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What mainly controls recession flows in river basins?

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ABSTRACT

The ubiquity of the power law relationship between dQ/dt and Q for recession periods ($-dQ/dt = kQ^{\alpha}$, Q being discharge at the basin outlet at time t) clearly hints at the existence of a dominant recession flow process that is common to all real basins. It is commonly assumed that a basin, during recession events, functions as a single phreatic aquifer resting on a impermeable horizontal bed or the Dupuit–Boussinesq (DB) aquifer, and with time different aquifer geometric conditions arise that give different values of α and k. The recently proposed alternative model, geomorphological recession flow model, however, suggests that recession flows are controlled primarily by the dynamics of the active drainage network (ADN). In this study we use data for several basins and compare the above two contrasting recession flow models in order to understand which of the above two factors dominates during recession periods in steep basins. Particularly, we do the comparison by selecting three key recession flow properties: (1) power law exponent α, (2) dynamic dQ/dt–Q relationship (characterized by k) and (3) recession timescale (time period for which a recession event lasts). Our observations suggest that neither drainage from phreatic aquifers nor evapotranspiration significantly controls recession flows. Results show that the value of α and recession timescale are not modeled well by DB aquifer model. However, the above mentioned three recession curve properties can be captured satisfactorily by considering the dynamics of the ADN as described by geomorphological recession flow model, possibly indicating that the ADN represents not just phreatic aquifers but the organization of various sub-surface storage systems within the basin.

1. Introduction

Infinitely heterogeneous earth surface and subsurface give rise to complex hydrological flow pathways that can evolve in both space and time, making it difficult to model flow variables using the known laws on water movement, such as Darcy's law. Thus, many of the flow phenomena in natural basins are not yet fully understood, e.g., the old water paradox (e.g., [31]), the scaling of flood peaks (e.g., [23]) and the time of concentration (e.g., [22]). Nevertheless, process understanding is necessary to model more accurately not only streamflows but also many of the environmental parameters such as solute concentration in river channels (e.g., [1,49,50,59,73,74]). Interestingly, despite their complexity, key features of the response of natural basins can be satisfactorily captured by simple conceptual models [3,56]. The simplicity of some general characters of the hydrological response points to the existence of dominant hydrological processes at the basins scale arising from the integration of micro-scale processes [33,39,55]. So for a proper understanding of the hydrological processes, the signatures contained in the hydrological response at basin scale need to be decoded by using suitable analytical or numerical tools. In this regard, appreciable amount of work has been carried out, particularly with respect to flood response (e.g., [30,47,48,50]). Here we focus on the modeling of recession flow curves, which has got relatively less attention.

Though scientific investigation on recession flows dates back as early as Boussinesq [11], a systematic recession flow analysis, to our knowledge, began with the work by Brutsaert and Nieber [16], who expressed $-dQ/dt$ as a function of Q (discharge observed at the basin outlet at time t):

$$-\frac{dQ}{dt} = f(Q) \tag{1}$$

This method essentially eliminates the need of identifying a reference time for a recession event, thereby setting a novel framework for quantifying recession curve characteristics objectively. Brutsaert and Nieber [16] found that $-dQ/dt$ vs. Q curves of a basin typically follow a power law relationship:

$$-\frac{dQ}{dt} = kQ^{\alpha} \tag{2}$$

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Since then many studies have confirmed the presence of the above power law relationship (Eq. (2)) in basins with different sizes and shapes situated across geographical boundaries and climatic zones [4,10,17,18,25,28,29,32,35–38,40,44,53,61,64,66,65]. The question arises thereupon is what causes the seemingly different natural basins to display the same type of power law relationship (Eq. (2)). Is there a distinct dominating flow process common to real basins that operates during recession periods? Brutsaert and Nieber [16] provided an explanation by studying the outflow from a phreatic (unconfined) aquifer resting on a horizontal impermeable bed, i.e., the Dupuit–Boussinesq (DB) aquifer, under different geometric conditions. Another explanation discussed in this study was given by Biswal and Marani [4], who argued that the temporal evolution of saturated channel network gives rise to the power relationship between $-dQ/dt$ and Q. Both the models can, however, be explained through a general mathematical framework [4].

1.1. A common framework for recession flow curve analysis

Rain water stored in the subsurface zones of a hillslope can adopt many possible flow mechanisms to reach surface water bodies. Broadly, ground water flow systems are classified into three categories: local, intermediate and regional [62]. In local flow system water flows to a nearby stream. In regional flow system water particles follow longer (subsurface) flow paths to reach higher order streams. If ground water flow paths are intercepted by one or more topographic highs or lows, it is called an intermediate flow system. Topography and distribution of hydraulic conductivity will decide which flow system dominates in a basin (e.g., [2,14,59]). Furthermore, streams themselves can play a major role during recession events by storing water in their banks and under their beds and releasing it later due to hydraulic gradient (e.g., [24,34,67,69]). Moreover, to make the analysis even more complex, flow paths may undergo changes in both space and time (e.g., [42,75]).

The complex and dynamic nature of flow processes calls for a meaningful conceptualization based on realistic assumptions. At any point of time t, Q can be expressed as a product of flow generation per unit length ($q(t)$) and total length of the channel network contributing flow ($G(t)$) [4]:

$$Q(t) = q(t) \cdot G(t) \tag{3}$$

Differentiating both sides of Eq. (3) with respect to t one finds:

$$\frac{dQ(t)}{dt} = \frac{dq(t)}{dt} \cdot G(t) + q(t) \cdot \frac{dG(t)}{dt} \tag{4}$$

The term $dq(t)/dt \cdot G(t)$ signifies dQ/dt due to aquifer depletion and $q(t) \cdot dG(t)/dt$ due to gradual shrinking of the part of the stream network that is actively draining water at time t or the active drainage network (ADN). In order to examine the relative contributions of the two factors, one can consider two extreme scenarios: (i) where the aquifer dynamics solely controls recession flow and (ii) where the ADN dynamics solely controls recession flow.

1.1.1. DB aquifer model

This model assumes that rectangular shaped phreatic aquifers only generate streamflow in a basin during recession events. Also, it is assumed that the phreatic aquifers in the basin rest on horizontal impermeable beds and are identical everywhere. The phreatic aquifers drain into their nearby stream channels or they follow local flow system. q in this system will be spatially constant, i.e., the role of ADN dynamics can be neglected or $dG(l)/dt \approx 0$. The expression for $Q(t)$ then becomes

$$Q(t) = q(t) \cdot G_0 \tag{5}$$

where G_0 is the total length of the channel network. In effect, this model treats a basin as a 'single' phreatic aquifer resting on a horizontal impermeable bed (DB aquifer). According to Eq. (4)

$$\frac{dQ(t)}{dt} = \frac{dq(t)}{dt} \cdot G_0 \tag{6}$$

$q(t)$ is then modeled by solving the one dimensional Boussinesq's equation under the fully penetrating stream condition and under the assumption that the rate of aquifer recharge is zero (e.g., [16]), also see Fig. 1):

$$f\frac{\partial h}{\partial t} = \psi \frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \tag{7}$$

where h is the height of water table at distance x and time t, f is the average drainable porosity and ψ is the average saturated hydraulic conductivity of the aquifer. It is assumed that different geometric conditions arise during a recession event, producing $-dQ/dt$ vs. Q curves (Eq. (2)) with different values of α [16,17,38,40,44,68]. Generally three types of geometric conditions are adopted, which have been summarized by Brutsaert and Nieber [16], who also calculated the values of α and k for all the three cases.

The first type of geometric condition applies when the width of the phreatic aquifer (X) is infinite. This condition is assumed to arise in the beginning of a recession event and it lasts for a relatively short period of time. Polubarinova–Kochina [45] found the value of α for this phase to be 3 and

$$k = 1.1334\frac{1}{\psi f H_0^3 G_0^2} \tag{8}$$

where H_0 is H (water table height at $x = X$, see Fig. 1) at $t = 0$. The second type of geometric condition appears when the water table profile can be assumed to be an inverse incomplete beta function. Boussinesq [13] found the value of α for this recession phase to be 1.5 and

$$k = 4.8038\frac{\psi^{0.5} G_0}{f A^{1.5}} \tag{9}$$

where A is area of the basin. This solution is applicable for late recession periods. The third type of geometric condition is characterized by relatively little change in the height of water table ($h(x,t)$, see Fig. 1) in the direction of flow, in which case the Boussinesq's equation (Eq. (7)) can be linearlized [15]. The solution for the linearized Boussinesq's equation was first provided by Boussinesq [12]: $\alpha = 1$ and

$$k = \pi^2 \frac{\psi p H_0 G_0^2}{f A^2} \tag{10}$$

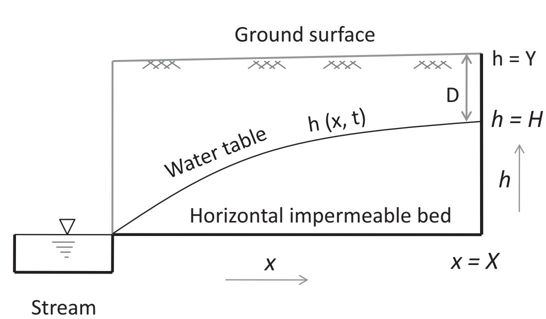

Fig. 1. A graphical illustration of Dupuit–Boussinesq (DB) aquifer (a rectangular unconfined aquifer resting on a horizontal impermeable bed) draining into a fully penetrating stream. There is no recharge into the aquifer, and drainage from the aquifer is expected to reflect recession flows in natural basins.

This condition appears when discharge is further reduced so that flow from other storage spaces (e.g., local ponds) dominates [44]. Thus the third recession phase can be considered to appear after the second recession phase though there is no such clear guideline given by any study; i.e., either $\alpha = 1.5$ or $\alpha = 1$ can be adopted for late recession periods (e.g., [40]). Note that the power law coefficient k characterizes the time varying relationship between $-dQ/dt$ and Q. Most of the past studies intended to obtain a single k value for a basin (e.g., [16,17,31,40,58,61,64,68]), even though DB aquifer model suggests that k varies across recession events (see the dependency of k on H_0 in Eqs. (8) and (10); also see, for e.g., [60]). The assumption of the existence of a single valued k for a basin essentially implies a unique relationship between discharge and water stored within the basin.

1.1.2. Geomorphological recession flow model

During a recession period a stream channel will drain water from the aquifers within its adjoining hillslopes as well as from the aquifers within its bank and under its bed. As the stream channel will receive flow from its upstream stream channel, it will not dry as long as its immediate upstream stream channel is draining water into it. This implies that a stream network during recession events will desaturate progressively in the downstream direction. Biswal and Marani [4] exploited this property of progressive desaturation of the ADN to model recession flows at the basin outlet by assuming that $dq(t)/dt \approx 0$ (also see Fig. 2a), i.e., they considered only the effect of ADN dynamics in recession analysis. Eq. (4) therefore turns into

$$\frac{dQ(t)}{dt} = q \cdot \frac{dG(t)}{dt} \tag{11}$$

They also assumed that the speed at which sources of the ADN configuration move downstream, c ($= dl/dt$, where l is the distance of a source in the ADN configuration at time t from its farthest channel head in the channel network), is constant both spatially and temporally (see Fig. 2a). This assumption of constant c allows us to interchange t and l whenever necessary. Therefore, Eq. (11) can be transformed into

$$\frac{dQ(t)}{dt} = q\frac{dl}{dt} \cdot \frac{dG(l)}{dl} = q \cdot c \cdot -N(l) \tag{12}$$

where $N(l)$ is the number of channel links at a distance l in the channel network or the number of sources in the ADN configuration at time t.

By using the expressions for Q (Eq. (3)) and dQ/dt (Eq. (12)) in Eq. (2) we get the expression for recession curve in terms of geomorphological parameters:

$$N(l) = \frac{kq^{\alpha-1}}{c} G(l)^{\alpha} \tag{13}$$

or

$$N(l) = \rho G(l)^{\alpha} \tag{14}$$

where

$$k = \rho c q^{1-\alpha} \tag{15}$$

Eq. (13) relates the morphological properties of a basin with its recession flow curve characteristics. The major difference between DB aquifer model and geomorphological recession flow model is that while the former takes only storage in the phreatic aquifers into account the latter considers storage in all forms that govern ADN dynamics. In this study we use data of daily average streamflow, water table depth and potential transpiration and compare results obtained from the above two recession flow models to find out whether ADN dynamics is more important or drainage from phreatic aquifers is more important during recession flow events in steep basins. Particularly, we select three key recession flow characteristics: (i) value of α, (ii) event dependent relationship between $-dQ/dt$ and Q and (iii) recession timescale.

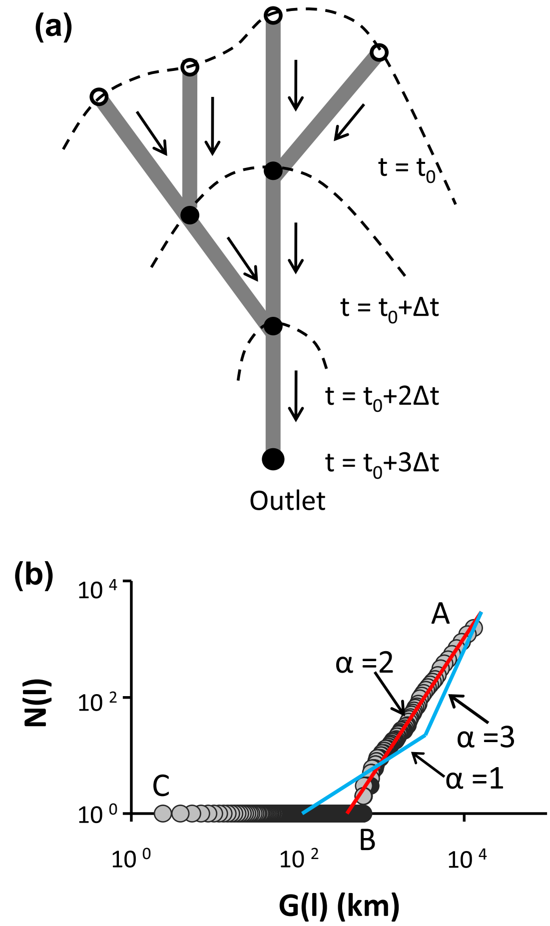

Fig. 2. (a) A hypothetical channel network undergoing desaturation during a recession event. The network is completely saturated in the beginning and with time it desaturates following the constant q and constant c assumption. The arrow marks indicate the direction of channel desaturation, and the dotted lines are the desaturation contours at different times. (b) The $N(l)$ vs. $G(l)$ (modeled) curve for Indian basin. The drainage network for the basin was obtained by imposing a flow accumulation threshold of 100 pixels. The $N(l)$ vs. $G(l)$ curve exhibits two scaling regimes (AB and BC). The regime AB has slope (α) nearly equal to 2 (red line). For comparison, the blue lines represents slopes predicted by DB aquifer model. The upper blue line has slope equal to 3 and the lower has 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Observed recession curves: how well the models predict?

We used available daily average discharge data for 34 USGS basins (see Fig. 3) for the analysis here (data available at: http://waterwatch.usgs.gov/). Daily average ground water table data for 9 of the basins (see Table 1) were used (each basin has one well) to investigate storage-discharge relationships. For 22 of the basins we used potential evapotranspiration data from MOPEX dataset (available at: http://www.nws.noaa.gov/oh/mopex/mo_datasets.htm) to analyze the effect of evapotranspiration on recession flow curve characteristics. We also used 10 min average discharge data for Shale Hills experimental watershed and 10 min average water table data for 3 wells situated within the watershed (data obtained from: http://www.czo.psu.edu/) (see Fig. 3). All the selected basins are situated in moderately steep to steep regions and free from significant human interventions. To extract geomorphic parameters

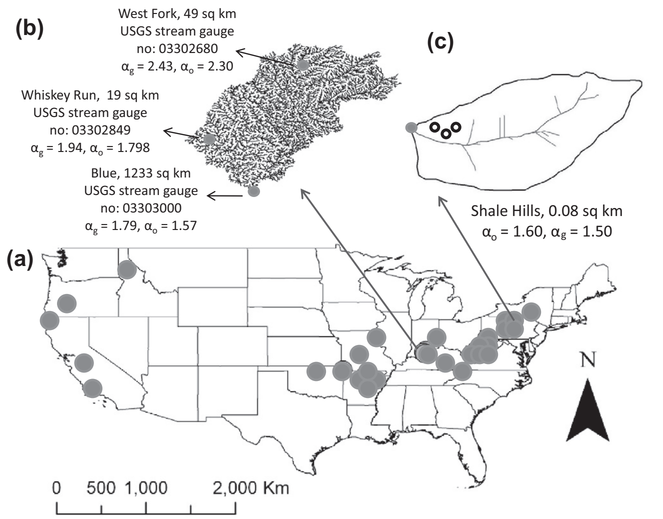

Fig. 3. Locations of the 35 study basins (closed circles) within a map of the US (a). Three of the basins are nested (blue is the basin and Whiskey Run and West Fork are its sub-basins) and situated in Illinois (b). Shale Hills watershed has three water table monitoring wells (open circle) within its boundary (c). Note that the drainage networks shown in (b) and (c) are not up to the scale. Other information about the watershed studied are given in Tables 1 and 2.

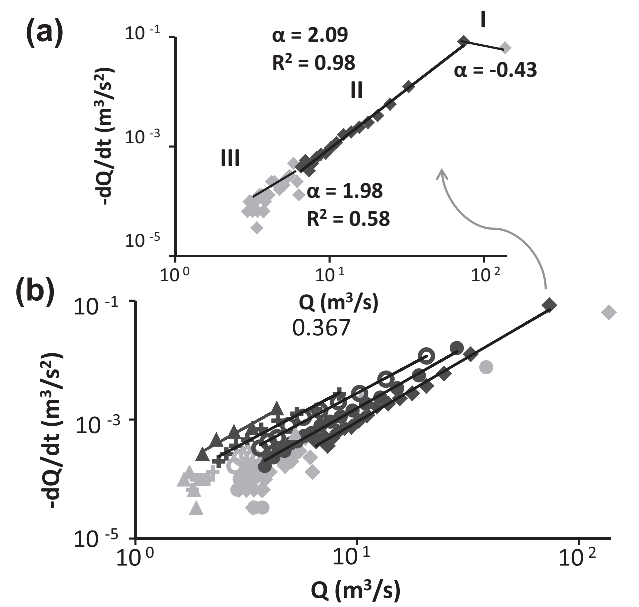

Fig. 4. (a) Five $-dQ/dt$ vs. Q curves selected from Blue basin displaying shifts from one another, indicating that $-dQ/dt$–Q relationship for a basin is not unique. (b) The inset shows an individual recession curve exhibiting three distinct scaling phases: phase I accounts for high flows; phase II, which lasts for an appreciable amount of time, exhibits a distinct power law scaling feature (R^2 is 0.98); phase III, which account for very low flow values, is dominated by observational errors (R^2 for phase III is 0.58, less than that of phase II).

for the study basins we used 30 m USGS digital elevation model (DEM) data for the USGS basins and 3 m USGS DEM data for Shale Hills watershed (obtained from: http://nationalmap.gov/viewer.html). We imposed suitable flow accumulation thresholds to extract drainage networks of the basins and computed their α_g (or geomorphic α, see Eq. (13)) values [43]. (Note that as the value of α_g is not very sensitive to the chosen flow accumulation threshold [4], the flow accumulation thresholds for the basins were arbitrarily chosen.) We define a recession curve as a continuously decreasing streamflow time series lasting at least five days and whose peak is greater than the average flow at the basin outlet. Following Brutsaert and Nieber [16] we computed $-dQ/dt$ and Q as: $-dQ/dt(t+\Delta t/2) = (Q(t) - Q(t+\Delta t))/\Delta t$ and $Q(t+\Delta t/2) = (Q(t) + Q(t+\Delta t))/2$, where $\Delta t = 1$ day (for Shale Hills watershed the data was averaged to daily time step before computing $-dQ/dt$ and Q). In this section we discuss three major recession curve characteristics and how the two models capture them.

2.1. The value of α

The observations by Biswal and Marani [4] show that a recession curve typically exhibits three distinct phases, which can be distinguished from one another based on its $-dQ/dt$ vs. Q profile (see also the inset Fig. 4a). Typically, α after the peak of a recession event increases with time for a short time interval (phase I), and this phase is likely to be significantly influenced by surface flows. Then in the second phase (phase II), which lasts for a appreciably long period of time, α remains fairly constant. The next phase (phase III) accounts for very low flows that are typically dominated by observational errors (see, for e.g., the marked decrease in correlation (R^2) from phase II (0.98) to phase III (0.58) in Fig. 4a) or which cannot be observed due to short time intervals between consecutive storms. In our observation, α in phase I is almost always less than that of phase II (sometimes even negative, see the inset of Fig. 4a, where phase I gives $\alpha = -0.43$), and α in phase III can either be more or less than that in phase II. Ideally, one should consider phase II only in an analysis, as α in this phase best represents recession flows in a basin. Biswal and Marani [4] found that while α remains fairly constant for a basin, k varies greatly across recession events, which implies that $-dQ/dt$ and Q relationship is dynamic or it changes across events (see Fig. 4b). Therefore, they computed α for phase II of recession curves individually for a basin

Table 1
Key geomorphological and observational recession flow parameters and the relationship between k and water table.
*** corresponds to Shale Hills watershed which does not belong to USGS database. 1–3 are three wells within the Shale Hills watershed.

Name of the basin	USGS id	Area (sq km)	α_g	No. of recession events	α_o	δ_{p8}	R^2_{p8}	γ_5	R^2_5	Well no.	θ_{wt}	R^2_{wt}
										1	0.64	0.12
Shale Hill	***	0.08	1.5	28	1.6	0.04	0.03	0.39	0.19	2	0.98	0.13
										3	0.82	0.09
North Sylamore	07060710	150.43	2.06	37	1.93	0.13	0.18	0.98	0.76	355927092122401	9.20	0.15
Cranberry	03187500	217.56	1.97	412	1.85	0.27	0.19	0.97	0.66	382008080292801	4.81	0.24
Little	03497300	276.54	2.11	406	2.29	0.53	0.45	1.11	0.62	353922083345600	1.19	0.03
Towanda	01532000	556.85	2.18	233	1.96	0.19	0.11	0.43	0.18	414330076280501	0.60	0.21
Dunkard	03072000	593.34	2.15	220	1.94	0.32	0.24	1.02	0.78	394655080014301	1.44	0.11
Indian	07188885	619.67	2.05	58	2.31	0.52	0.55	1.01	0.70	364313094121101	1.46	0.01
Pomme de Terre	06921070	714.13	1.95	268	2.08	0.41	0.40	1.15	0.85	373701093151601	3.78	0.21
Wheeling	03112000	727.79	2.07	311	1.98	0.50	0.43	1.06	0.81	400233080261301	15.31	0.15
Muscatatuck	03366500	758.87	2.05	321	2.06	0.38	0.38	1.20	0.89	384949085251901	2.52	0.42

and considered the median of the distribution as its representative α (α_o). Biswal [5], however, found that almost the same α_o is obtained by discarding only the peaks of the recession curves (supposed to eliminate phase I of the recession curves). We followed this scheme to compute α_o in this study.

Biswal and Marani [4] computed α_o for a large number of natural basins and found that the median of the distribution to be close to 2 (with a standard deviation of 0.18). The median of α_o values obtained for the 35 basins here is 1.95 (with a standard deviation of 0.21). α_o being close to 2 was also observed by Shaw and Riha [54]. These observations suggests that the generally accepted value of α by DB aquifer model based studies (1.5) is quite different from 2, the value obtained from real observations. Again, the temporal α profile as produced by DB aquifer model under different geometric conditions arising during different phases of a recession event (α being 3, 1.5 and 1 in phase I, phase II and phase III, respectively) does not reflect the real recession curve behavior. Technically, DB aquifer based studies do not provide an objective method to identify how and when different geometric conditions arise. Recession characteristics are generally obtained by fitting power law curves with different α values onto $(-dQ/dt, Q)$ data clouds (e.g., [16,17,40,44,68]). Furthermore, the geometric conditions assumed by DB aquifer model so far, to our knowledge, have no experimental basis.

We did not find any appreciable correlation between α and either potential evapotranspiration (P_{et}) or water table depth (D, see Fig. 1) for any of the basins considered in this study (linear correlation in the all cases is less than 0.1). Furthermore, Biswal [5] found that the value of α_o is independent of basin size and average streamflow (an indicator of climatic conditions). These observations indicate that α is only a shape parameter chiefly dependent on the structural properties of the basin. Geomorphological recession flow model gives the value of α for a basin that is entirely dependent on its channel network structure - an observable entity. Due to this reason, a direct comparison can be performed between α_g (modeled α, see Eq. (13)) and α_o (observed α). Two distinct scaling regimes can be identified in the $N(l)$ vs. $G(l)$ curve of a basin: AB representing early recession flows and BC representing late recession flows ([4], also see Fig. 2b). As late recession flows are generally not observed, only regime AB can be considered for an evaluation. Like Biswal and Marani [4], we found that α_g (of AB regime) is nearly equal to α_o of the basin in most cases. The median of α_g of the 35 study basins is 2.08, quite close to the median of the α_o values, 1.98 (with a standard deviation of error equal to 0.22). In the following sections we carry out further analysis by considering that $\alpha_g = \alpha_o = \alpha$.

2.2. Dynamic properties of recession curves

DB aquifer model based studies consider a basin to behave as a single phreatic aquifer as they assume flow generation to be spatially constant. It suggests that for $\alpha = 3$ and $1, k$ is free to vary across events, but its value is constant for $\alpha = 1.5$. However, it is observed that, for $\alpha > 1$ and large n, k is a function of the characteristic discharge Q_n (average discharge at the basin outlet in the nth day after the peak), denoted by a power law:

$$k(Q_n) \propto Q_n^{-\lambda_n} \tag{16}$$

and $\lambda_n = \alpha - 1$ [8]. Note that k for a recession event is computed by fixing α at α_o of the basin. The above power law relationship (Eq. (16)) is robust for all the study basins here (see the values of λ_n and R_n^2 for $n = 5$ for the basins here in Tables 1 and 2) and it implies that k becomes independent of Q_n (a parameter that is dependent on dynamic factors like rainfall and evapo-transpiration) i.e., k becomes constant for a basin when α is nearly equal to 1, not when $\alpha = 1.5$. Eq. (16) suggests that $k(Q_n) \propto Q_n^{-0.5}$ and $k(Q_n) \propto Q_n^{-2}$, respectively for $\alpha = 1.5$ and $\alpha = 3$. This demonstrates the limitation of DB aquifer model in capturing the dynamic $-dQ/dt$–Q relationship of a basin. Geomorphological recession flow model needs both the parameters to remain constant throughout a particular recession event but they are free to vary across recession events, thus allowing the dQ/dt–Q relationship to change from one recession event to another. Eq. (15) implies that k is a function of both q and c. Though we are not aware of any experimental study on how c varies across events, it is quite intuitive that flow generation (represented by q) will increase with subsurface storage. Thus if we assume c to be constant across recession events, Eq. (15) gives $k \propto q^{-(\alpha-1)}$, a relationship analogous to Eq. (16). The argument that k mainly depends on subsurface storage is also supported by other studies (e.g., [6,8,35]).

Using observed discharge data and water table data Rupp et al. [52] showed that Q vs. D curves for different time periods with minimal rainfall display significant shifts from one another. We

Table 2
Key geomorphological and observational recession flow parameters and the relationship between k and potential evapotranspiration.

Name of the basin	USGS id	Area (sq km)	α_g	No. of recession events	α_o	δ_{P8}	R^2_{P8}	λ_5	R^2_5	γ_{ET}	R^2_{ET}
Council	07163000	80.29	2.03	258	1.82	0.39	0.26	1.11	0.95	0.193	0.02
Haldey	05502040	188.29	2.04	391	1.99	0.35	0.33	1.02	0.87	0.029	0.00
North Branch Potamac	01595000	189.07	2.07	606	2.23	0.42	0.26	1.13	0.63	0.63	0.19
Las Gatos	11224500	248.12	1.94	324	1.65	0.82	0.65	0.70	0.81	0.27	0.03
Williams	03186500	331.52	2.08	1005	1.85	0.29	0.24	0.90	0.62	0.38	0.19
Cadron	07261000	437.71	2.04	363	1.91	0.32	0.29	0.77	0.59	0.39	0.20
Dunning	01560000	445.48	2.35	720	1.86	0.25	0.25	0.66	0.46	0.41	0.12
Owego	01514000	479.15	2.17	528	2.31	0.75	0.64	1.03	0.88	0.22	0.08
Little Coal	03199000	696.71	1.95	575	1.98	0.47	0.38	1.05	0.70	0.27	0.07
Sisquoc	11138500	727.79	2.16	403	1.91	0.81	0.79	0.97	0.87	0.15	0.01
Dry Fork	03065000	903.91	2.13	1094	1.95	0.66	0.60	0.86	0.85	0.39	0.17
South Umpqua	14308000	1162.91	2.13	747	2.22	0.52	0.33	0.96	0.56	0.23	0.07
Cowpasture	02016000	1193.99	2.14	1109	2.57	0.38	0.35	0.44	0.42	0.39	0.08
Strawberry	07074000	1225.07	2.46	617	2.55	0.53	0.42	1.25	0.83	0.60	0.13
Tug Fork	03213000	1300.18	2.18	705	2.61	1.17	0.76	1.41	0.9	0.12	0.01
Pine	01548500	1564.36	1.97	1117	1.99	0.70	0.65	0.79	0.82	0.24	0.07
Smith	11532500	1590.26	2.26	564	2.43	0.42	0.39	0.72	0.46	0.58	0.13
Sinnemahoning	01543500	1774.15	2.15	1199	1.97	0.78	0.69	0.86	0.86	0.33	0.12
South Fork Kentucky	03281500	1869.98	2.05	1135	1.92	0.67	0.62	0.86	0.87	0.35	0.14
Buffalo	07056000	2147.11	2.45	1046	2.07	0.58	0.63	0.73	0.78	0.11	0.05
Coeur	12413000	2318.05	2.09	1028	2.81	0.57	0.61	0.60	0.62	0.01	0.00
North Bosque	08095000	2507.12	2.11	832	2.09	0.77	0.6	1.02	0.85	0.55	0.03

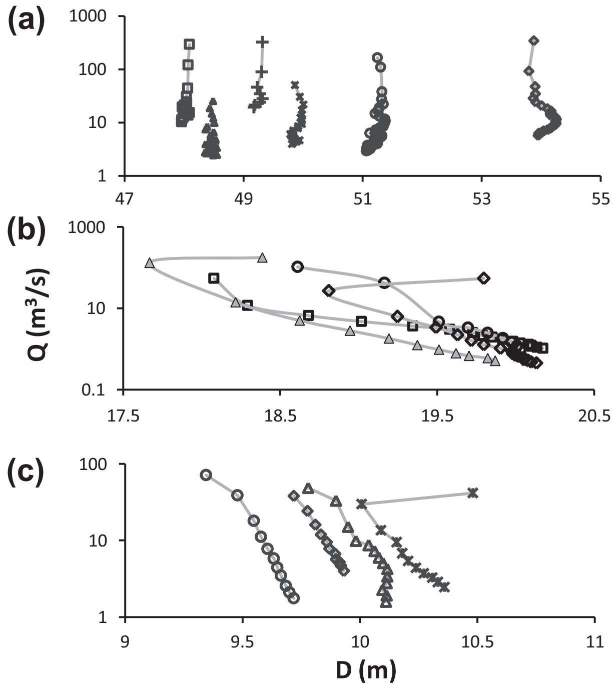

Fig. 5. Selected discharge (Q) vs. water table depth (D) curves for: (a) Indian, (b) North Sylamore and (c) Dunkard. Though Q is observed to be decreasing with increasing D for individual recession events (the relationship is evident particularly after the peak), Q vs. D curves across recession events display significant shifts from one another, implying that storage discharge relationship is not unique for a basin.

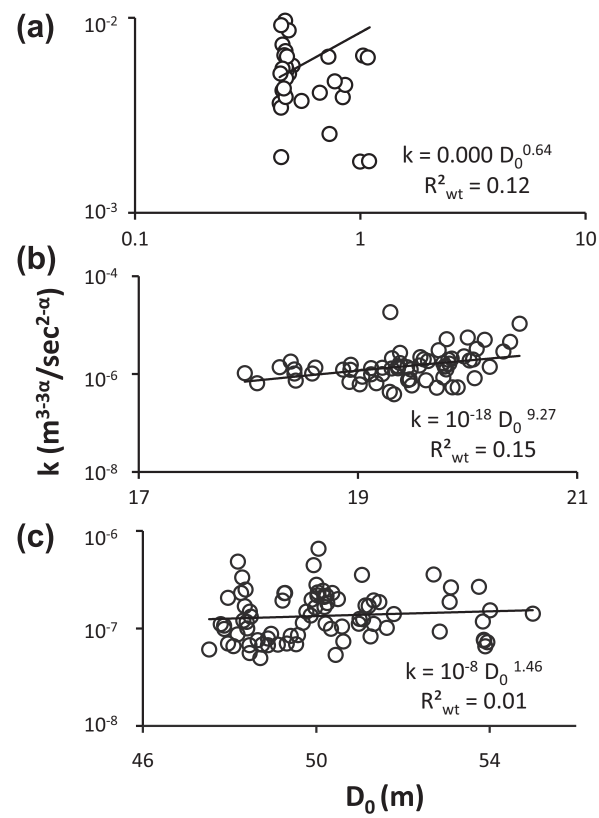

Fig. 6. k vs. D_0 curves for: (a) Shale Hills ($\alpha_o = 1.60$) (for well 1), (b) North Sylamore ($\alpha_o = 1.93$) and (c) Indian ($\alpha_o = 1.94$). k for a basin was computed by fixing α for each recession curve at its representative α (α_o). The weak R^2_{wt} values indicate that phreatic aquifers have insignificant control over recession flows.

observed similar behavior while plotting Q vs. D curves for individual recession events and found that Q decreases as D increases, often when observations after 1 day of the peak are considered (Fig. 5). We used water table data to investigate the role of phreatic aquifers during recession periods using DB aquifer model. We assume that the observed depth of water table measured at a well in a basin is $Y - H$ (which is equal to D, where Y is the maximum height of the aquifer), and it represents the subsurface storage within the phreatic aquifers of the basin. To investigate whether Eqs. (8) and (10) reflect the dynamic dQ/dt–Q relationship for a basin, we analyzed the relationship between k (obtained from the observed $-dQ/dt$ vs. Q curve of the basin by fixing α at α_o, see the previous subsection) and D_0 ($Y - H_0$, i.e., initial water table depth for the event at $x = X$). We then fitted (k, D_0) data points from a basin onto a power law equation ($k \propto D_0^{\theta_{wt}}$, see Fig. 6) using the linear regression method as suggested by DB aquifer model. Interestingly, we observed that θ_{wt} is positive for all the basins considered, which implies that discharge at any given time increases with initial water table height, H_0 (as discharge increases with decrease in k, see Eq. (16)). However, we observed the power law correlation (R^2_{wt}) between k and D_0 (an indicator of H_0) to be weak (see Table 1), which further strengthens the argument that phreatic aquifers may not have significant control over recession flow curves.

Another factor influencing k is evapotranspiration (e.g., [16,19,54]). Weiseman [72] computed k by fitting discharge values of a recession event onto $Q = Q_0 e^{-kt}$ curve and found that k is dependent on P_{et}. However, he did not quantify the relationship between k and P_{et}. Similarly, Shaw and Riha [54] noted that k exhibits seasonal variation, though he did not give a quantitative picture of it. In this study, we tried to quantify the effect of P_{et} on k by fitting (P_{et}, k) data points from a basin onto the power law equation: $k \propto P_{et}^{\gamma_{et}}$ (see Fig. 7). We found the power law exponent γ_{et} to be positive in all cases, implying that Q decreases as P_{ET} increases. But the correlation (R^2_{et}) was found to be weak (less than 0.2 in all cases, see Table 2), which indicates that evapotranspiration does not affect recession flow characteristics significantly. It should be noted here that DB aquifer model does not take the effect of evapotranspiration into account as it considers flow from phreatic aquifers only. On the other hand, geomorphological recession flow model takes the effect of evapotranspiration into account as the parameter q actually represents the net flow generation per unit length, i.e., the flow generation per unit length by ground water storage units minus the loss of flow per unit length due to evapotranspiration.

The results here indicate that neither phreatic aquifer nor evapotranspiration has significant control over k. According to geomorphological recession flow model the system of connected subsurface storage elements within a basin is represented by its ADN. The strong correlation between k and Q_n (16) suggests that k is dependent on q, controlled by various subsurface storage systems (not by phreatic aquifers only). This hypothesis is further supported by the observational evidence that a fairly good power law relationship exits between k and the past average discharge (a proxy for past storage) from 10 to 2 days before the recession peak (Q_{p8}): $k \propto Q_{p8}^{-\delta_{p8}}$ ([6], see also Tables 1 and 2). The positive value of δ_{p8} in all cases implies that Q increases with (past) subsurface storage in various subsurface storage systems. In fact, it is already acknowledged that recession flow is a result of interaction between both saturated and unsaturated subsurface storage elements (e.g., [26,41,53,63]) that undergo spatial and temporal evolution [1,27,57]. Now coming back to the observation by Shaw and Riha [54], it is very likely that the seasonal variation of k is actually caused by the seasonal variation of storage. k can also be sensitive to many other factors like temporal rainfall variation [10], spatial rainfall variation [6] human interventions [4,70,71], and observational and numerical errors [35,66].

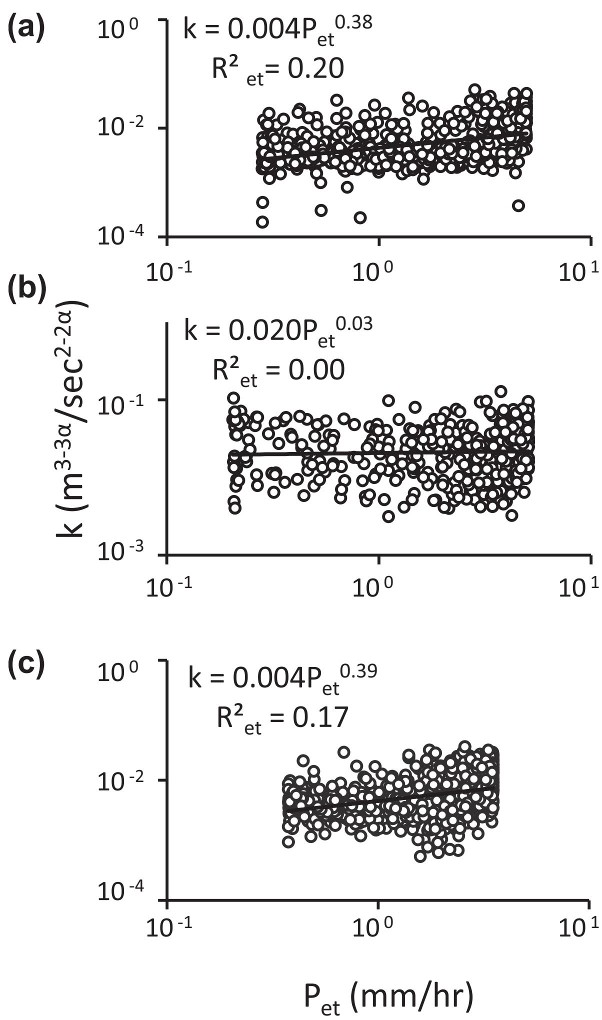

Fig. 7. k vs. P_{et} curves for three selected basins: Cardon ($\alpha_o = 1.91$), Haldey ($\alpha_o = 1.99$) and Dry Fork ($\alpha_o = 1.95$). k was computed for a basin by fixing α at its α_o. The weak value of R^2_{et} suggest that evapotranspiration may not be significantly affecting recession curve characteristics.

2.3. Recession timescale

Another key property of a recession flow curve is timescale, the period of time the recession event lasts. DB aquifer generates recession flow profiles with timescales independent of basin size. However, it is well known that in real basins lower order streams dry before higher order streams, i.e., ADNs during recession periods contract in downstream direction (e.g., [9,20,21]). Recession flow in a basin will last as long as its longest stream or main stream does not dry completely. Geomorphological recession flow model assumes a constant speed of stream desaturation. Thus, recession flow in a basin will last for a time period, T_R, equal to L/c, where L is the length of the main stream. According to Hack's law L is related to basin area as $L \propto A^h$, where h is Hack's exponent. The recession timescale T_R, if c remains constant, is then related to basin area as

$$T_R \propto A^h \tag{17}$$

It is not possible for us to check if natural basins are strictly following Eq. (17) due to lack of data in hand. Typically recession events do not last longer than characteristic recession timescales. However, our analysis on the three nested basins (one main basin and other two are its sub-basins) situated in Illinois (see Fig. 3; streamflow observation considered from the year 1986) gives some interesting results. Particularly, we investigated how the size of a basin affects the number of dry or no-flow days it witnesses, which indicates how quickly the basin dries. It is remarkable that while Blue basin does not have a single no-flow day, its sub-basins West Fork and Whiskey Run have 175 and 438 number of no-flow days, respectively. This implies that bigger basins are likely to sustain flow for longer time periods, and vice versa, although whether real basins follow Eq. (17) or not needs to be investigated.

3. Concluding remarks

Natural basins are highly heterogeneous and structurally complex. As a result, it is very challenging to apply traditional flow equations for the prediction of basin-scale responses. An alternative avenue is thus to identify the signatures contained in a recession curve and find its links with the catchment scale physical properties. Brutsaert and Nieber [16] provided a robust analytical framework to study recession flow curve properties by expressing negative time derivative of Q ($-dQ/dt$) as a function of Q itself, which presently serves as the foundation for recession flow analysis. $-dQ/dt$ vs. Q curves, across recession events and across basins, generally follow a power law equation of the following type: $-dQ/dt = kQ^{\alpha}$. The physical origin of the power law relationship can be explained by using two existing recession flow models: (1) DB aquifer model that considers drainage from phreatic aquifers only and (2) geomorphological recession flow model that considers dynamics of ADN only. It should be noted that there are other modeling frameworks mentioned in the hydrologic literature that deal with recession flows. However, the main motivation behind the selection of the above mentioned two models was to understand the relative importance of aquifer depletion and ADN dynamics.

Our observations do not support the hypothesis by DB aquifer model that α takes different values (3, 1.5 and 1) during a recession event. For most of the basins considered in this study the value of α is nearly equal to 2, which is captured well by geomorphological recession flow model. We found the correlation between water table depth and k to be weak in all the cases, which strongly indicates that phreatic aquifers in a basin do not significantly control its recession flow characteristics as suggested by DB aquifer model. Again we found that evapotranspiration does not significantly control the value of k, though DB aquifer model does not take this factor into account. Geomorphological recession flow model seems to incorporate the dynamic behavior of k correctly by linking it with q and c. DB aquifer model generates recession curves with timescales independent of basin size. In reality, recession events in a bigger basin are expected to last for longer time-spans. This is supported by the indirect observation here that smaller basins witness more no-flow days.

Results here suggest that DB aquifer model does not capture well the recession flow characteristics of the study basins. However, they should be interpreted in a proper context. The selected basins are steep/mountainous, which may only be suggesting that DB aquifer model is not suitable for such heterogeneous regions where homogeneous phreatic aquifers cannot be expected to exist. That means, DB aquifer model may be relevant for homogeneous regions where its assumptions are valid. May be non-phreatic storage elements, such as hyporheic zones (e.g., [24]) and unsaturated zones [26], play an important role during recession events in steep and heterogeneous regions. Thus DB aquifer model, which considers a basin as a monolithic phreatic aquifer that follows only local flow system, may not be suitable to model recession flows resulting from interaction between various subsurface storage elements connected to one another through different flow systems. The observations here suggest that recession flow composed of drainage from various subsurface storage systems is linked to active drainage network dynamics. Further investigation along this line (e.g., [7,46]) may help in modeling recession flows more reliably.

Finally, we draw a parallel between geomorphological recession flow model and geomorphological instantaneous unit hydrograph model [50], in the sense that both of them exploit properties of channel network to predict hydrological response directly at basin scale. The purpose is to support the notion that channel networks best represent natural basins, in the way they organize themselves as well as in the way they respond to rainfall inputs [51].

Acknowledgments

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