Journal of Environmental Informatics 16(1) 11-18 (2010)

Journal of Environmental Informatics

www.iseis.org/jei

Disaggregation Model of Daily Rainfall and Its Application in the Xiaolihe Watershed, Yellow River

L. He*, G. Q. Wang, and X. D. Fu

Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

Received 3 June2009; revised 25 November 2009; accepted 12 January 2010; published online 10 September 2010

ABSTRACT. In the continuous simulation of the whole sediment process in Coarse Sediment Area, one of the outstanding problems is getting rainfall data with high spatial and temporal resolution. For the calculation in Digital Watershed Model of Yellow River, one characteristic is huge calculation, as calculation is carried out on each river segment, with 797 river segments in a drainage area of 807km^2. A down-scaling method was proposed which could disaggregate daily rainfall data into one-hour timescale rapidly. This method was based on rain-cell conception and relationships between rainfall depth and duration time grouped by month. Secondly, several event-related characteristics, the distribution of event amount, event start time and the concurrency of number of events on a day of the generated hourly rainfall series, were compared with the observed data. Thirdly, this method was used in the hydrology simulation of water and sediment erosion in Xiaolihe Watershed. The analysis indicated that, the proposed method could be used to down-scale daily rainfall series to hourly, and then used in the simulation of sediment process with Digital Watershed Model of Yellow River.

Keywords: down-scaling method, rain-cell, hydrology simulation, huge calculation, digital watershed model of Yellow River

1. Introduction

Continuous rainfall–runoff simulation is increasingly becoming the preferred option over the use of isolated events data for hydrological systems design and performance analysis (Gyasi-Agyei and Mahbub, 2007). For simulating rainfall-runoff and soil erosion processes, rainfall data with different temporal and spatial resolution will significantly affect simulation results (Zhang et al., 2004). However, availability of rainfall data with fine temporal and/or spatial resolution is limited in hydrological studies, as the number of rain gauging stations is limited, and rainfall data usually have coarser temporal resolution. So, a method to get rainfall series with fine spatial/temporal resolution is necessary for continuous hydrological simulation.

Onof and Wheater (1994) pointed out that stochastic model based on Poisson processes is usually used to simulate continuous-time rainfall process. Stochastic models of point rainfall time series have more potential advantages over traditional approaches to rainfall representation, being able to provide a wide range of first and higher order rainfall statistics, be parsimonious with parameterization, and can generate extensive synthetic time series (Onof and Wheater, 1994). Neyman-Scott (NS) and Bartlett-Lewis (BL) type cluster based models and the variation of two models are the major types of cluster based models (Koutsoyiannis and Onof, 2001; Frost et al., 2004). For example, the model by Cowpertwait (1991) is based on the Neyman-Scott aggregation process, and the model of Kim and Kavvas (2006) is a combination of Neyman-Scott Rectangular Pulse Model and Gumbel's Type-II Bivariate Exponential Distribution. These models differ in the displacement of cell origins relative to storm origins (Frost et al., 2004).

However, the applicability of an existing method needs verification before being applied in a new drainage area. For example, for the rainfall data within central Queensland, the Bartlett-Lewis models failed to adequately reproduce statistics of the finer timescale, even when these statistics were included in the model parameter calibration (Gyasi-Agyei and Willgoose, 1997). So, it is necessary to verify the applicability of a down-scaling model based on the rainfall data of local rainfall gauges before being used in hydrology simulation. Besides, rain storm is defined differently, Connolly et al. (1998) analyzed rainfall events with interval time larger than 30 mins and got the cumulatively frequency of four event related characteristics, while Hershenborn and Woolhiser (1987) defined rainfall events as rainfall depth larger than 0.254 mm and interval time larger than 10 mins. To Yellow River basin, rainfall event in the observed hourly rainfall data is classified by rainfall depth, with no consideration of interval time. For instance, in the observed data of Yellow River, two adjacent events may have an interval time of 0 min and different rainfall depth, which is different from neither Connolly et al. (1998) nor Hershenborn

---

* Corresponding author. Tel.: +86 10 62795864. *E-mail address:* he-li@mail.tsinghua.edu.cn (L. He).

ISSN: 1726-2135 print/1684-8799 online

doi:10.3808/jei.201000173

and Woolhiser (1987). Furthermore, for a disaggregation method aiming to be used in Digital Watershed Model of Yellow River, the calculation speed is one important aspect, as it will be used in millions of river segments, more than 0.12 million river segments in Coarse Sediment Area. So, a method adapt to huge calculation is required before the simulation of the whole sediment process in Loess Plateau.

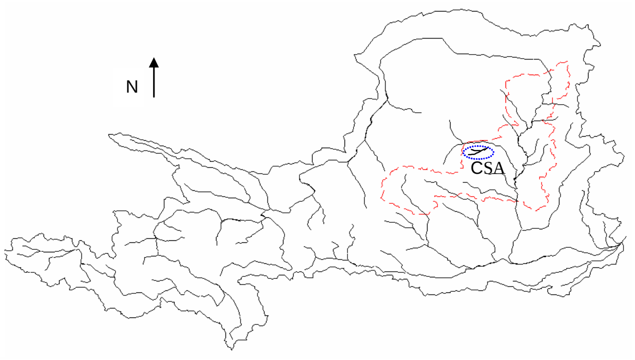
This paper aims to propose a down-scaling method for disaggregating daily rainfall data into hourly data, which can reproduce the rainfall series and be applied in the hydrological simulation with Digital Watershed Model of Yellow River. Firstly, the new method is proposed based on data analysis in the representative drainage area, the Xiaolihe drainage area, Yellow River. Then, the event related characteristics (including the distribution of event amount, event start time and the concurrency of number of events on a day) were compared with the observed data, which implies its capability of reproducing rainfall series. At last, the method is applied in the hydrology simulation of Xiaolihe Watershed with Digital Watershed Model of Yellow River. All the analyses indicate that the new method can reproduce rainfall series and then can be used in Digital Watershed Model of Yellow River.

2. Study Area

A representative watershed is selected in Coarse Sediment Area. And the criterions for selecting a representative area are the average controlling area of rainfall gauging stations and the total number of river segments of the extracted river network. If the controlling area of rainfall gauging stations is too large, the spatial interpolation will affect the accuracy, while the number of river segments is too little, fluvial process will be more sufficient.

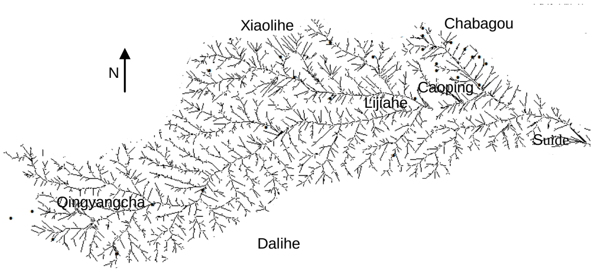
Xiaolihe and Chabagou Watersheds are part of Dalihe tributary (Figure 1), which is located in Loess Plateau and typical area with severe soil erosion. The density of rainfall gauging station in the Xiaolihe Watershed is 201 km^2, and the density of rainfall gauging station in the adjacent watershed, Chabagou, is 16 km^2. The measured rainfall data from gauging stations located in the Chabagou watershed will also be used in the spatial interpolation when generating daily rainfall data of the Xiaolihe Watershed. It means, the density of rainfall gauging station in Xiaolihe Watershed would be more closer to the criterion for rainfall gauging station network planning, five rainfall gauging stations in a river basin with drainage area of 100 km^2 (Li et al., 1999). When the river network is extracted with a resolution of 100 × 100 m, the total number of river reaches in Xiaolihe Watershed is 797 in the extracted river network (Figure 2), while the number for Chabagou is 187. So, Xiaolihe Watershed (Figure 1) is selected as a reprehensive drainage area to develop and verify the down-scaling method.

The Xiaolihe Watershed is one of the secondary tributaries of the Wudinghe watershed, which is a typical area with severe soil and water loss in the Loess Plateau (Figure 1). The drainage area of the Xiaolihe Watershed is 807 km^2. According to the measured data from 1959 to 1999, the average annual precipitation is 397 mm, and the range of annual rainfall depth recorded by rainfall gauging stations ranges from 150 to 670 mm. The Lijiahe Hydrological Station, located at the outlet of the watershed, has an average annual runoff of 28.0 × 10^6 m^3.



Note: the red dashed area is Coarse Sediment Area, the ellipse is Dalihe and Xiaolihe Watershed.

Figure 1. Sketch map of Xiaolihe Watershed and Yellow River basin**.**



Note: the dot is rainfall gauging station.

Figure 2. Sketch map of river networks and rainfall gauge stations of the Dailihe, Xiaolihe and Chabagou Watershed.

3. Methodology

Firstly, a preparing data analysis is carried out based on the observed rainfall data from the representative watershed, Xiaolihe drainage area. Then, the down-scaling method is constructed, and a detailed procedure for applying in simulation is provided.

3.1. Data Analysis

The purpose of this paper is proposing a downscaling method which can reflect the monthly distribution of rainfall series and also be suitable for the hydrology simulation in Digital Watershed Model of Yellow River, So, 1977 was selected as a typical year because of its low runoff with high sediment concentration. The historical rainfall data (both with daily and sub-daily resolution) of 21 rainfall gauging stations in and around the Xiaolihe Watershed in 1977 were collected and analyzed.

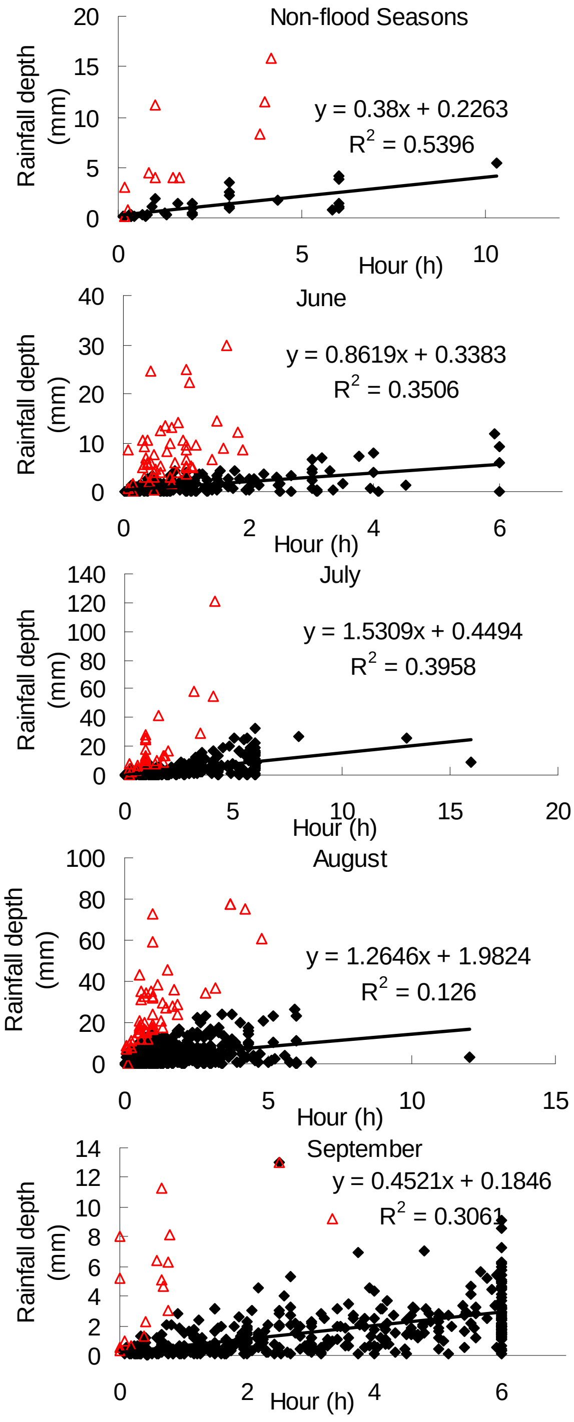


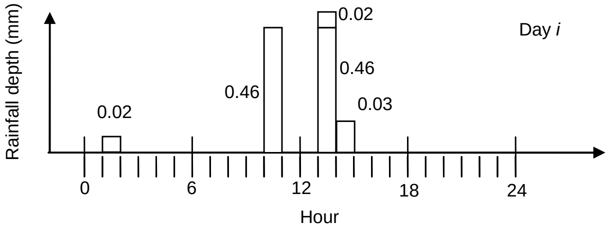
Figure 3. Relationships between rainfall depth and duration hour in Xiaolihe Watershed.

Firstly, the historical sub-daily rainfall data were grouped by month (Figure 3), and analyses were carried out for each month, as Onof and Wheather (1994) presupposed that inner characteristic of monthly rainfall was approximately stationary over the month. Then the relationship between rainfall depth and duration time were obtained following Cernesson et al. (1996). The inner assumption was that the monthly relationships could represent the annual distribution of rainfall, but no representation of the inter-annual. There were two linear trend-lines for each month in Figure 3, indicating two rainfall patterns (Wu et al., 2006), the convective and stratiform (Cowpertwait and O'Connell, 1997). The lower one was selected by rainfall characteristic in this region, as the frontal rain had more propriety in Yellow River Basin. The regression equations of the lower one were shown in Figure 3, and the average R^2 of linear trend-line was 0.34. Based on these developed relationships (Figure 3), a simplified down-scaling method was constructed.

3.2. Downscaling Method

Patrick and Jacques (1999) pointed out that, the basic theory of stochastic model indicates that rainfall can be linked to a random and intermittent process whose evolution is described by stochastic laws. And it is also based on the hypothesis of independence between variables describing hyetographs and on the hypothesis of the stationary nature of the phenomenon studied (Patrick and Jacques, 1999). Rain-cell model is one kind of stochastic rainfall models (Wu et al., 2006), which suppose the rainfall sequences are composed of multiple rain cells. Cluster based models conceptualize rainfall as a series of storm arrivals, with rainfall cells (with a random duration and intensity) associated with each storm, such that the total intensity at any time is the sum of the intensities of all cells activating at that time (Frost et al., 2004). Cluster process model is based on a combination of two random processes: occurrence and position of rainy cells, and cells' depth and duration processes (Patrick and Jacques, 1999). The method here was a stochastic one based on the conception of rain cell.

To the rain-cell based stochastic models (Onof et al., 2000; Velghe et al., 1994; Onof and Wheather, 1994; Koutsoyiannis, 1994; Wu et al., 2006), variables related to storm (including storm arrival and duration of the storm) and cell (number of cells, depth and duration of cell, and cell arrival (inter-event time)) can be calculated. So, the basic framework of the method here is (Figure 4): a Poisson process simulates the arrival of a storm; each storm event has a random number of cells represented by a rectangular pulse with random cell intensity and duration (Kim and Kavvas, 2006). For a hydro-meteorological forecasting chain, the downscaling model should be simple, robust and computationally fast (Rebora et al., 2005a, b). Considering the extremely large number of river segments in Digital Watershed Model of Yellow River (797 river segments in a drainage area of 807 km^2 with resolution of 100 m × 100 m), calculation speed had more priority. Fixed cell duration was used, the rain cell was rectangular and the duration of rain cell was constant, one hour (Figure 4). The number of rain cells depended on the observed daily rainfall depth and the trend lines in each month in Figure 3. The intensity of each rain cell was a function of daily rainfall depth and the number of rain cells. Storm at time t was an accumulation of rain cells falling at time t.



Note: It’s a possible situation for the downscaling of daily rainfall with depth of 1mm and duration time of 5 hours on day i. The value on or beside rectangular is the rainfall depth of each rainfall cell.

Figure 4. Sketch map of rainfall cell, including its duration time, rainfall depth, location on a day and the accumulation of two or more cells.

3.3. Procedure for Application

To simulate the whole sediment process in Coarse Sediment Area with Digital Watershed Model of Yellow River, the first thing is getting the hourly rainfall series of each river segment. And the hourly rainfall series of river segment *t* on day *i* could be calculated from the observed daily rainfall data on each rainfall gauging station by the following steps (Figure 5): (1) Based on the historical daily data from rainfall gauging stations around the river segment *t*, the daily rainfall data on it ($P_{i,t}$) can be generated by spatial interpolation, distance interpolation method with weighted shielding coefficient. The distance is defined with the longitude and latitude of the middle point of river segment *t* and rainfall gauging stations around it. The assumption is that, one river segment represents a small sub-watershed, and the rainfall in it is uniformly distributed. (2) Identify which month the day *i* belongs to, and then select a corresponding rainfall-depth and duration-hour relationship according to the month. As the rainfall-depth and duration-hour relationship is determined, the daily rainfall depth of day *i* has a corresponding duration time (following the two arrows in June, Figure 3), *H*. (3) According to the duration hour in Step (2) and the interpolated daily rainfall depth $P_{i,t}$ in step (1), the daily rainfall is then divided into *N* cells, with the total number being equal to the duration hours *H*, $N = H$. For example, if the duration time is five hours, the daily rainfall is then divided into five rain cells. (4) The location of one cell on the day *i* is generated by a random number, rand()%24 in Visual C++. There are 24 possible locations for one rain-cell, so that two or more rain-cells may be located at the same hour, which will be accumulated in step (6). (5) The rainfall depth of each rain cell (denoted as h_j, where *h* is the rainfall depth of rain cell; *j* is the cell index, $j = 1, 2 \ldots N$; *N* is the total number of cells) is calculated by the rest of daily rainfall depth ($P_{i,j}$) and the duration hours H ($H = N$,). To calculate the rainfall depth of the *j*-th cell, firstly, a random number less than 20 (denotes as *T*) is generated randomly (the random number generator is T = rand()%20, in Visual C++)) for each cell by assuming a normal random variable, so that a number series with length of *H* is formed, and the average value of this series is 10. Then, the rest rainfall depth for *j*-th cell on day *i* is $P_{i,j} = P_{i,t} - \sum_{k=0}^{j-1}(P_{i.k})$, and the rainfall depth of the *j*-th cell $h_j = (T \times P_{i,j})/[10 \times (H + 1 - j)]$. For example, if the duration hour is 2 hours, and the rain depth of the first cell is $h_1 = (T \times P)/20$. (6) The rainfall amount at the same hour period *o* on day *i* is finally accumulated, forming the storm at time *o*. (7) At last, this rain depth is used as hourly rainfall series to the distributed hydrological model for simulating rainfall-runoff and sediment erosion processes with Digital Watershed Model of Yellow River.

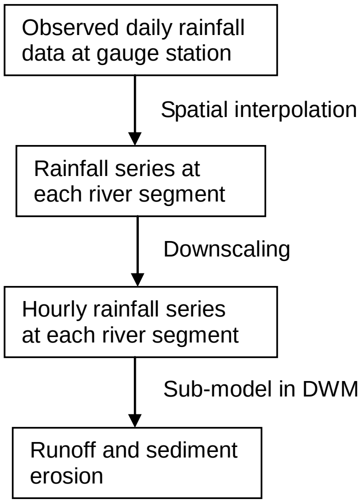


Figure 5. Procedure of calculation.

4. Model Verification

4.1. Event Related Characteristics

Firstly, the event related characteristics of rainfall series (including the event amount, event start time and number of events on a day) were compared with observed hourly data. The observed hourly rainfall data were drawn from recorded sub-hourly data of 21 rainfall gauge stations used in Figure 3, including nearly 1800 rainfall events occurred during May to October, 1977. Two hourly rainfall series were reproduced: one hourly rainfall series were downscaled with the daily data of two rainfall gauging stations, and the other one with all the daily rainfall data of these 21 rainfall stations. The comparison of two downscaled hourly rainfall series aimed to find the effect of different data amount used during downscaling. It compared the cumulative frequency and frequency distribution of event amount (Figure 6), event start time (Figure 7) and number of events on a day (Figure 8).

The minimum event amount varies, for the observed rainfall data, the minimum event amount was 0.1 mm, while the minimum value simulated was 0.01 mm, but only 2% simulated events with rainfall depth smaller than 0.1mm. For observed data, the cumulative frequency of the event amount on a day could be described by the following function:

$$F(x,k,\theta) = \frac{\gamma(0.54, x/6.4)}{\Gamma(0.54)} \tag{1}$$

The standard deviation comparing with the fitting curve were 0.0001 (observed), 0.003 (data with 2 rainfall gauge stations) and 0.004 (data with 21 rainfall gauge stations), respecttively. The frequency distribution was not included, as the event amount simulated was quite different from the observed.

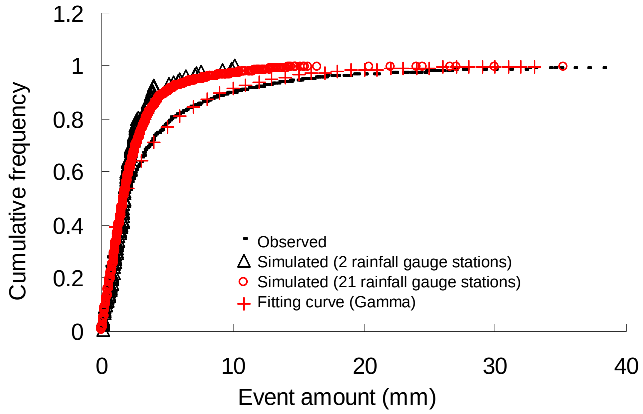


Figure 6. Distribution of event amount.

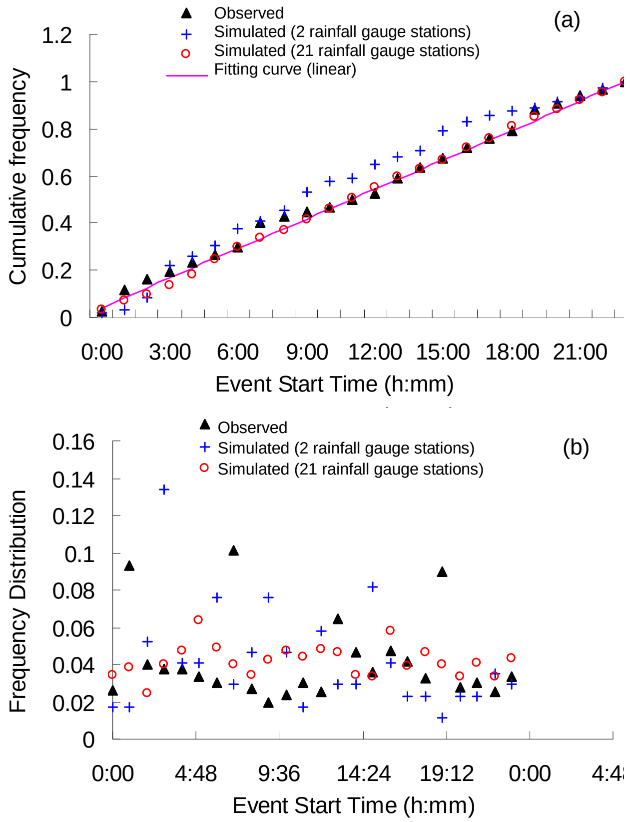


Figure 7. Distribution of event start time.

The fitting curve of the cumulative frequency of event starting time was, $F(x) = 0.0417x$, and the standard deviation comparing the fitting curve were 0.0007 (the observed series), 0.006 (data with 2 rainfall gauge stations) and 0.0002 (data with 21 rainfall gauge stations), respectively. Normally, the frequency of events occurring in a certain hour on a day varied between 0.02 and 0.06, with an average of 0.04 (Figure 7b). Figure 6 and Figure 7 showed that, the simulated series down scaled with more observed daily data (e.g. data with 21 rainfall gauges stations) approached the observed one better, both of event amount and event start time.

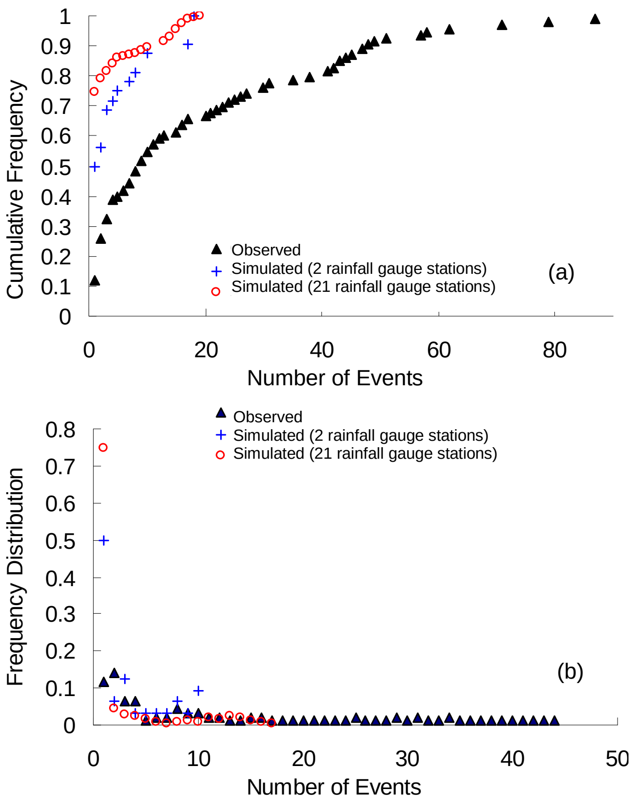


Figure 8. Daily concurrency of event number.

The number of rainfall events occurring on a day was one important characteristic of rainfall (Connolly et al., 1998). As the simulated one had a constant event duration time (one hour),the number of events on a day would absolutely less than that of observed data, whose duration time would range from 0 second to several hours. The maximum number of events on a day in simulated data would be around 20 (Figure 8b), while the number for observed would be 45, in which the influence of event duration time could not be ignored. The occurrence frequency of number of events on a day decreased with the increasing of number of events, decreasing gradually from 0.1 to 0 with events number rising to 45 (Figure 8b). However, both of the cumulative frequency of observed data and simulated results could be represented by logarithm functions. It indicated that the distribution of number of rainfall event occurring on a day was simulated appropriately. From Figures 6 to 8, the cumulative frequency and frequency distribution of these three event-related characteristics were revealed by the calculated hourly rainfall series reasonably.

4.2. Hyetographs

Then, rainfall distribution was compared between the ob-

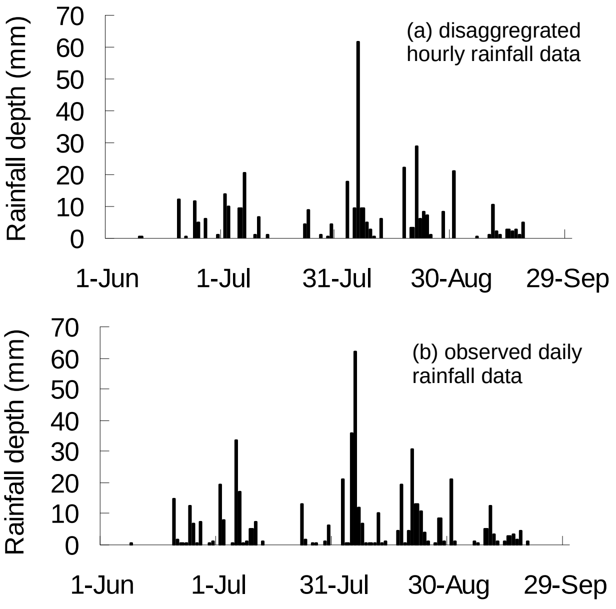


Figure 9. Comparison of hyetographs.

served data and disaggregated series. In Figure 9(a), the observed daily rainfall data on rainfall gauging stations were firstly downscaled to hourly series following steps in Section *Procedure for Applying*, then, the generated hourly rainfall series of the river segment which represents Lijiahe hydrology station was aggregated to daily, and compared with the observed daily series of Lijiahe hydrology station (Figure 9b). From the comparison in Figure 9, these two series were consistent with each other, both the occurrence of rain storm and the rainfall depth of most of the storms. There were 99 days with rain fall depth larger than 0 mm, and 71% were simulated correctly, with an average error of 0.029 mm.

4.3. Application in Hydrological Simulation

To verify the application of developed down-scaling method in Digital Watershed Model of Yellow River, the disaggregated hourly rainfall data were used to simulate rainfall-runoff and sediment erosion processes during the period from June 1 to September 30, 1977, Xiaolihe Watershed. The model used was Digital Watershed Model of Yellow River (Wang et al., 2007b), which is a physically-based, distributed-parameter and continuous simulation model for the Loess Plateau.

Firstly, the DWM was calibrated with observed daily rainfall data and the calibrated results were verified with historical data at the Lijiahe hydrological Station (Figure 10). The calibrated parameters were listed in Table 1. Then, the disaggregated hourly rainfall data were used as inputs to the DWM to simulate runoff and sediment amount during the same time period in the Xiaoli River basin. The comparison of the simulated hourly results and the measured one were shown in Figure 10 and Table 2. The comparison indicated that the simulated runoff and sediment amount were consistent with the measured value very well. However, the relative error of the peak values of both runoff and sediment amount was relatively high.It might be resulted from the excessively heavy rainfall in August, Hujierte rainfall gauging station, which generated significant influence on the daily rainfall disaggregation process. Moreover, the lower density of rainfall gauging stations in the Xiaoli River basin might also affect the simulation accuracy. The verification results indicated that the developed downscaling method could be used to disaggregate daily rainfall data at a fine timescale and then simulate rainfall-runoff and soil erosion processes in river basins.

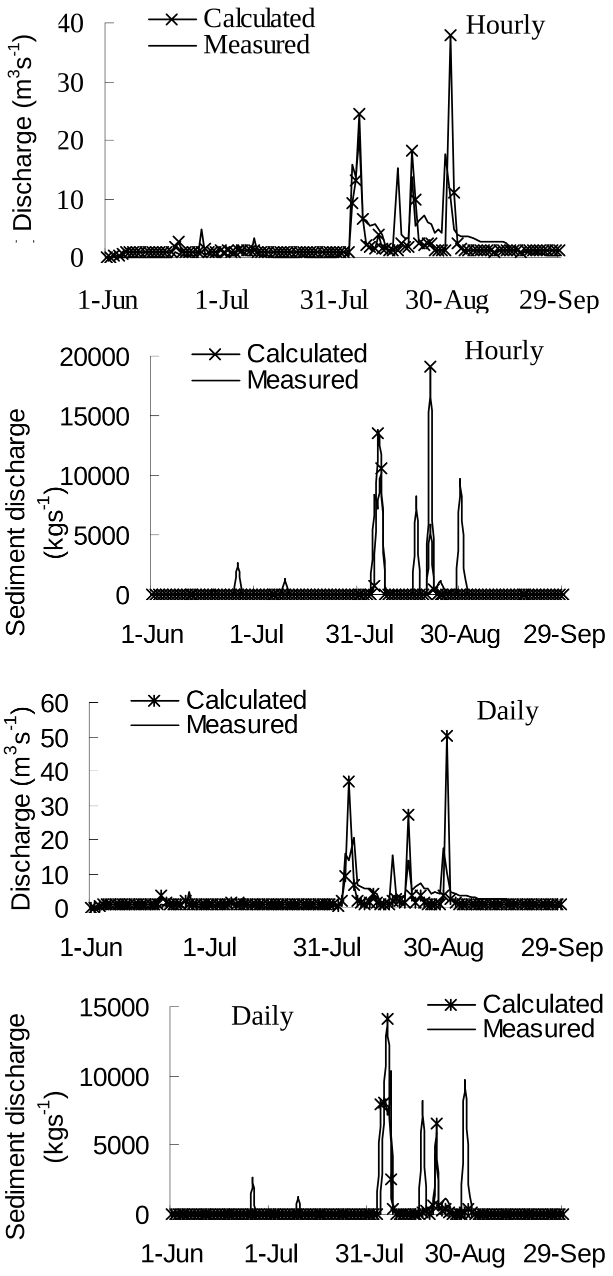


Figure 10. Comparison of simulated and measured rainfall data at Lijiahe hydrological Station.

Table 1. Main Parameters of the Underlying Surface

Para.	Value	Availability	Implication
K_{zus}	0.00011	Measured + Adjustment	Saturated hydraulic conductivity for the surface layer (m/h)
$K_{u\text{-}ds}$	0.0001	Calculated + Adjustment	Saturated vertical hydraulic conductivity between the surface soil and under layer soil (m/h)
K_{hu}	0.0004	Calculated + Adjustment	Horizontal penetration parameters for the surface layer and under layer soil (m/h) , respectively
K_{hd}	0.0003	Calculated	
θ_{us}	0.516	Measured	Saturated water contents of the surface layer and under layer soil (m^3/m^3), respectively
θ_{ds}	0.522	Measured	
θ_{uf}	0.212	Measured	Field water capacities for surface layer and under layer soil (m^3/m^3), respectively
θ_{df}	0.207	Measured	
LAI	0.10~0.86	Remote Sensing	Leaf area index (m^2/m^2), transformed from the normalized vegetation index (NDVI) acquired by remote sensing data
I_0	3.6	Calculated	River closure index of vegetation canopy (mm), related to vegetation

Table 2. Statistics for Simulated and the Measured Rainfall Data*

	Measured	Calculated		Error (%)	
		Hourly	Daily	Hourly	Daily
Water（×10^7 m^3）	2.41	2.26	2.36	-6.22	-2.07
Flood Peak (m^3/s)	20.7	24.37	37.09	17.72	79.18
Sediment (10^4 kg/s)	6.33	4.47	4.28	-29	-32
Sediment Peak (kg/s)	10100	13502	14071	33.68	39.31

* The compared peak occurred in August 7th, 1977.

5. Conclusions

As rainfall series is the main input of simulating the rainfall-runoff process for hydrology simulation in Digital Watershed Model of Yellow River, one problem is finding a method to get hourly rainfall series from observed daily data. The method should meet the necessity of huge calculation in Coarse Sediment Source Area and the definition of rainfall event in observed data. A down-scaling method was proposed, based on the concept of rain cell. The rain cell is identified as a rectangular with different high and constant width, which represents the constant duration time of rain cell, one hour. The method was verified by comparison of storm related characteristics and rainfall distribution. With these three characteristics, a rainfall distribution can be represented. Then, the calculated hourly rainfall series was applied in the hydrology simulation of Xiaolihe Watershed. The comparison results indicated that, the proposed down-scaling method could be used to disaggregate daily rainfall data to hourly, and facilitate simulating rainfall-runoff and soil erosion processes in river watersheds in Digital Watershed Model of Yellow River.

Acknowledgments. This paper was supported by the National Science & Technology Pillar Program of China in the Eleventh Five-year Plan Period (No. 2007BAC06B06) and by the National Natural Science Foundation of China (No. 50725930).

References

Cernesson, F., Lavabre, J., and Masson, J.M. (1996). Stochastic model for generating hourly hyerographs, *Atmos. Res.*, 42, 149-161.

Connolly, R.D., Schirmer, J., and Dunn, P.K. (1998). A daily rainfall disaggregation model, *Agric. For. Meteorol.*, 92, 105- 117.

Cowpertwait, P.S.P. (1991). Further developments of the Neyman-Scott clustered point process for modelling rainfall, *Water Resour. Res.*, 27(7), 1431-1438, doi:10.1029/91WR00 479.

Cowpertwait, P.S.P., and O'Connell, P.E. (1997). A regionalised Neyman-Scott model of rainfall with convective and stratiform cells, *Hydrol. Earth Sci.*, 1, 71-80.

Frost, A.J., Srikanthan, R., and Cowpertwait, P.S.P. (2004). *Stochastic generation of point rainfall data at sub-daily timescales: a comparison of DRIP and NSRP*, Report 04/09, Cooperative Research Centre for Catchment Hydrology, 1813-1819.

Gyasi-Agyei, Y., and Mahbub, S.M.P.B. (2007). A stochastic model for daily rainfall disaggregation into fine time scale for a large region, *J. Hydrol.*, 347, 358-370, doi:10.1016/j.jhydro l.2007. 09. 047.

Gyasi-Agyei, Y., and Willgoose, G.R. (1997). A hybrid model for point rainfall modeling, *Water Resour. Res.,* 33(7), 1699-1706.

Hershenhorn, J., and Woolhiser, D.A. (1987). Disaggregation of daily rainfall, *J. Hydrol.,* 95, 229-322.

Kim, S., and Kavvas, M.L. (2006). Stochastic point rainfall modeling for correlated rain cell intensity and duration, *J. Hydrol. Eng.,* 11(1), 29-36, doi:10.1061/(ASCE)1084-0699(20 06)11:1(29).

Koutsoyiannis, D. (1994). A stochastic disaggregation method for design storm and flood synthesis, *J. Hydrol.*, 156, 193-225, doi: 10.1016/0022-1694(94)90078-7.

Koutsoyiannis, D., and Onof, C. (2001). Rainfall disaggregation using adjusting procedure on a Poisson cluster model, *J. Hydrol.*, 246, 109-122, doi:10.1016/S0022-1694(01)00363-8.

Li, Z.W., Di, F.H., and Na, J.K. (1999). Rain station network density analysis in small valleys, *J. Heilongjiang Hydraul. Eng. College*, 26(4), 13-14. (in Chinese).

Onof, C., and Wheater, H.S. (1994). Imprvoved fittling of the Bartlett-Lewis Rectangular puls model for hourly rainfall, *Hydrol. Sci. J.*, 39(6), 663-680.

Onof, C., Chandler, R.E., Kakou, A., Northrop, P., Wheater, H.S., and Isham, V. (2000). Rainfall modeling using Poisson-cluster processes: A review of developments, *Stochastic Environ. Res. Risk Assess.*, 14, 384-411, doi:10.1007/s004770000043.

Patrick, A., and Jacques, L. (1999). Using a stochastic model for generating hourly hyetographs to study extreme rainfalls, *Hydrol. Sci. J.*, 44(3), 433-446.

Rebora, N., Ferraris, L., Hardenberg, J.V., and Provenzale, A. (2005a). Stochastic downscaling of LAM predictions: an example in the Mediterranean area, *Adv. in Grosciences*, 2, 181-185.

Rebora, N., Ferraris, L., Hardenberg, J.V., and Provenzale, A. (2005b). RainFARM: Rainfall downscaling by a filtered autoregressive model, *J. Hydrometeorol.*, 7, 724-738, doi:10.1 175/ JHM517.1.

Velghe, T., Troch, P.A., De Troch F.P., and Van de Velde J. (1994). Evaluation of cluster-based rectangular pulses point process models for rainfall, *Water Resour. Res.*, 30(10), 2847-2857.

Wu, S.J., Tung, Y.K., and Yang, J.C. (2006). Stochastic genera- tion of hourly rainstorm events, *Stoch. Environ. Res. Risk Assess.*, 21, 195-212, doi:10.1007/s00477-006-0056-3.

Zhang, X.S., Hao, F.H, and Zhang, J.Y. (2004). Study on effect of uncertainty in special distribution of rainfall on runoff and sediment modeling, *Res. Soil Water Conserv.*, 11(1), 9-12. (in Chinese).

Wang, G.Q., He, L., Li, T.J., and Cai-Wang, B.D. (2007a). Daily rainfall disaggregation at one-hour timescale for hydrologic modeling in the Xiaoli River basin, *Proc. Of International Society for Environmental Information Science 2007 Annual Conference*, 2007, Bangkok, Thailand.

Wang, G.Q., Wu, B.S., and Li, T.J. (2007b). Digital Yellow River Model, *J. Hydro-Environ. Res.*, 1, 1-11.