in the 9 study watersheds are smaller than 1 and over 70.2 % of the α values are smaller

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than 0.5. This result indicates a significant underestimation of evaporation based on recession analysis.

4.3 Temporal variability of β

The underestimation of storage by storage–discharge relationship is reflected in the values of β which is the ratio of estimated storage to total storage. Figure 6 plots the CDF curve of β values in the 9 study watersheds. The values of β are less than 1.0 for 94.5 % of data points, and 0.5 for 72.7 % of data points. Focusing on small watersheds with drainage area less than 100 km^2, Krakauer and Temimi (2011) compared the storage inferred from the recession curve and the storage measured by GRACE and found that the variability of storage by storage–discharge functions derived from recession curves is typically smaller by a factor of 10. The effect of partial contributing storage contributes to the discrepancy was also observed in their study.

The underestimations of both evaporation and storage change based on recession analysis are due to the partial contributing storage to base flow. Furthermore, the storage changes between two consecutive days (ΔS and ΔTS) are computed, and the ratios between them, $\Delta S/\Delta TS$, are obtained. Figure 7 plots $\Delta S/\Delta TS$ versus α (i.e., E/E^{obs}) from the Spoon River watershed. The correlation coefficient between $\Delta S/\Delta TS$ and E/E^{obs} is 0.84. Therefore, the underestimations of evaporation and storage change are highly correlated.

The value of β can also be interpreted as the percentage of water storage contributing to the base flow during low flow periods when riparian groundwater storage is the major source for base flow. Column 5 in Table 2 shows the computed relative storage by Eq. (5a), and the last column shows the estimated β by Eq. (11) from water balance. As shown in Table 2, β does not change significantly during a recession event. The value of β is around 0.38 for the Spoon River watershed and varies from 0.38 to 0.32 for the Nodaway River watershed. Compared with the declining trend of α during a recession event, the value of β is relatively more stable. The implication of stable value of β is

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that the ratio of riparian groundwater storage to total watershed groundwater storage is relatively stable during a recession event.

On the other hand, β reflects the level of shallow groundwater connectivity in the watershed. The groundwater storage connectivity is dependent on the groundwater table depth. Therefore, the value of β may be correlated with groundwater table depth. It is fortunate that the observation of the shallow groundwater table depth in the Spoon River watershed is available (Wang, 2012a). As shown in Fig. 8, the values of β decrease as the groundwater table depth increases and the correlation coefficient is 0.41, which indicates that when the groundwater table drops down, the contributing storage to base flow will decrease. The seasonal variability of water table depth is significant ranging from 86 mm to 510 mm as shown in Fig. 8. Correspondingly, the seasonal variability of β is also significant ranging from 0.027 to 0.799 (Fig. 6), even though the variation of β is not significant during a recession event.

4.4 Variability of storage–discharge relationship

The effect of partial contributing storage induces variable storage–discharge relationship at the watershed scale. Figure 9 presents the estimated total relative storage (TS) and discharge (Q) relationship for the Spoon River watershed. The red solid line represents the storage–discharge function derived from the lower envelope of Fig. 2, i.e., Eq. (5), which is equivalent to the case of $\beta = 1$. The blue circles represent the estimated total watershed relative storage by considering variable β values based on water balance at the watershed scale. The data points ($\beta < 1$) are below the red solid line ($\beta = 1$). From Fig. 10, the TS–Q relation tends to follow a power law within a recession event but varies among different recession events due to the variability of β among recession event. Given the same values of discharge, the corresponding total watershed water storage may vary between recession events. Therefore, the storage–discharge relation during recession periods may not be a one-to-one function. Other factors can also contribute to the multi-valued storage–discharge relationship (Rupp et al., 2009; Haught and Meerveld, 2011; Clark et al., 2011). Sloan (2000) demonstrated

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that single-valued storage discharge functions are often incapable of representing the actual storage–discharge characteristics of a watershed and proposed an alternative discharge function based on hillslope groundwater hydraulics. Therefore, the effect of partial contributing storage is one of potential contributions to the variable storage–discharge relationship.

5 Summary and conclusion

The impact of subsurface hydrologic connectivity, which is represented by the partial contributing storage, on the storage–discharge functions at 9 watersheds in different climate regions was evaluated. The hydrologic connection among hillslope-riparian-stream zones decreases with the decline of water table. The effect of the partial contributing storage is one possible cause for the multi-valued storage–discharge relationship. The seasonal variations of hydrologic connectivity and contributing storage can cause variable storage–discharge functions given the same value of streamflow. As a result, when the entire watershed storage is assumed to be connected with the watershed outlet, water storage and evaporation based on the storage–discharge function may be underestimated systematically. The underestimation of evaporation and storage change based on the storage–discharge function was evaluated using α as the ratio between estimated evaporation and remote sensed evaporation and β as the ratio between estimated storage and total storage, respectively. Based on the values of α and β, significant underestimation was observed for both evaporation and storage. The value of α decreases during a recession event while the value of β is relatively stable during a recession event but varies significantly among the recession events.

The effect of partial contributing storage on storage–discharge function increases with the spatial heterogeneity of water storage. In small catchments, it may be reasonable to assume fixed storage–discharge function. However, information on the spatial variability of storage may need to be incorporated into the lumped storage–discharge function for watersheds with significant seasonality of water table dynamics. Further research will be focused on validating partial contributing storage in experimental watersheds with detailed observations on spatial variability of soil moisture and groundwater table as well as the response of base flow.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/10/5767/2013/hessd-10-5767-2013-supplement.pdf.

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Table 1. Watershed name, USGS gage number, drainage area, climate aridity index (E_p/P), and estimated recession parameters for the 9 case study watersheds.

Watershed	USGS gage	Drainage area (km^2)	E_p/P	Recession parameter a_1	b_1	a_2	b_2
Spoon River, IL	05570000	4237	1.09	0.035	2.2	0.01	1.2
Holston River, VA	03473000	785	0.61	0.02	2.3	0.03	1.4
Nantahala River, NC	03504000	134	0.39	0.0015	2.9	0.01	1.5
Little Sioux River, IA	06606600	6475	1.34	0.022	2.5	0.02	1.5
Valley River, NC	03550000	265	0.38	0.004	3	0.017	1.5
Clinch River, VA	03524000	1380	0.68	0.025	2.9	0.035	1.5
Powell River, VA	03531500	827	0.60	0.025	2.9	0.035	1.5
Nodaway River, IA	06817000	1972	1.17	0.05	2.8	0.025	1.5
Big Nemaha River, NE	06815000	3468	1.34	0.15	3	0.025	1.3

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Table 2a. One recession event from the Spoon River watershed in Illinois.

Date	P (mm d^{-1})	Q (mm d^{-1})	$-\mathrm{d}Q/\mathrm{d}t$ (mm d^{-2})	S (mm)	Estimated E (mm d^{-1})	E^{obs} (mm d^{-1})	α	β
15 May 1994	0.40	0.84						
16 May 1994	0.00	0.78						
17 May 1994	0.00	0.71	0.0665	76.22	2.18	3.33	0.656	0.437
18 May 1994	0.00	0.65	0.0491	73.57	1.72	3.16	0.543	0.431
19 May 1994	0.00	0.61	0.0373	71.55	1.33	3.08	0.432	0.429
20 May 1994	0.00	0.57	0.0258	69.71	0.86	3.10	0.278	0.427
21 May 1994	0.00	0.56	0.0255	68.72	0.92	3.35	0.274	0.431
22 May 1994	0.00	0.52						
23 May 1994	0.81	0.50						

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Table 2b. One recession event from the Nodaway River watershed in Iowa.

Date	P (mm d^{-1})	Q (mm d^{-1})	$-dQ/dt$ (mm d^{-2})	S (mm)	Estimated E (mm d^{-1})	E^{obs} (mm d^{-1})	α	β
14 Jun 1995	0.51	0.70						
15 Jun 1995	0.00	0.65						
16 Jun 1995	0.00	0.60	0.0497	61.87	1.90	4.37	0.436	0.384
17 Jun 1995	0.00	0.55	0.0428	59.46	1.75	4.02	0.435	0.357
18 Jun 1995	0.00	0.51	0.0329	57.28	1.33	3.75	0.353	0.330
19 Jun 1995	0.00	0.49	0.0298	55.81	1.22	3.91	0.313	0.319
20 Jun 1995	0.04	0.45						

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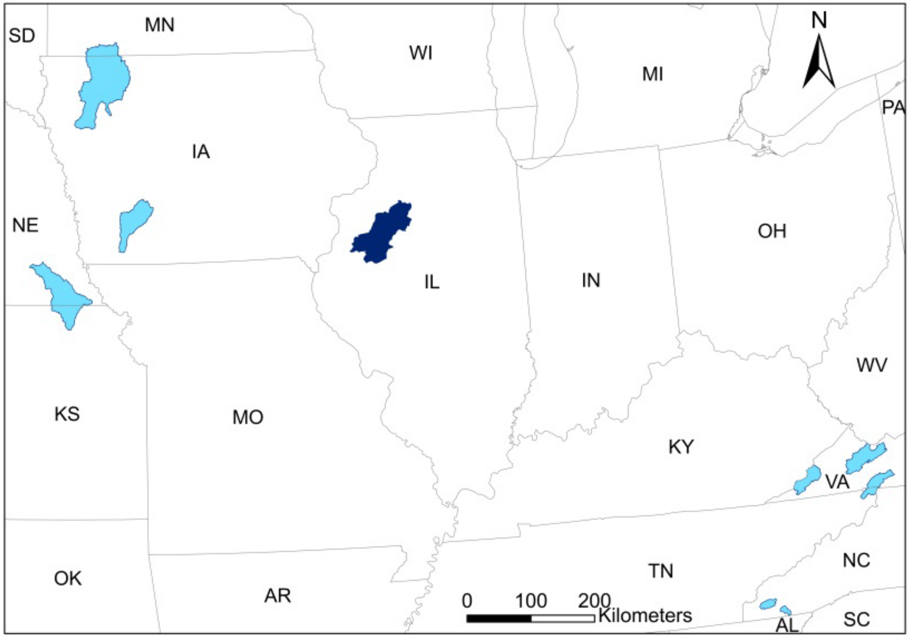

Fig. 1. Locations of the 9 study watersheds with Spoon River watershed located in Illinois highlighted with dark blue.

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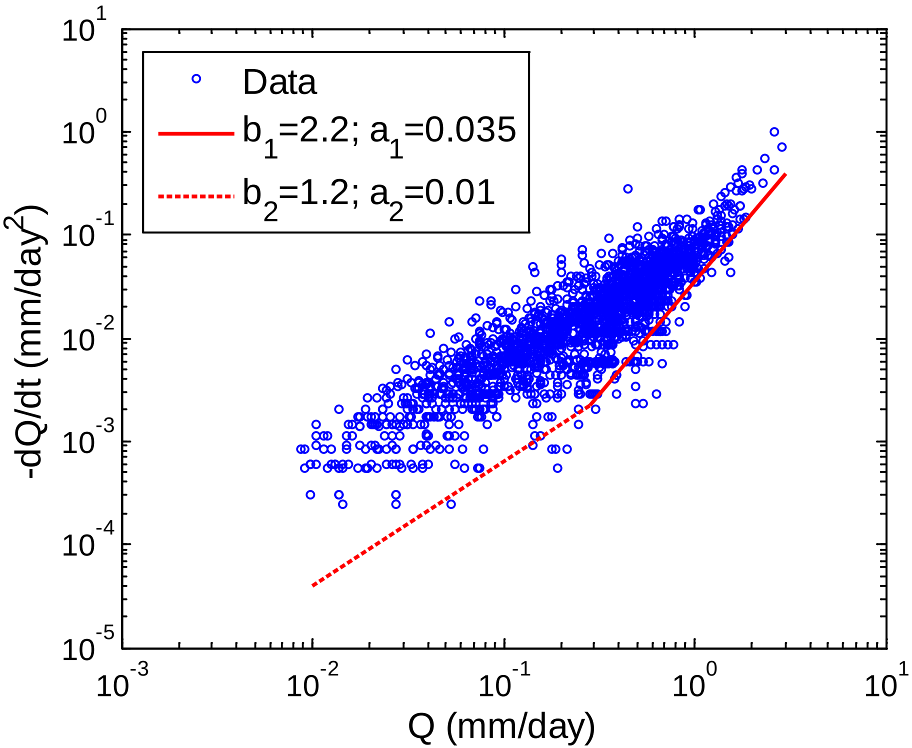

Fig. 2. $-\mathrm{d}Q/\mathrm{d}t$ versus Q and the lower envelope for the Spoon River water based on daily streamflow data during 1 January 1983–31 December 2003.

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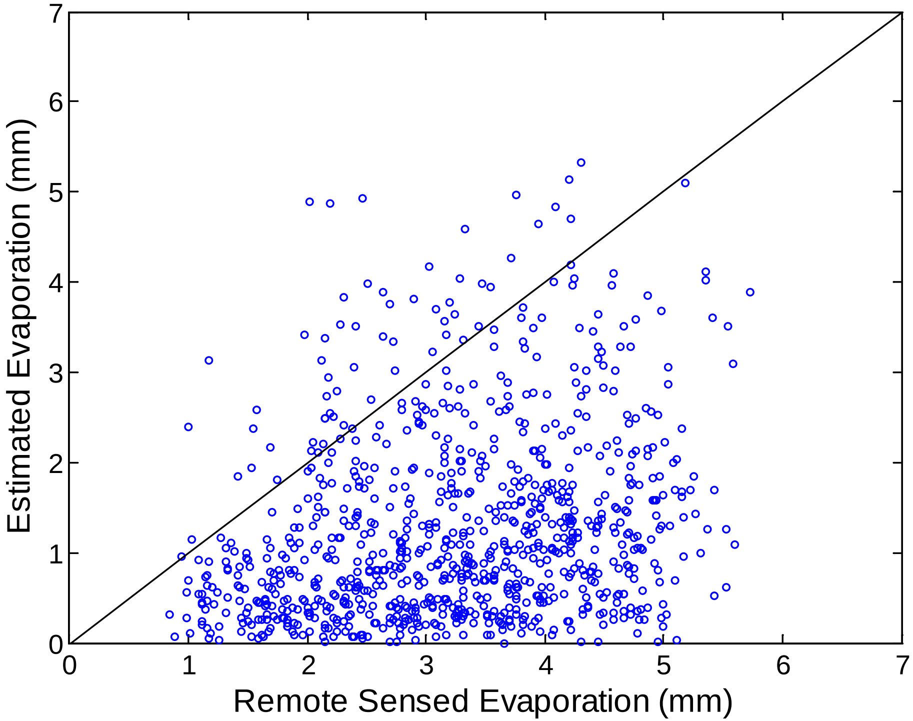

Fig. 3. Comparison between estimated evaporation from recession analysis and evaporation from remote sensed data.

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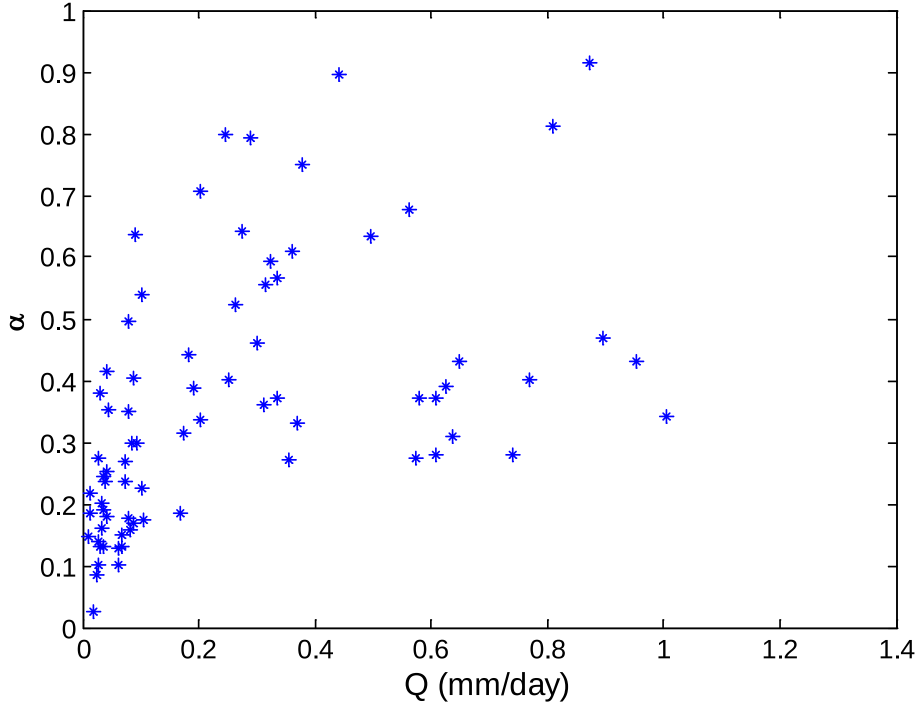

Fig. 4. Estimated α versus discharge (Q) from the Spoon River watershed.

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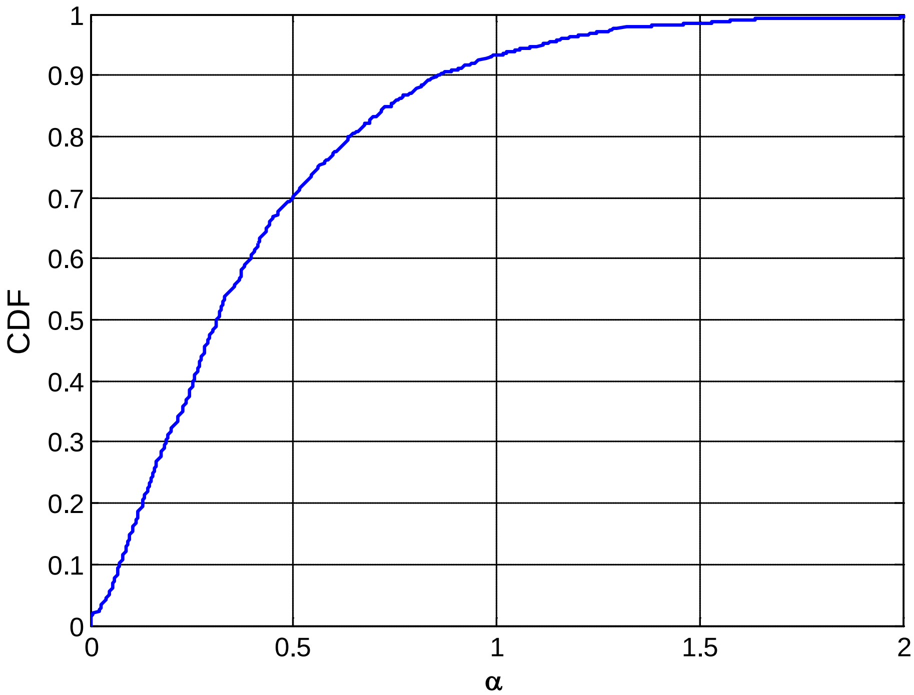

Fig. 5. Cumulative distribution function of α from all the study watersheds.

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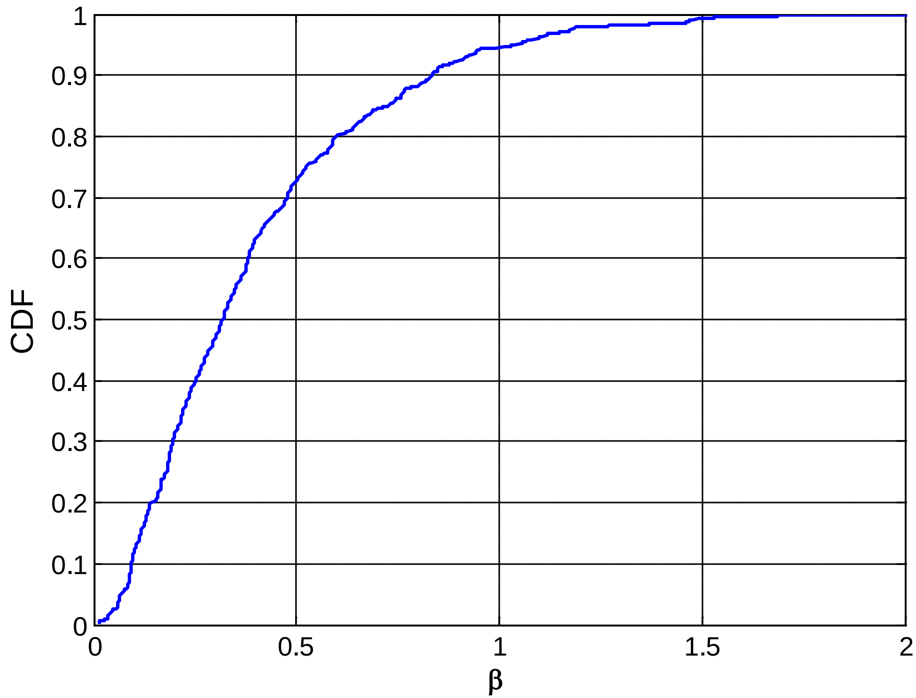

Fig. 6. Cumulative distribution function of $\beta = S/TS$ from all the study watersheds.

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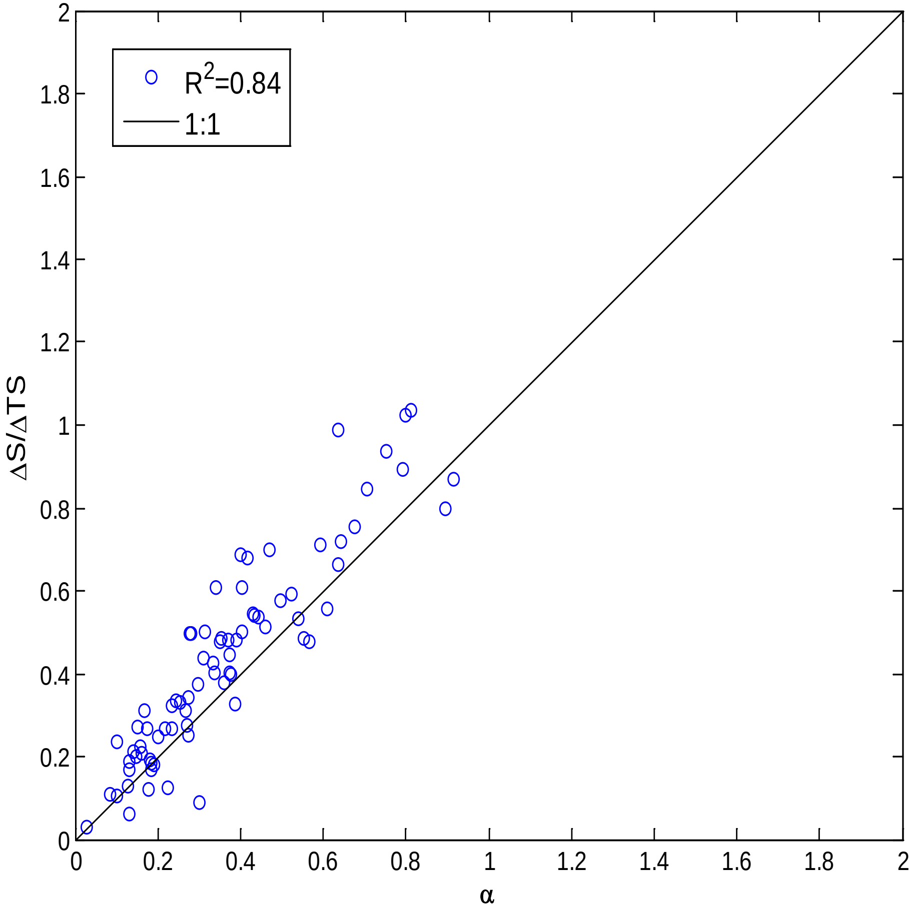

Fig. 7. Correlation between $\Delta S/\Delta TS$ and α in the Spoon River watershed.

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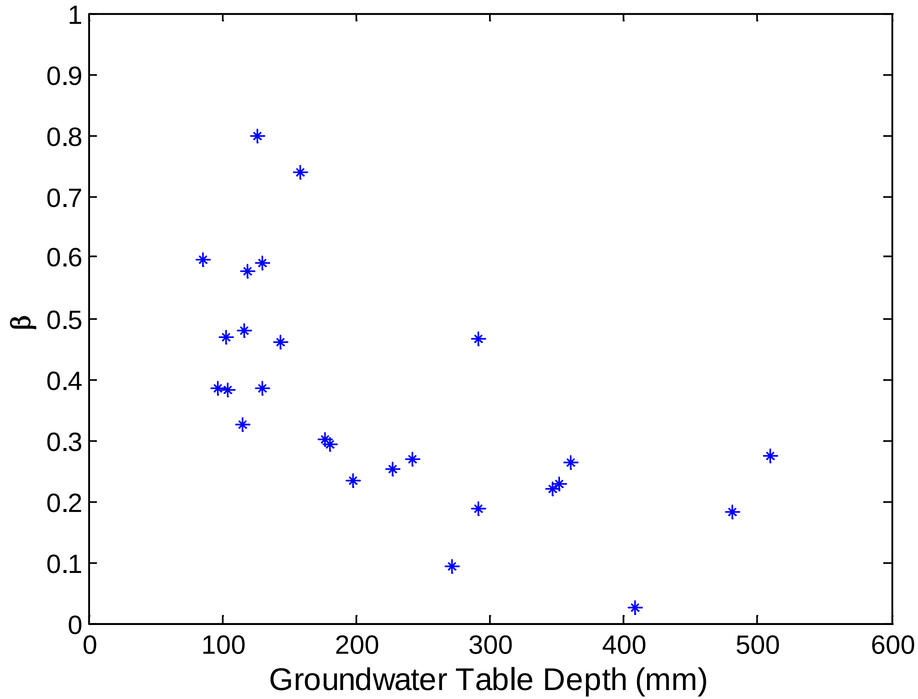

Fig. 8. The relationship between estimated β and observed shallow groundwater table depth at the Spoon River watershed.

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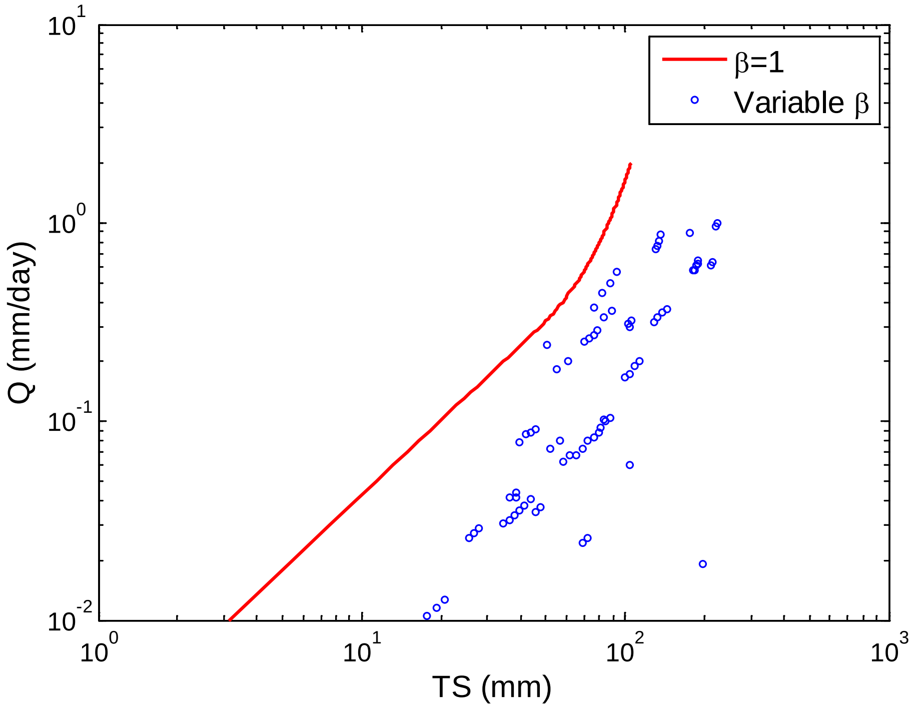

Fig. 9. The impact of variable contributing storage on the total storage–discharge relationship at the Spoon River watershed.

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