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Special Article

Temporal and Spatial Signatures of Sediment Transport at the Watershed Scale: An Approach to Understand the Behavior of the Watershed

Huellas temporales y espaciales del transporte de sedimentos en la escala de la cuenca hidrográfica: una aproximación para entender el comportamiento de la cuenca hidrográfica

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Abstract

Sediment yield is affected by many factors, such as climate, geology, geomorphology, land use and human activities. Sediment signatures are the statistic indices or curves that are able to effectively describe the temporal and spatial characteristics of sediment transport and evaluate the ability of the streamflow to deliver the sediment. In this study, the sediment signatures of Upper Sangamon River Basin, which is an intensively managed watershed for agriculture development, are analyzed. Firstly, a semi-distributed model of sediment transport is built up based on the Tsinghua Representative Elementary Watershed (THREW) model, and it is applied to the Upper Sangamon River Basin. The result of sediment simulation is analyzed by four sediment signatures, i.e. specific sediment yield, sediment delivery ratio, cumulative sediment curve and effective discharge. The sediment signatures are consistent with each other and accord with the fact of the agricultural production in Upper Sangamon River Basin.

Keywords: Sediment, soil erosion, effective discharge, sediment delivery ratio, hydrological model.

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Introduction

Sediment transport is a key issue in the river basin management all over the world and the research of sediment transport is essential for better management practices including the land use management, river restoration, pollution control, water supply and so on. The relations of the magnitude and the frequency of sediment transport were discussed by Wolman and Miller (1960) and the important concept of effective discharge was introduced. Walling (1983) reviewed the limitation of the sediment delivery ratio concept and considered the problems of temporal and spatial lumping and its black nature. Many research has been done to analyze effective discharge (Crowder and Knapp, 2002), magnitude-frequency of bed load transport (Torizzo *et al.*, 2004), sediment delivery ratio (Lu *et al.*, 2005, Parsons *et al.*, 2006), sediment yield (Hassan *et al.*, 2008) and other indices or relations. Meanwhile, many sediment simulation models were proposed based on different methods (Arnold *et al*., 1990, Viney *et al*., 1999, Singh *et al*., 2008). However, the temporal and spatial characteristic of sediment transport within the river basin is still a complex issue and the knowledge of the associated processes of sediment transport still represents an important research need (Walling, 1983).

Over the last few decades, global climate change has been reported by many researchers and regional climate change is also an important topic because regional climate change has a more direct effect on the regional water resources, agriculture, forest and others (Dvorak *et al.*, 1997, Christensen *et al.*, 2004). In order to deal with the effect of the climate change on the watershed management, especially on the land use and management, some indices or signatures are needed to estimate the soil erosion on the hillslope and sediment delivery in the stream network quantitively.

The Upper Sangamon River Basin (USRB) in the center of Illinois State of USA is intensively managed, following conversion to intensive agricultural production during the late 19th Century through the formation of drainage districts, excavation of drainage ditches and installation of subsurface drainage tiles and is dominant by agricultural production nowadays. The suspended sediment data in USRB were gauged by the US Geological Survey and Illinois State Water Survey separately. As one of the streams in Illinois State, the effective discharges in USRB have been estimated with available data (Crowder and Knapp, 2002) and further analysis is required. In this paper, a semi-distributed model of sediment transport is built up based on a hydrological model, Tsinghua Representative Elementary Watershed (THREW) model, and then the model is applied to Upper Sangamon River Basin. The effects of crop transpiration and tile drainage are involved in the model. The modeling of evapotranspiration is improved by introducing the Leaf Area Index (LAI) and the tile drainage as an important type of interflow is introduced into the model. The result of sediment simulation is analyzed by the sediment signatures due to the poor observed sediment data. The study aims to reveal the characteristics of sediment transport of the watershed scale in terms of the temporal and spatial signatures, i.e. specific sediment yield, sediment delivery ratio, cumulative sediment curve and effective discharge.

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Study Area

The Upper Sangamon River Basin (USRB) is 3150 km^2 at the confluence of the Illinois River in the center of Illinois State, USA. Average annual precipitation (1984-2007) is approximately 870 mm/year, while snow represents approximately 5% of it. Average annual potential evaporation (1984-2007) is approximately 1630 mm/year. The annual average temperature in the basin is 11℃, and the monthly average temperature is from −5℃ in January to 24℃ in July. Average annual water yield measured at the USGS stream gauging station at Monticello (Drainage area of 1425 km^2, Figure 1) during 1971-2000 is approximately 300 mm/year.

The USRB is intensively managed, following conversion to intensive agricultural production during the late 19th Century through the construction of railroads, the formation of drainage districts, excavation of drainage ditches and installation of subsurface drainage tiles. Poorly drained soils and ephemeral wetlands used to be common, but have been significantly modified through the construction of tile drains. Native vegetation used to be tallgrass prairie but has since been replaced by row crops (Alexander and Darmody, 1991). Approximately 84% of the land in the basin is currently devoted to agricultural production, while land in the Conservation Reserve Program covers 7.2% of the basin, urban land 4.5% and wetlands cover 2.4%.

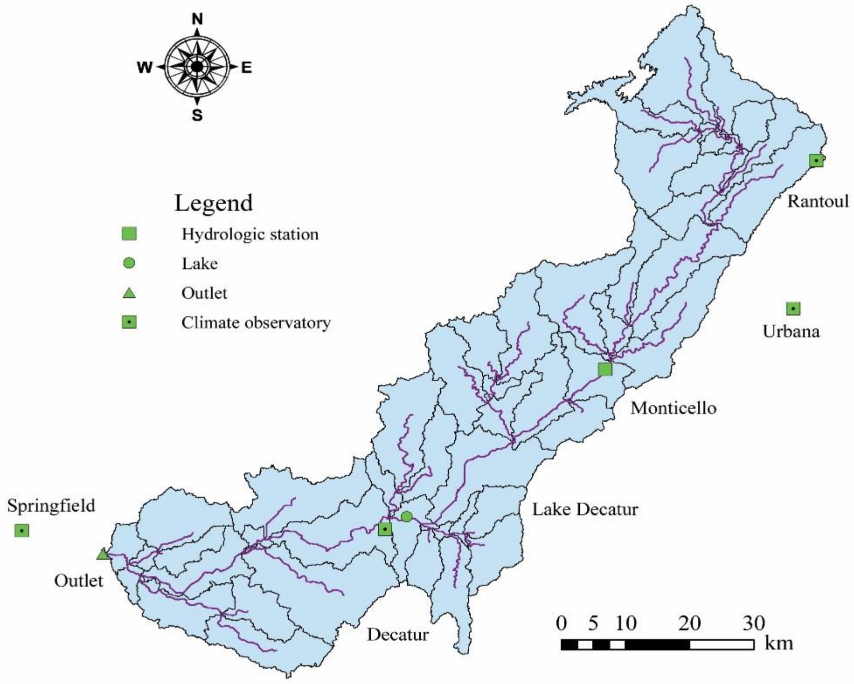

Figure 1. Map of USRB and distribution of ground stations.

Lake Decatur locates at the middle stream of USRB with the watershed area of 2400 km^2, and it is a water supply reservoir that supplies water to the City of Decatur with a population of 86,000. The dam of the reservoir was modified in 1956 and the maximum capacity of the lake increased to 34.56 million m^3 (Keefer and Bauer, 2005). The operation regime of the reservoir is unknown, so the USGS stream gauging station at Monticello (as shown in Figure 1) is selected for the calibration and validation of the model, which is at the upstream of the reservoir with the drainage area of 1425 km^2.

Data

The data used in the modeling include Digital Elevation Model (DEM), soil class, LAI, Normalized Difference Vegetation Index (NDVI), land cover, precipitation, potential evaporation, observed stream flow, observed sediment concentration and discharge. The geographic data are extracted from a DEM with the resolution of 1 arc second. The soil class is mainly extracted from the STATSGO database. The LAI is extracted from the product of "MODIS/Terra Leaf Area Index/FPAR 8-Day L4 Global 1km SIN Grid V004", NDVI from "MODIS/Terra

Vegetation Indices Monthly L3 Global 1km SIN Grid V004”, and land cover from “MODIS/Terra Land Cover Type Yearly L3 Global 1km SIN Grid V004”. The hourly precipitation data from DS3240 dataset of the National Climatic Data Center (NCDC) of NOAA are used in the model. The potential evaporation is extracted from North American Regional Reanalysis (NARR) of NOAA. Observed streamflow at Monticello is downloaded from the website of USGS. The observed sediment concentration and discharge at Monticello comes from the Benchmark Sediment Monitoring Program by Illinois State Water Survey. The air temperature and snow data at Urbana used in the discussion are obtained from the Illinois State Climatologist's Office, Illinois State Water Survey.

Model

Tsinghua Representative Elementary Watershed (THREW) model (Tian, 2006, Tian *et al*., 2008) is applied to the Upper Sangamon River Basin in the USA. THREW model is a semi-distributed hydrological model based on the Representative Elementary Watershed (REW) approach, and the model has been successfully applied to many watersheds in China, USA and Austria(Tian, 2006; Tian *et al.,* 2008; Liu *et al.*, 2009; Li *et al.*, 2010; Li *et al.*, 2012; Tian *et al.*, 2012; Liu *et al.*, 2012; Sun *et al.*, 2014; He *et al.*, 2014; He *et al.*, 2015; Liu *et al.*, 2015). The soil erosion and suspended sediment delivery are simulated based on the THREW model, which is named Tsinghua Representative Elementary Watershed model including Sediment (THREWS).

Hydrological Process

Tian *et al.* (2006) have extended the Representative Elementary Watershed approach for cold regions. The details are shown in Tian *et al.* (2006) and Mou *et al.* (2008). In the THREW model, each REW is partitioned into six surface sub-regions and two subsurface sub-regions. The hydrological processes of each sub-region in THREW model are described in Lee *et al.* (2007) and Tian *et al.* (2008).

In USRB, the river basin is divided into 51 REWs as shown in Figure 1. In each REW, there are four sub-regions (or zones) in the surface layer,

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and they are a bare soil zone, a vegetated zone, a sub-stream-network zone, and the main channel reach zone. There are three sub-regions in the sub-surface layer, which are an upper unsaturated zone, a lower unsaturated zone and a saturated zone. The hydrological processes including ground surface depression, canopy interception, saturation and infiltration excess runoff, overland and channel routing are modeled as described in THREW model.

After the initial calibration of the THREW model, it is supposed that the dominant factors in the evapotranspiration and runoff generation in USRB are different from them in the other study areas where the THREW model has been applied (Tian, 2006; Mou *et al.*, 2008). Through the investigation and diagnosing, crop transpiration and tile drainage are supposed to be important in the rainfall-runoff process. The effects of crop transpiration and tile drainage are involved into THREW model.

As introduced previously, approximately 84% of the land in USRB is currently devoted to agricultural production, while land in the Conservation Reserve Program covers 7.2% of the basin, urban land 4.5% and wetlands cover 2.4%. Especially, in the Lake Decatur watershed, the row crops of corn and soybean in 1994 covered 85.3% of the land. The grassy crops of small grains and hay covered only 2.4% and nonagricultural land uses 12.3% of the land. Corn and soybeans nearly equally cover the cropland area at 42.0% and 43.3%, respectively (Demissie and Keefer, 1996). The 1995 Illinois land cover/land-use database indicates that 80% of the Lake Decatur watershed area was agricultural land. The remaining acreage is grassland (11.8%), forest (2.8%), wetlands/marsh (1.4%), urban/transportation (2.9%), and water (0.7%). Corn and soybeans, the dominant crops, comprised 82% of the Lake Decatur watershed in 2002 (Keefer and Bauer, 2005).

As the crop transpiration is significant in the evapotranspiration due to the high fraction of vegetation cover in USRB, the modeling of evapotranspiration (E_T, m/s) is improved by introducing LAI (Allen *et al*., 1998, Amenu and Kumar, 2008), as shown in Equation (1).

$$E_T = \alpha \cdot E_P \cdot F_{root} \cdot LAI \cdot S_u \quad (1)$$

Where α is empirical parameter depending on crop type and is typically 0.5, E_p is potential evaporation (m/s), F_{root} is the fraction of the root distribution, LAI is the leaf area index, and S_u is soil moisture saturation degree.

As reported by Demissie and Keefer (1996), interflow is the relatively quick movement of water in the shallow soil layers, and baseflow sustains the flow in the stream during late summer and fall as well as during drought years in Sangamon River. The investigation of soil water balance in the Sangamon River basin indicates that more water contributes the stream through the combined effects of interflow and baseflow than from surface runoff (Demissie and Keefer, 1996). So the contribution of interflow and baseflow to the stream flow in USRB is very important.

Because of the extensive installation of subsurface drainage tiles in USRB to lower the groundwater table, the tile drainage as an important type of interflow is introduced into the model. While estimating saturated hydraulic conductivity in a tile-drained field, Rupp (2004) derived an analytical solution of tile drainage for an initial saturated unconfined rectangular aquifer. Green *et al.* (2006) proposed a formula of tile drainage on the daily scale for SWAT when they used SWAT2005 to evaluate streamflow in tile-drained regions. As the initial states of the aquifer and the distribution of the tiles in USRB are unknown and the time step in the THREW model is usually less than a day, a formula called linear reservoir model from conceptual model, especially Xin'anjiang Model, is used in the model, as shown in Equation (2) and Figure 2.

$$Qtile = \begin{cases} 0 \\ KD \cdot KSs\left(\frac{y_s-(Z-Ztile)}{Ztile}\right)^{KA} \end{cases} \quad (2)$$

if $y_s \leq Z - Ztile$, *if* $y_s > Z - Ztile$

where *Qtile* is the discharge per unit area of tile drainage (m/s), y_s is the average thickness of the saturated zone (m), *Z* is total soil thickness in the modeling (m), *Ztile* is depth of tile drainage (m), *KSs* is saturated hydraulic conductivity in saturated zone (m/s), *KD* is a linear parameter for tile discharge, and *KA* is an exponential parameter for tile discharge.

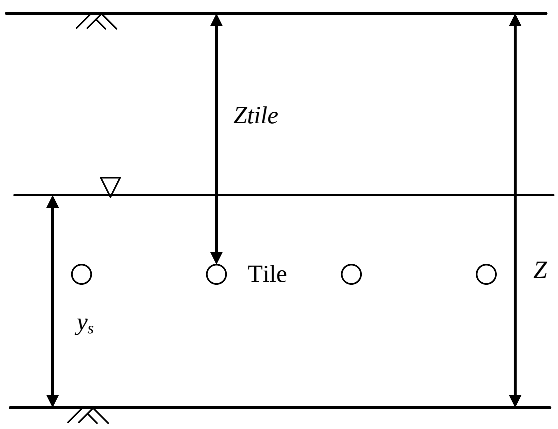

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Figure 2. Schematic of tile drainage.

Sediment Process

The sediment processes in the model include sediment erosion from the hillslope, deposition, re-entrainment and bed degradation in the main channel. The sediment is generated from the hillslope and is transported to the main channel by surface runoff. In the main channel, the sediment in the water is allowed to deposit to channel floor while the loose sediment would be removed by the stream flow. If all of the loose sediment on the channel is removed, the degradation of the channel bed will happen. In the main channel, the sediment is transported together with water flux from the upstream by the stream flow and then to downstream.

In the model, sediment erosion from the hillslope to the main channel is assumed to associate with surface runoff from sub-stream-network zone to the main channel reach zone, and the formula of sediment erosion rate (Q_{st}, kg/s) is a further conceptualization of the Modified Universal Soil Loss Equation (Neitsch *et al*., 2005; Viney *et al*., 1999), as shown in Equation (3).

$$Q_{st} = C \cdot s_t \cdot (Q_t \cdot A)^{\delta} \tag{3}$$

where C and δ are the empirical parameters, s_t is the slope of the sub-stream-network zone, and Q_t is the water discharge from sub-stream network to the main channel (m^3/s), A is the area of the REW(km^2).

The modeling of deposition, re-entrainment and bed degradation in the main channel followed the SWRRB model (Simulator for Water Resources in Rural Basins) (Arnold *et al*., 1990), i.e. the original of SWAT. A new zone for the sediment storage on main channel floor (sf-zone) is added to THREW model to model the sediment exchange between the water and the channel floor.

The sediment deposition in the main channel depends on the falling velocity of the sediment particles. The falling velocity formula (v_f, m/s) used in this study is an approximate form widely used in practice (Shao and Wang, 2005), as shown in Equation (4).

$$v_f = -9\frac{v}{d} + \sqrt{\left(9\frac{v}{d}\right)^2 + \frac{\gamma_s - \gamma}{\gamma} gd} \tag{4}$$

where γ_s is the density of sediment (kg/m^3) and γ is the density of water (kg/m^3), g is the gravity acceleration (m/s^2), d is the sediment particle diameter (m), and ν is the kinematic viscosity coefficient of water (m^2/s).

Travel time in the main channel of each REW (t, s) is

$$t = L_c / v \tag{5}$$

where L_c is the length of the channel (m), and v is the velocity (m/s).

The height that sediment of particle will fall during travel time (y_f, m) is

$$y_f = v_f \cdot t \tag{6}$$

The instantaneous sediment delivery ratio in each main channel (DR) is

$$DR = \begin{cases} 1 - 0.5 y_f / y_r \\ 0.5 y_r / y_f \end{cases} \tag{7}$$

if $y_f \leq y_r$, *if* $y_f > y_r$

where y_r is water depth in the main channel (m).

The deposition rate in the main channel (dep, kg/s) is

$$dep = \frac{S_{sr}}{t} (1 - DR) \tag{8}$$

where S_{sr} is the sediment storage in the water of the main channel (kg).

If there is loose sediment on the channel floor, i.e., the sediment storage in sf-zone (S_{sf}, kg) is positive, the sediment re-entrainment occurs. Otherwise, the degradation of the channel floor begins. The riverbed degradation (deg, kg/s) is the sum of the sediment re-entrainment and channel floor degradation, as shown in Equation (9).

$$deg = \begin{cases} k_1 \cdot \gamma \cdot Q_r \cdot s_r \\ k_1 \cdot k_2 \cdot \gamma \cdot Q_r \cdot s_r \end{cases} \tag{9}$$

if $S_{sf} > 0$, *if* $S_{sf} \leq 0$

where k_1 and k_2 are parameters, Q_r is the stream flow in the main channel (m^3/s), and s_r is the slope of the main channel.

Simulation Results

In the simulation, the water year is from October to September of next year. The period from Oct. 1993 to Sep. 1994 is selected for the model's warming up to eliminate the impact of the initial conditions. The period for the calibration is from Oct. 1994 to Sep. 1997 and the period for the validation is from Oct. 1997 to Sep. 2007. The simulated stream flow with the hourly time step at Monticello is used in the calibration and validation. Two standard indices, i.e. Nash-Sutcliffe efficiency coefficient (*NSEC*), and the coefficient of determination (R^2), and two signature curves, i.e. the regime curve and the hydrograph, are used to guide manual calibration of the hydrological model.

During the 3-year calibration period, we obtained *NSEC* within 0.69~0.86, and R^2 within 0.70~0.87 as shown in Figure **3**. For the whole calibration period, *NSEC* is 0.72 and R^2 is 0.74. Figure 4 presents the seasonality of the water balance in the whole simulation period. After the calibration, the simulated runoff curve, i.e. the regime curve, shows good consistency with the observed runoff curve in the simulation period.

Using the parameters obtained by calibration, the model is then validated from Oct. 1997–Sep. 2007. During the 10-year validation period, we obtain *NSEC* within 0.12~0.79, and R^2 within 0.48~0.82 as shown in Figure **3**. For the whole validation period, *NSEC* is 0.69 and R^2 is 0.70. The maximum *NSEC* and R^2 are obtained simultaneously in the year Oct. 2004-Sep. 2005, while the minimum *NSEC* in the year Oct. 1999-Sep. 2000 and minimum R^2 in the year Oct. 2000-Sep. 2001. Because the

annual precipitation from Oct. 1999 to Sep. 2000 is 689mm and that from Oct. 2000 to Sep. 2001 is 701mm, which is 20.8% and 19.4% less than the average annual precipitation (870mm) respectively, the model's performance from Oct. 1999 to Sep. 2001 is unexpected as shown in
Figure **3**.

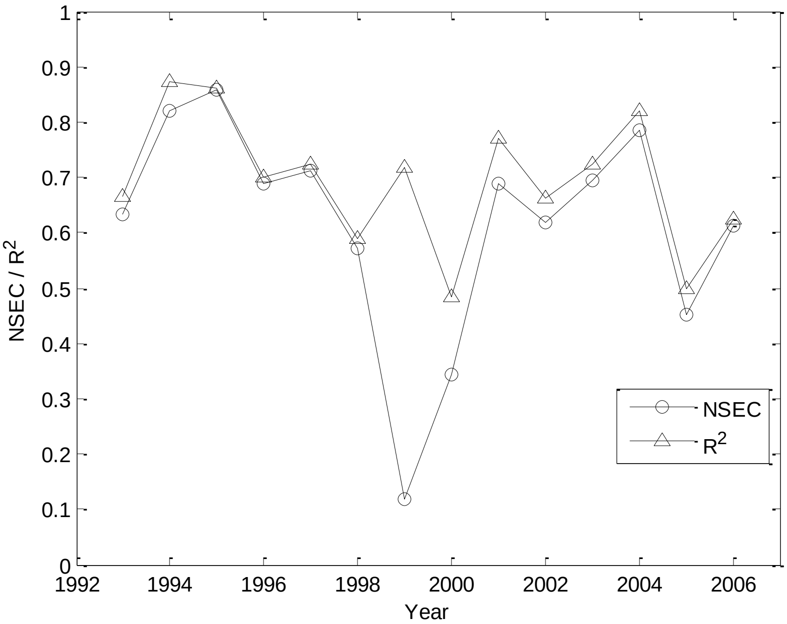

Figure 3. The evaluation indices of the simulation.

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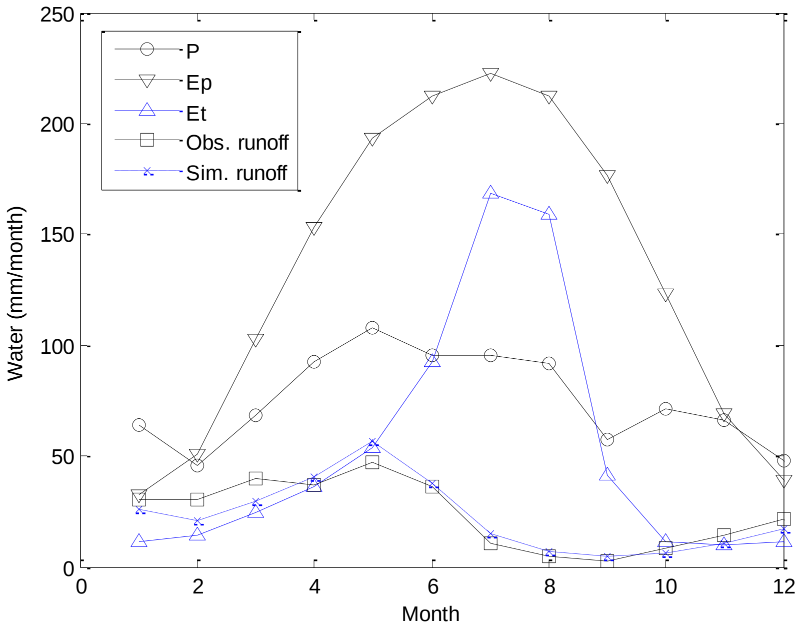

Figure 4. The seasonality of the water balance.

The observation of sediment discharges at Monticello isn't regularly daily and sometimes there are several sediment discharges in one day. On the other hand, the sediment discharge is not observed on some days. In the simulation period from Oct. 1, 1993, to Sep. 30, 2007, there are only 615 data, so the sediment model is not calibrated. The calibration of the sediment model is just used to confirm that the simulated sediment discharges are reasonable as shown in Figure 5.

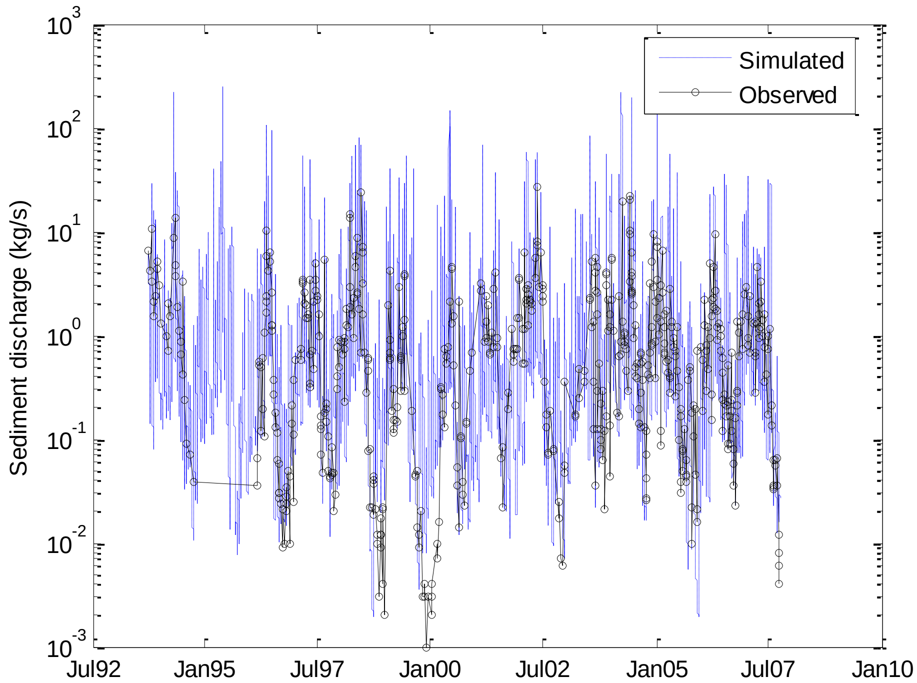

Figure 5. Simulated and observed sediment discharge at Monticello.

Sediment Signatures

There have been many statistic indices and curves for the analysis of sediment erosion and transport in the river basin, such as specific sediment yield, sediment delivery ratio (Walling, 1983), water-sediment cumulative percentage curve (Torizzo *et al.*, 2004) and effective discharge (Wolman and Miller, 1960). They are useful to analyze the temporal and spatial characteristics of sediment and evaluate the ability of the streamflow to deliver the sediment, which can be named as sediment signatures. However, the application of sediment signatures is limited by the available observed sediment data in the river basin.

The specific sediment yield, sediment delivery ratio, cumulative sediment curve and effective discharge, as the sediment signatures, are discussed in this section. Because of the small amount of observed sediment data, only simulated sediment discharges are used in the analysis of the sediment signatures.

Specific Sediment Yield

Sediment yield from a basin is a portion of soil eroded from the hillslope and it's the result of the combination of sediment erosion, deposition, re-entrainment and river bed degradation. To depict the scale property of sediment at the river basin scale, a lot of observed data will be required (Hassan *et al.*, 2008). And then problems will come, including limited length and irregular frequency of the data, the poor spatial distribution of the stations. However, with the simulation of sediment process in USRB, long-term regular, well-distributed sediment discharges are available to analyze the relationship of specific sediment yield and drainage area.

In THREWS model, one REW and all of its upstream REWs make up of a subbasin and the annual sediment yield and specific sediment yield of all subbasins are calculated as shown in Figure 6 and Figure 7.

Figure 6 shows that sediment yield increases with drainage area, but there is no significant trend for the relation of specific sediment yield and drainage area as shown in Figure 7. In USRB most of the land is farmland with corn and soybean, so the status of sediment erosion is nearly uniform all over the basin. The variability of specific sediment yield mainly comes from the heterogeneity of the river channel.

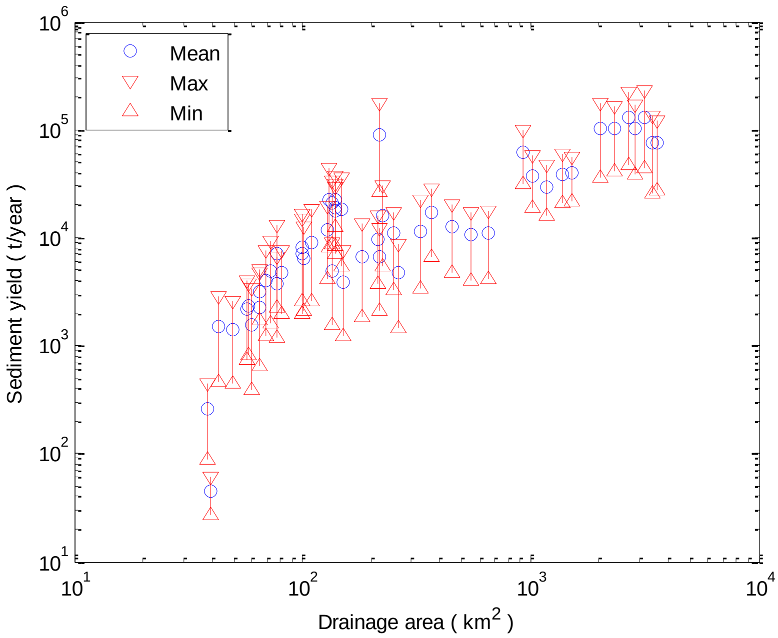

Figure 6. Sediment yield of all subbasins in USRB.

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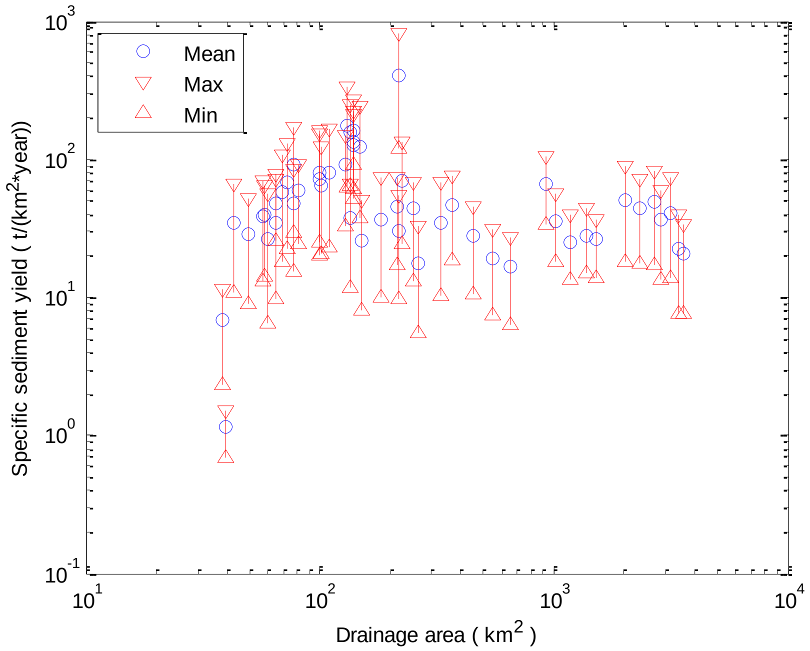

Figure 7. Specific sediment yield of all subbasins in USRB.

Sediment Delivery Ratio

Sediment delivery ratio (SDR) is used to estimate the quantity of sediment erosion on the hillslope by many researchers (Walling, 1983, Lu *et al.*, 2005), while some researchers think that the concept of sediment delivery ratio is a fallacy (Parsons *et al.*, 2006). However, at a proper temporal and spatial scale, the SDR concept is still a useful tool to describe the characteristics of a watershed. In this study, the SDR is defined as the ratio of annual sediment yield to annual sediment erosion in the watershed. In the modeling, sediment delivery ratio can be calculated with the annual sediment yield and annual sediment erosion. So the annual sediment delivery ratios of all subbasins in the simulation period are got, and the mean, the maximum and the minimum for each subbasin are shown in Figure 8.

In the simulation period, the sediment delivery ratio for each subbasin didn't vary too much. Figure 8 shows a relation that sediment delivery ratio decrease as the area of the subbasin increase and the result is consistent with the other research (Lu *et al.*, 2005).

However, there are some unexpected points which are larger than 1 or smaller than 0.01. There are 6 SDR which are larger than 1 for REW 47 (REW 47 is a subbasin) in the simulation period and the mean is 0.97. The SDR larger than 1 suggests that the riverbank and riverbed are degraded by the streamflow and the river channel is a source of sediment. For subbasin 18 (drainage area is 1168km^2) corresponding to REW 18, the mean SDR is 0.119, so in comparison with the SDR of upstream subbasin the river channel of REW 18 is a sink of sediment and most of the sediment is deposited on the riverbed. This is in accordance with the small specific sediment yield as shown in Figure 7.

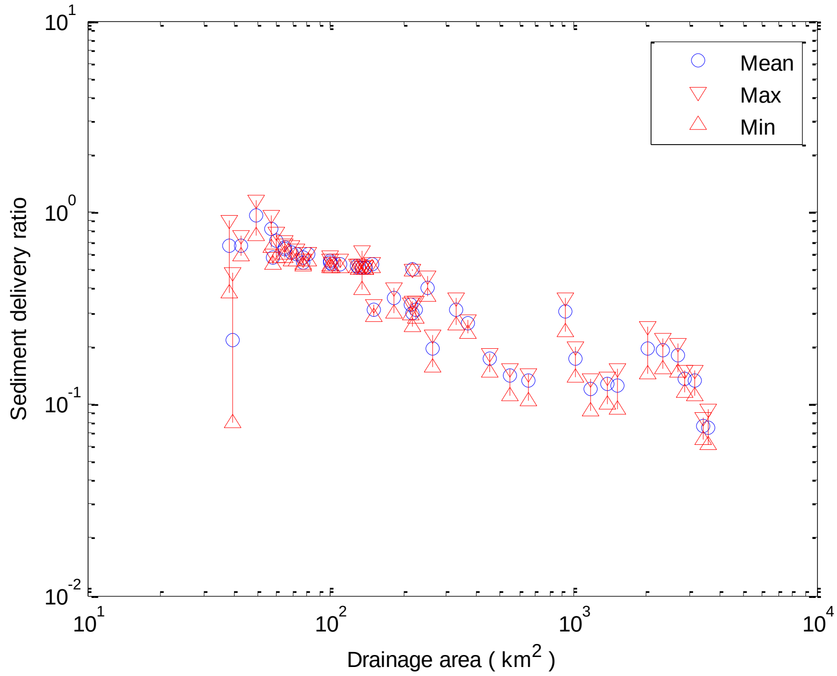

Figure 8. Sediment delivery ratio of all subbasins in USRB.

Cumulative Sediment Curve

Torizzo *et al.* (2004) used the water-sediment cumulative percentage curve to attempt to show the ability of the different magnitude streamflow (i.e. water discharge) to transport the sediment. Because the water-sediment cumulative percentage curve doesn’t show the contribution of the different magnitude of streamflow clearly, the cumulative sediment curve is introduced.

To plot the cumulative sediment curve, both of the streamflow data and the sediment discharge data of one year are arranged by the ascending

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order of the streamflow, the sediment discharge data are cumulated ascendingly only, and then the cumulative sediment discharge data are normalized by the total sediment. The ascending streamflow data and the normalized cumulative sediment data are plotted in the figure. The cumulative sediment curve at Monticello is shown in Figure 9. Although the annual maximum streamflow changed from 48.2m^3/s to 222.3m^3/s in the simulation period, the streamflows corresponding to the 50% sediment always were not larger than 46.6m^3/s as shown in Figure 9. So the main contributor of the sediment transport is the small streamflows and all of the curves are upward concave curves. Otherwise, if the main contributor is the large streamflows, the curve will be downward concave curves.

The critical streamflows, which are corresponding to 25%, 50% and 75% of cumulative sediment, are named as Q_{25}, Q_{50} and Q_{75} as shown in Figure 10. Although Q_{75} changed from 26.5m^3/s to 114.8m^3/s, Q_{25} and Q_{50} didn't change too much and the ranges were from 7.8m^3/s to 27.0m^3/s, and from 12.6m^3/s to 46.6m^3/s, respectively.

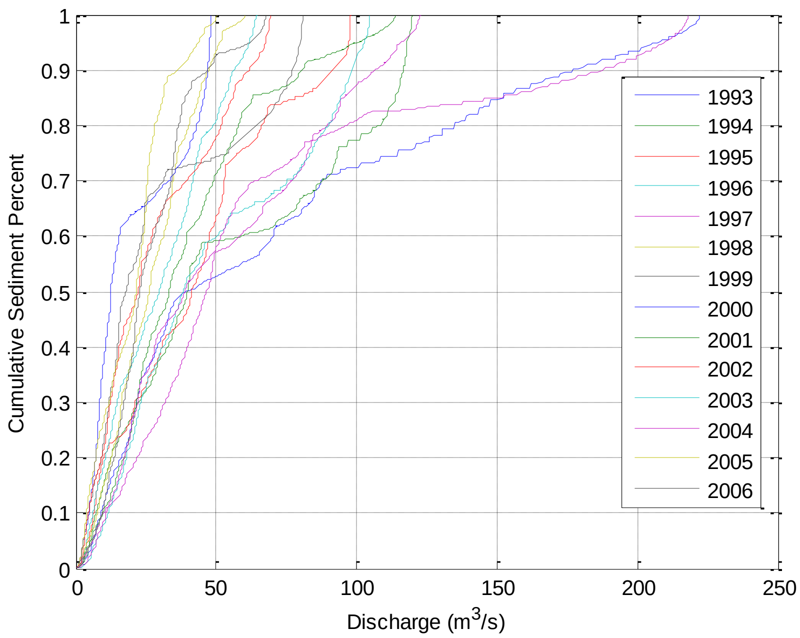

Figure 9. Cumulative sediment curve at Monticello in USRB.

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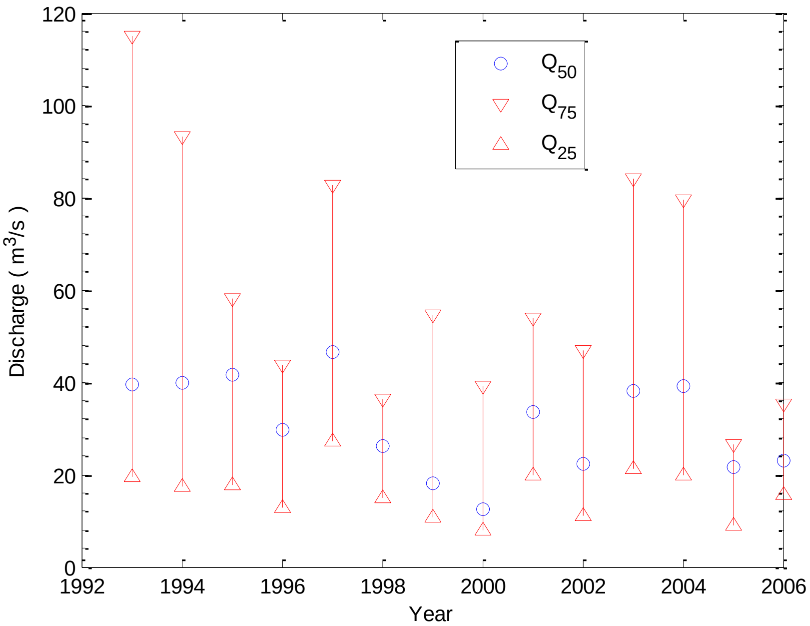

Figure 10. Critical streamflows of sediment transport at Monticello in USRB.

Effective Discharge

The effective discharge is a concept introduced by Wolman and Miller (1960) and widely used in the research of sediment transport (Torizzo *et al.*, 2004). The effective discharge is defined as the range of water discharges which transports the largest portion of the annual sediment yield. In the study, the length of the discharge intervals used to subdivide the entire streamflow series chooses to be 20m^3/s after it is tried several times and the central value represents the range after here. The absolute quantity of suspended sediment load, which is carried by each discharge interval within one year, is computed to graph sediment load histogram and the effective discharge is the central value of the discharge interval carrying the most sediment load.

The effective discharges of the outlets of all subbasins in USRB are calculated and are shown in Figure 11. For all subbasins, the minimum effective discharge in the simulation period is 10m^3/s and the mean and maximum effective discharge increase with the area of the subbasin slightly. But the largest mean effective discharge is only 57.1m^3/s, which is quite small. The effective discharge with the observed suspended sediment data from 1981 to 2000 at Monticello is 16.5m^3/s

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(Crowder and Knapp, 2002). The mean effective discharge of REW 16 corresponding to Monticello is 21.4m^3/s, which is near to observed effective discharge. In USRB, the small streamflows transport the largest portion of sediment yield and the conclusion is consistent with the result of cumulative sediment curve.

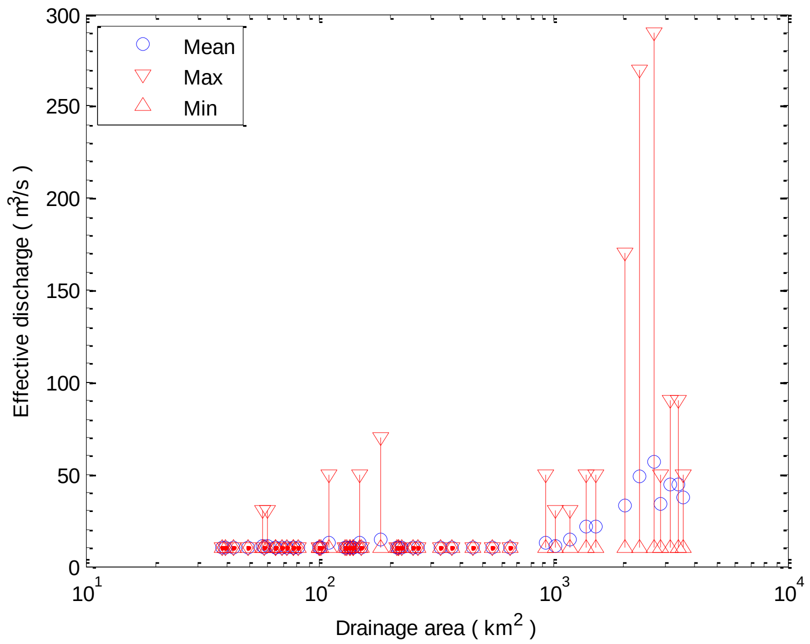

Figure 11. Effective discharges of all subbasins in USRB.

Discussion

Precipitation Data

In the modeling, all of the precipitation is assumed to be rainfall and the freeze of the soil moisture is neglected in the model. However, the snow depth on the ground as shown in Figure 12 is notable at Urbana, one of the main climate observatories used in the modeling (Figure 1), and the duration when there is snow on the ground continuously is quite long in some winters, as shown in Figure 13.

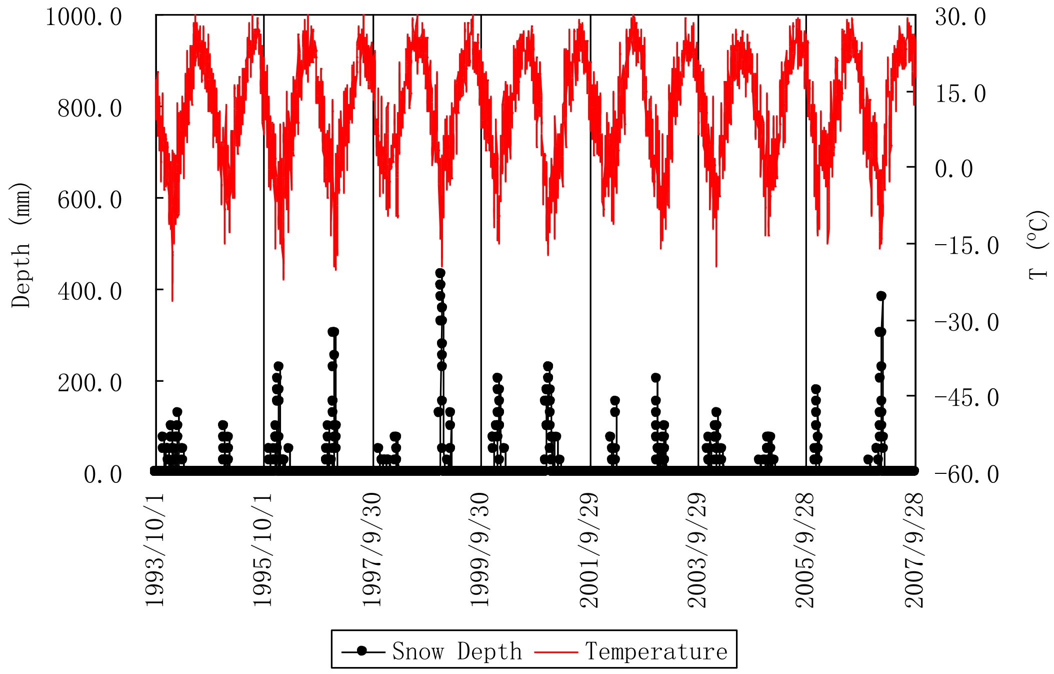

Figure 12. Snow depth and air temperature at Urbana.

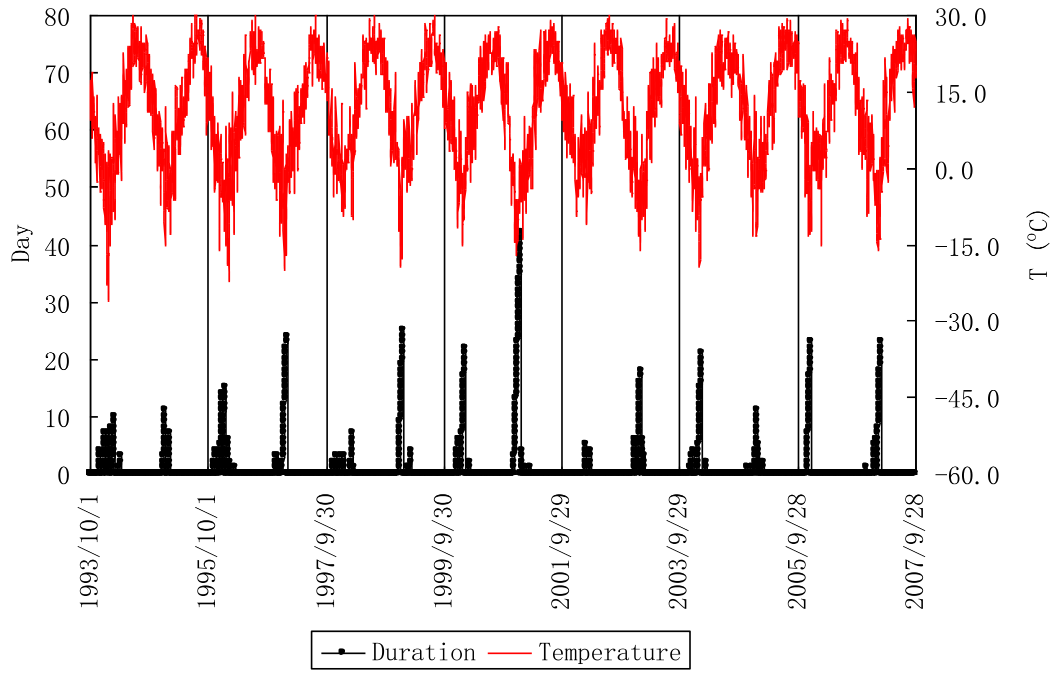

Figure 13. Duration and air temperature at Urbana.

Especially in Dec. 2000 and Jan. 2001, the daily mean temperatures of 53 days were below 0 ℃, and the precipitation was mainly in the form of snow and stored on the ground. The period when there is snow on the ground continuously is 42 days, from Dec. 12, 2000, to Jan. 22 2001, as shown in Figure 14. In Feb. 2001, the air temperature fluctuated around 0 ℃ and the freezing soil started to melt. So the saturation of the soil should be very high. On Feb. 24, 2001, the rainfall at Urbana is 47mm and a large flood peak of 168.5 m^3/s appeared in the next several days.

Therefore, the model which neglects snow and freeze of the soil moisture should be unable to capture the rainfall-runoff process due to snow and freeze of the soil moisture and in the future modeling of the area, the snow and freeze of soil moisture should be brought into the model.

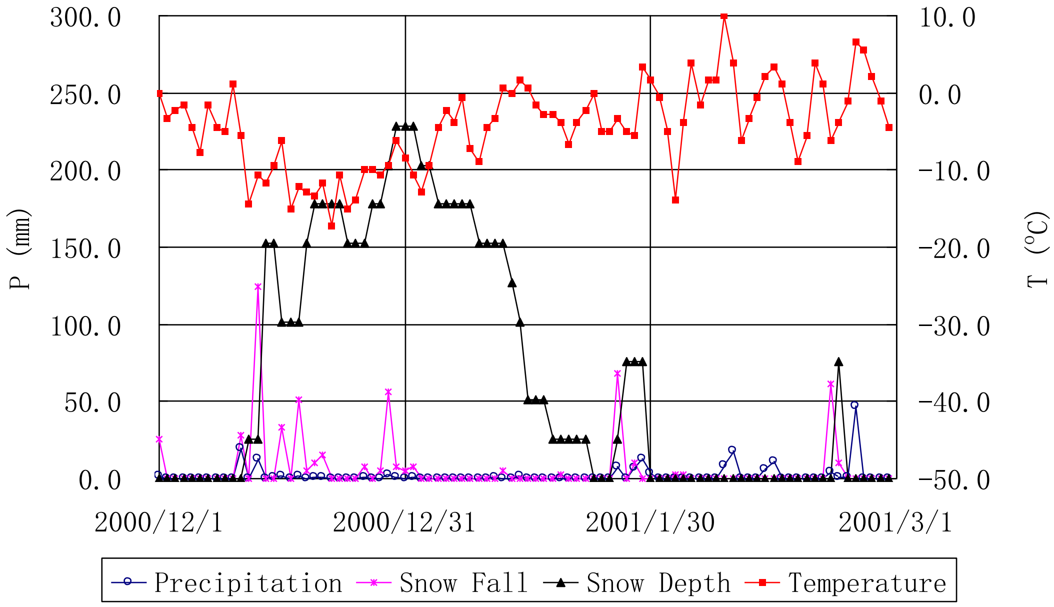

Figure 14. Precipitation and air temperature at Urbana from Dec. 2000 to Feb. 2001.

Strange Years

NSEC of simulated discharges in the water years of 1999-2000 and 2000-2001 are quite low and they are strange years due to the larruping precipitation and runoff regimes as shown in Figure 15. The annual precipitation of the water years of 1999-2000 and 2000-2001 is 689mm and 701mm, respectively, but the average annual precipitation of the basin is 870mm. It seems that the poor performance of the model

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in the two water years is due to the weak ability of the model to simulate the hydrological process in dry years, but in fact, the rainfall-runoff processes in the two years are absolutely different. The observed runoff coefficient at Monticello of the two years is 0.11 and 0.31, respectively, and then the water year of 1999-2000 is a dry year indeed as well as in name, as shown in Figure 15. However, the observed runoff coefficient in Feb. and Mar. 2001 is 0.96 and 1.81, respectively, which are unconventionally high, near or larger than 1. The high observed runoff coefficient is mainly due to the snow and freeze of the soil moisture in winter and spring, which should be the main cause of the model’s poor performance. The high runoff coefficient, which is near or larger than 1, also appears in the other years in the simulation period.

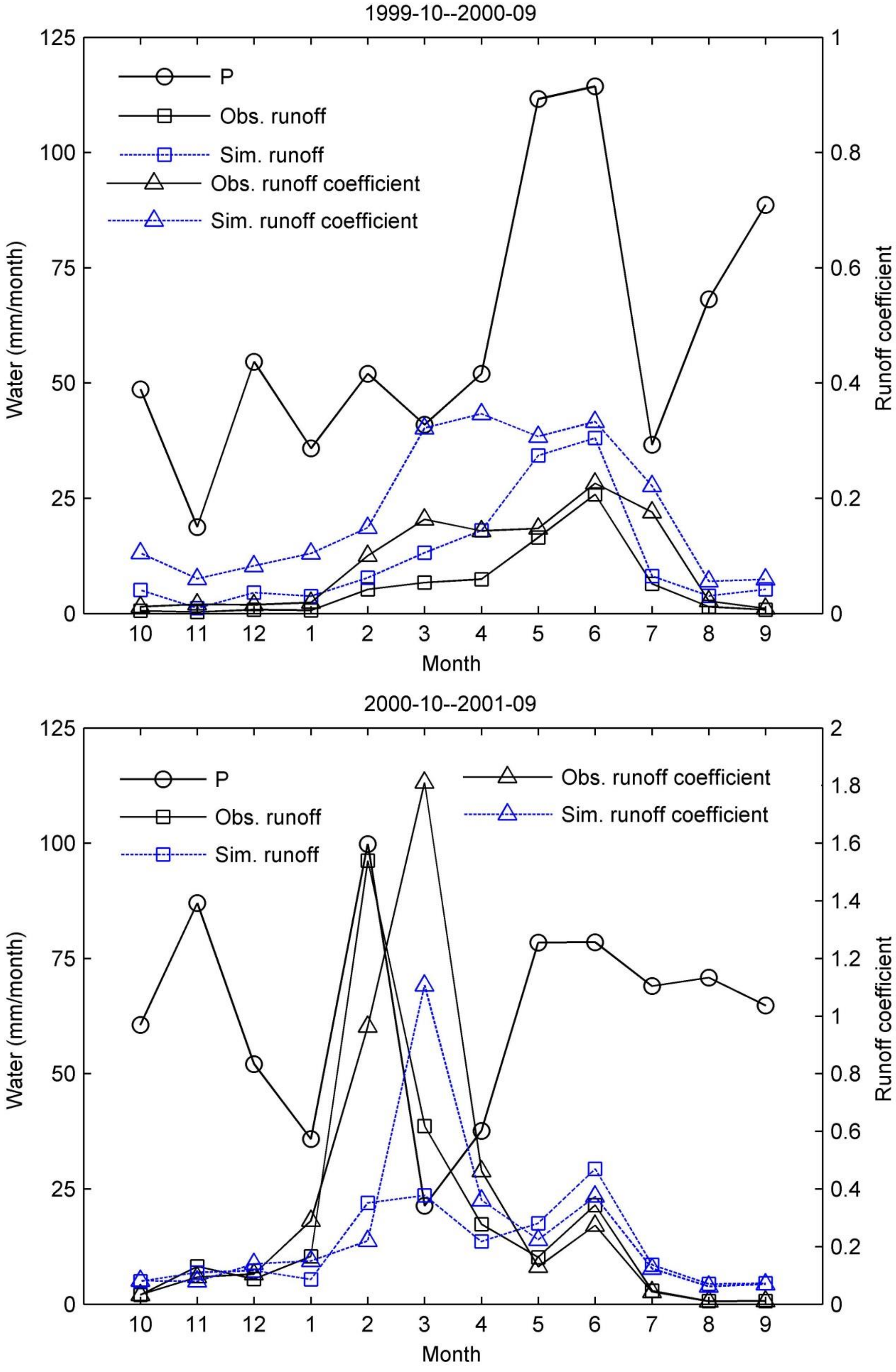

Figure 15. Monthly precipitation and runoff from Oct. 1999 to Sep. 2001.

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Sediment Observation

From Oct. 1, 1993, to Sep. 30, 2007, there are only 615 observed data of sediment discharges, so the observed data can't be used in the analysis of the sediment signatures. In order to understand the temporal and spatial characteristics of sediment delivery in USRB, the observation of sediment discharge should be improved to be regular and it's suggested that the regular daily observation of sediment concentration is required at least. In the next step, the analysis of sediment signatures will be applied in a well-gauged basin and new signatures will be brought in.

Conclusion

Through the investigation and diagnosing in Upper Sangamon River Basin, the closure relationships in THREW model are improved in this paper. Crop transpiration and tile drainage are found to play important roles in the hydrological process due to agricultural activities in USRB. So the modeling of evapotranspiration is improved by introducing LAI and the tile drainage as an important type of interflow is brought into the THREW model. Although THREW model with the improvement performs quite well in the moderate years, the closure relationships will be improved further due to the poor performance in the extremely dry years and cold months.

A semi-distributed sediment simulation model, THREWS, is built up based on the modeling framework of THREW model by introducing the sediment processes in the watershed, which include sediment erosion from the hillslope, deposition, re-entrainment and bed degradation in the main channel. The result of the simulation is used in the analysis of the sediment signatures in the paper.

Four sediment signatures, i.e. specific sediment yield, sediment delivery ratio, cumulative sediment curve and effective discharge, are applied in the analysis of the sediment simulation in USRB. The characteristics of the sediment transport in USRB which are represented by the sediment signatures are consistent with each other and accord with the fact of the agricultural production in USRB.

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