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Simulation of baseflow accounting for the effect of bank storage and its implication in baseflow separation

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Summary Most baseflow separation methods for measured streamflow discharge series are based on linear and non-linear solutions of the Dupuit–Boussinesq stream–aquifer model and do not take diverse geological, hydrological, and morphological factors into account. Therefore, a key issue in baseflow separation and drought flow estimation is to reveal baseflow variations related to these factors. This study analyzed the baseflow generated from the return of bank storage to the stream using a numerical groundwater model. Under different stream–aquifer hydrologic conditions in terms of river flood-wave shapes, hydraulic conductivities, stream–aquifer interconnection, recharge and evapotranspiration, and regional hydraulic gradients, baseflow was simulated in order to investigate the non-linearity in the baseflow recession process and to evaluate the baseflow separation methods for drought flow analysis. A comparison between flood recession derived from the Boussinesq equation and that from numerical models indicated that a linear aquifer system does not hold for bank storage effects. Analyses of numerically simulated baseflow discharge also demonstrate that values of power indices of the widely used storage–discharge functions which are derived from the single-valued power law are not constant but depend on hydraulic conductivities, stream–aquifer interconnection, and other surface hydrologic conditions. Bank storage due to the stream flood-stage fluctuation reduces groundwater discharge into the channel considerably in the flood stage rising period. Thus, neglecting the influence of bank storage on baseflow would result in a large error in baseflow separation for non-ideal stream–aquifer systems.

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Introduction

For rivers in some areas of plains, flood events through rivers and diffuse recharges into riparian aquifers are among the major causes of baseflow variations. Brater (1940) found that a quick stream rise could cause water to flow back into the aquifer because the stream rise can temporarily reverse the normal groundwater hydraulic gradient. Studies of Todd (1954, 1955), Rorabaugh (1963), and Cooper and Rorabaugh (1963) not only confirmed Brater's concept but also showed that considerable time may be required for the resulting bank storage to drain. In fact, a large part of baseflow may be supplied by bank storage (Kunkle, 1965, 1968; Meyboom, 1961). Simulated results reported in Chen and Chen (2003) and Squillace (1996) demonstrate that the bank-storage zone includes the volume beneath the streambed in addition to the area on both sides of the channel (Fig. 1).

The movement of bank storage water between surface water and groundwater can be described analytically or using numerical flow models. Analytical solutions that describe and quantify the movement of bank storage water between surface water and groundwater have been presented by many researchers (e.g., Cooper and Rorabaugh, 1963; Rorabaugh, 1963; Moench et al., 1974; Morel-Seytoux, 1975; Dever and Cleary, 1979; Gill, 1985; Newsom and Wilson, 1988; Hunt, 1990). However, it should be noted that their assumptions including Dupuit–Forcheimer conditions, homogeneity, and full penetration of streams may yield erroneous results (Sharp, 1977). On the other hand, numerical flow models can also simulate the highly complex movement of bank storage water in the alluvial aquifer. Pinder and Sauer (1971) simulated how bank storage modifies flood wave by using a numerical model for simulating coupled processes of two-dimensional transient groundwater flow and one-dimensional open channel flow. Squillace (1996) constructed a two-dimensional vertical section of groundwater flow model to quantify the movement of the bank storage water at the Palisades adjacent to the Cedar River, Iowa. Chen and Chen (2003) constructed a three-dimensional groundwater flow model to discuss the results of the water exchange rate between a stream and aquifer, the storage volume of the infiltrated stream water in the surrounding aquifer (bank storage), and the storage zone. Their investigation reveals the effects of stream-stage fluctuation, aquifer properties, hydraulic conductivity of streambed sediments, regional hydraulic gradients, and recharge and ET rates on the zone of bank storage.

Bank storage may considerably attenuate the flood wave, decrease the peak discharge, and extend the base time of hydrograph. Therefore, bank-storage effects can cause interpretive difficulties in connection with hydrograph separation. Singh (1968) pointed out that the existence of a very pervious and extensive flood plain along the stream, or controlled flow causing high stages to be maintained for a considerable time, will have to be dealt with individually in baseflow separations. In this study, qualitative analysis of how bank storage affects baseflow led to a conclusion that if the time to the peak of the total hydrograph at the basin outlet is labeled t_c, a major portion of bank outflow and ET loss would occur within 1.0–1.5 times t_c after the time to the peak. The distortion of the baseflow curve can be expected to be limited to about two to three times t_c from the beginning of the hydrograph rise. The numerical modeling results of Squillace (1996) showed that bank storage caused the groundwater flux to the river to increase by a factor of five during the first three weeks of baseflow after runoff and that it required about five weeks of baseflow for bank storage water to discharge from the alluvial aquifer after the peak river stage.

The purpose of this study was to evaluate the effects of various stream–aquifer hydrologic conditions on the baseflow process and its variations. The rate of baseflow recession is plotted as $\log(Q)$ versus t and $\log(-dQ/dt)$ versus $\log(Q)$ to examine the characteristics of baseflow recession and to calculate the values of a and b in the recession equation $\frac{dQ}{dt} = -aQ^b$ for non-ideal stream–aquifer conditions. Our analyses were based on numerical simulations that account for three-dimensional stream–aquifer conditions. Whereas our previous work concentrated on the analysis of characteristics of stream water infiltration, bank storage and storage zone (Chen and Chen, 2003), this study focuses on the analysis of characteristics of baseflow and baseflow separation due to flooding fluctuation.

Baseflow separation techniques

Separation of hydrograph components has been of great interest for more than 100 years and is still one of the most common techniques in use in hydrology (Hewlett and Hibbert, 1967; Nathan and McMahon, 1990). Many techniques

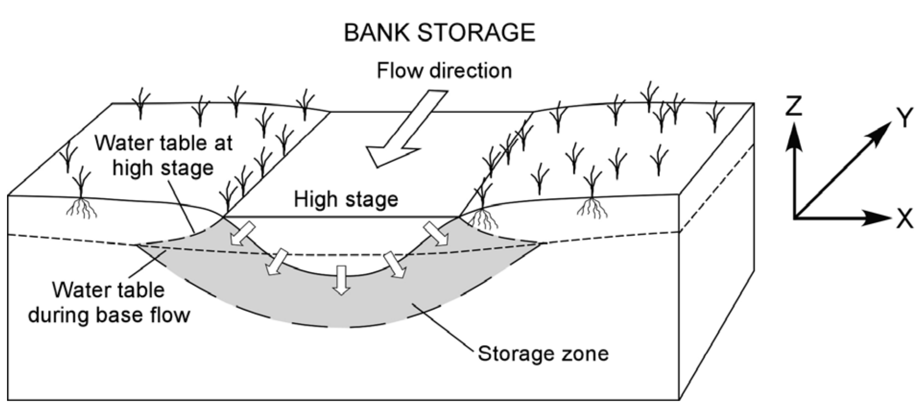

Figure 1 Schematic diagram of bank storage zone (modified from Winter et al. 1998).