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Soil Moisture Accounting (SMA) based sediment graph models for small watersheds

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ABSTRACT

The sediment graph models are useful for computation of sediment yield as well as total sediment out flow from watershed. In this study, the analytical development of proposed sediment graph models is based on Soil Moisture Accounting (SMA) procedure coupled Soil Conservation Service-Curve Number (SCS-CN) method, Nash's Instantaneous Unit Sediment Graph (IUSG)model and Power law. This coupling has led to the development of four sediment graph models (SGMs), i.e., SMA-SGM1, SMA-SGM2, SMA-SGM-3 and SMA-SGM4 depending on the four different hydrologic conditions as: (i) initial soil moisture (V_0) = 0 and initial abstraction (I_a) = 0, (ii) initial soil moisture (V_0) ≠ 0andinitialabstractionI_a = 0, (iii) initial soil moisture (V_0) = 0 and (I_a) ≠ 0, and (iv) initial soil moisture (V_0) ≠ 0 *and* initial abstration (I_a) ≠ 0, respectively. These models are applied on six natural watersheds with nineteen storm events having different land use/land cover, climatic condition (arid, semi-arid, humid and sub-tropical), rainfall and land slope conditions. The goodness-of-fit statistics is evaluated in terms of Nash Sutcliffe efficiency (NSE) and relative error (RE) between observed and simulated (calibrated and validated) sediment graphs. Further, the performance of these models is also compared with the sediment graph model of Bhunya et al. (2010) (BSGM) on all the six study watersheds. It is found that the proposed models perform very well in simulating sediment yield generation process for all the watersheds and show significant improvement over the BSGM model.

1. Introduction

Time-distributed sediment yield modeling has paramount importance in hydrology, water resources and environmental engineering. It has been recognized to be fundamental to a range of applications such as river morphology, natural resource conservation planning, land management, soil and water conservation and agricultural and water resource planning. The process of sediment yield generation is extremely complex and mainly consists of detachment and transport of sediment particles by raindrop and runoff (Tyagi et al., 2008). The sediment yield modeling is more complex as compared to other types of watershed modeling, as it arises from a complex interaction of several hydro-geological processes, and the knowledge of the actual process and extent of suspended materials is far less detailed (Bennett, 1974).

The sediment flow rate plotted as a function of time during a storm at a given location is known as sediment graph. Without a sediment graph, only the average sediment rate for the storm can be computed. The average sediment yield is not adequate for computing dynamic suspended sediment load and pollutants load during the storm (Raghuwansh et al., 1994). Rendon-Herrero (1978) developed a sediment graph model based on unit sediment graphs (USG) approach defined as the unit sediment graph generated from one unit of sediment for a given duration distributed uniformly over a watershed.

The sediment yield models can be classified into three groups: (1) lumped, (2) quasi-lumped and (3) distributed (Singh et al., 2015a, 2015b). Probably the most widely used lumped model for estimating sediment yield from small agricultural watersheds (agricultural, forest, and urban) is the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). To apply USLE to large watersheds, the concept of sediment delivery ratio (ratio of sediment generated to the amount of erosion) has been incorporated. Another lumped sediment yield model was developed by Mishra et al. (2006a, 2006b) by coupling the Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1956) and USLE. Later on, a sediment yield was developed by Tyagi et al. (2008) by utilizing the SCS-CN based infiltration model for computation of rainfall-excess rate and the SCS-CN-inspired

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proportionality concept for computation of sediment-excess. Singh et al. (2008) and Bhunya et al. (2010) developed conceptual sediment graph models based on SCS-CN method, Nash's IUSG and power law from an agricultural watershed.

The development of storm-wise sediment graph model is a reasonable solution to understanding the complexities and to reducing the uncertainties. However, these models ignore the concept of Soil Moisture Accounting (SMA) in their formulation. Notably, a sound SMA has to incorporate all soil moisture conditions (Mishra and Singh, 2004; Michel et al., 2005; and Kannan et al., 2008). The SMA procedure is based on the notion that higher the moisture store level, higher is the fraction of rainfall that is converted into runoff (Michel et al., 2005). Camici et al. (2011) termed it as 'design soil moisture' and argued that it is the most important factor to determine the predictive outcome of an event (De Michele and Salvadori, 2002; Brocca et al., 2009). On the contrary, however, other investigations have inferred that it might be not so critical, particularly in the case of large events (Bronstert and Bárdossy, 1999; Castillo et al., 2003).

Therefore, looking into the importance of sediment graph based studies and SMA concept in event based rainfall-runoff-sediment yield modeling, this study aimed at (1) to develop improved sediment graph models (SGMs) based on coupling of Soil Moisture Accounting (SMA) procedure in the SCS-CN method, Nash's, IUSG model and Power law, (2) to test the applicability of the proposed model by using data of six small watersheds, and finally (3) to compare the performance of the proposed model with the existing Bhunya et al. (2010) sediment graph model (BSGM).

2. Existing Soil Conservation Service Curve Number (SCS-CN) method

The SCS-CN method for computing storm runoff from event rainfall was developed by the Soil Conservation Service (SCS) of United States Department of Agriculture (USDA, 1972). For the storm as a whole, the depth of excess rainfall realizable as direct runoff Q is always less than, or equal to, the depth of rainfall P; likewise, once runoff begins, the additional depth of water retained in the watershed (F), is less than or equal to, some potential maximum retention (S). There is some amount of rainfall (Ia) (initial abstraction before ponding) for which no runoff will occur; so the potential runoff is (P-Ia).

The hypothesis underlying this method is that the ratio between the two corresponding actual quantities is the same as between the two corresponding potential quantities. Analytically, the equations can be written as:

$$P = I_a + F + Q \tag{1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2}$$

$$I_a = \lambda S \tag{3}$$

in which, P is the rainfall (mm), Q is the direct surface runoff (mm), F is the cumulative infiltration (mm), excluding Ia (the initial abstraction, mm), S is the potential maximum retention (mm), and $\lambda$is the initial abstraction coefficient. Coupling Eq. (1) and Eq. (2) leads to the existing SCS-CN method as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{4}$$

Eq. (4) is valid for $P \geq I_a$, Q = 0, otherwise. Coupling of Eq. (4) with Eq. (3) for $\lambda = 0.2$enables determination of S from the rainfall-runoff data. In practice, S is derived from a mapping equation expressed in terms of curve number (CN).

$$S = \frac{25400}{CN} - 254 \tag{5}$$

The non-dimensional CN is derived from the tables given in the National Engineering Handbook, Section-4 (NEH-4) (SCS, 1956) for catchment characteristics, such as land use, types of soil, antecedent moisture condition (AMC). The CN values vary from 0 to 100. The higher the CN value, the greater the runoff factor, C, or runoff potential of the watersheds, and vice versa (Sahu et al., 2010, 2012; Ajmal et al., 2015; Singh et al., 2015a, 2015b; Shi et al., 2009).

2.1. SMA coupled SCS-CN sub-model

This section deals with the development of SMA coupled SCS-CN model as follows.

For Ia = 0, Eq. (4) can be written as:

$$Q = \frac{P^2}{P + S} \tag{6}$$

Assume V_0 represents the soil moisture storage level at the beginning of the storm event and V is the soil moisture storage at any time t. If P and Q are the accumulated rainfall and corresponding runoff, then the following expressions can be easily obtained as (Michel et al., 2005):

$$V = V_0 + P - Q \tag{7}$$

Coupling of Eq. (6) and Eq. (7) yields.

$$V = V_0 + P - \frac{P^2}{P + S} \tag{8}$$

A further simplification of Eq. (8) yields

$$V = \frac{V_0(P + S) + PS}{P + S} \tag{9}$$

Now the simplified form of the GR4J runoff model (Perrin et al., 2003) can be expressed in cumulative form as:

$$Q = (P - PE) \times \left(\frac{V}{S + S_a}\right)^2 \quad P > PE \tag{10}$$

where PE is the potential evapotranspiration and is assumed negligible because the runoff from rainfall usually lasts for an event of sufficiently limited duration. Hence simplification of Eq. (10) yield

$$Q = P \times \left(\frac{V}{S + S_a}\right)^2 \tag{11}$$

Eq. (11) yields Q = P for $V = S + S_a$ as a maximum capacity of V, where S_a is an intrinsic parameter equal to $S_a = (V_0 + I_a)$ (threshold soil moisture). Substituting the expression for V from Eq. (9) into Eq. (11) and simplifying yields

$$Q = P\left[\frac{V_0(P + S) + PS}{(P + S)(S + S_a)}\right]^2 \tag{12}$$

Threshold soil moisture (S_a) is defined as growing linearly with initial soil moisture and initial abstraction, it is mathematically expressed as (Michel et al., 2005):

$$S_a = V_0 + I_a \tag{13}$$

Now, substituting Eq. (13) into Eq. (12) and simplifying yields

$$Q = P\left[\frac{V_0(P + S) + PS}{(P + S)(S + V_0 + I_a)}\right]^2 \tag{14}$$

Simplification of Eq. (14) in the form of runoff coefficient it is an analytically expressed as

$$\frac{Q}{P} = \left[\frac{V_0(P + S) + PS}{(P + S)(S + V_0 + I_a)}\right]^2 \tag{15}$$

Eq. (15) it represent in the form of runoff coefficient (C) for model formulation

Table 1
Hydro-climatic characteristics of the watersheds selected for the study.
Source: Mishra et al. (2006a, 2006b).

S No	Watershed/Size/Location	Climate	Av. Annual Rainfall (mm)	Soils	Av. Slope (Percent)	Land Use (Percent)	Source of Watershed Details/Rainfall-Runoff-Sediment Yield data	No. of events used in the study
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1.	Karso (27.93 km^2) Hazaribagh, Bihar, India (85° 24′ 20″ and 85° 28′ 06″E) (24° 16′ 47″ and 24° 12′ 18″ N)	Sub-humid, tropical	1243	Light sandy loam	7.3	AG = 49 FO = 41 OS = 10	SWCD (1991; 1993; 1994; 1995; 1996)	4
2.	Banha (17.51 km^2) Hazaribagh, Bihar, India (85° 12′ 02″ and 85° 16′ 05″ E) (24° 13′ 50″ and 24° 17′ 00″ N)	Sub-humid, tropical	1277	Sandy loam, Loam, clay loam	3.5	AG = 32 FO = 35 WL = 18 GR = 15	SWCD (1993; 1994; 1995; 1996)	5
3.	Mansara (8.70 km^2) Barabanki, Uttar Pradesh, India (81° 23′ 42″ and 81° 26′ 15″ E) (26° 41′ 04″ and 26° 43′ 15″ N)	Semi-arid, sub-tropical	1021	Loam, sandy loam, sandy	1	AG = 84 OS = 16	SWCD (1994; 1996) Agriculture Dept. (1990)	4
4.	W6 Goodwin Creek (1.25 km^2) Batesville, Mississippi, USA (89° 51′ 44.665″ E) (34° 16′ 16.082″ N)	Humid	1440	Silty, silt loam	5	AG = 35 GR = 23 Idle = 10 FO = 32	Blackmarr (1995); http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/Goodwin.html	2
5.	W7 Goodwin Creek (1.66 km^2) Batesville, Mississippi, USA (89° 51′ 34.479″ E) (34° 15′ 10.342″ N)	Humid	1440	Silty, silt loam	4	AG = 28 GR = 49 Idle = 3 FO = 20	Blackmarr (1995); http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/Goodwin.html	2
6.	W14 Goodwin Creek (1.66 km^2) Batesville, Mississippi, USA (89° 52′ 53.252″ E) (34° 15′ 07.040″ N)	Humid	1440	Silty, silt loam	5	AG = 34 GR = 40 Idle = 9 FO = 17	Blackmarr (1995); http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/Goodwin.html	2

2.2. Nash IUSG sub-model

The suspended sediment dynamics for a linear time distributed watershed is reported by a spatially lumped form of the continuity equation and linear-storage discharge relationship. The first linear reservoir model, it can be analytically expressed as

$$I_{s1}(t) - Q_{s1}(t) = dS_{s1}(t)/dt \quad (16)$$

$$S_{s1}(t) = K_s Q_{s1}(t) \quad (17)$$

In which $I_{s1}(t)$ is the sediment input to the first reservoir (kN/h), $Q_{s1}(t)$ is the sediment discharge (kN/h), $S_{s1}(t)$ is the sediment storage within the reservoir (kN), and K_s is sediment storage coefficient (h). If A_w is the watershed area (km^2), and Y is the mobilized sediment per storm (kN/km^2), the total amount of mobilized sediment $Y_T = A_w Y$ (kN). If it occurs instantaneously and is one unit (i.e. $I_{s1}(t) = 0$), coupling of Eq. (16) and Eq. (17) it is mathematically expressed as

$$Q_{s1}(t) = (1/K_s)\exp(-t/K_s) \quad (18)$$

Eq. (18) indicates that the rate of sediment output from the first reservoir, and analytically from the $n_s th$ reservoir, the resultant output is given as

$$Q_{sn_s}(t) = \frac{1}{K_s \Gamma(n_s)}(t/K_s)^{n_s-1}\exp(-t/K_s) \quad (19)$$

In which Γ() is the Gamma function. For the condition, at $t = t_{ps}$, the time to peak sediment flow rate; $dQ_{sn_s}(t)/dt$=0. Therefore,

$$K_s = t_{ps}/(n_s - 1) \quad (20)$$

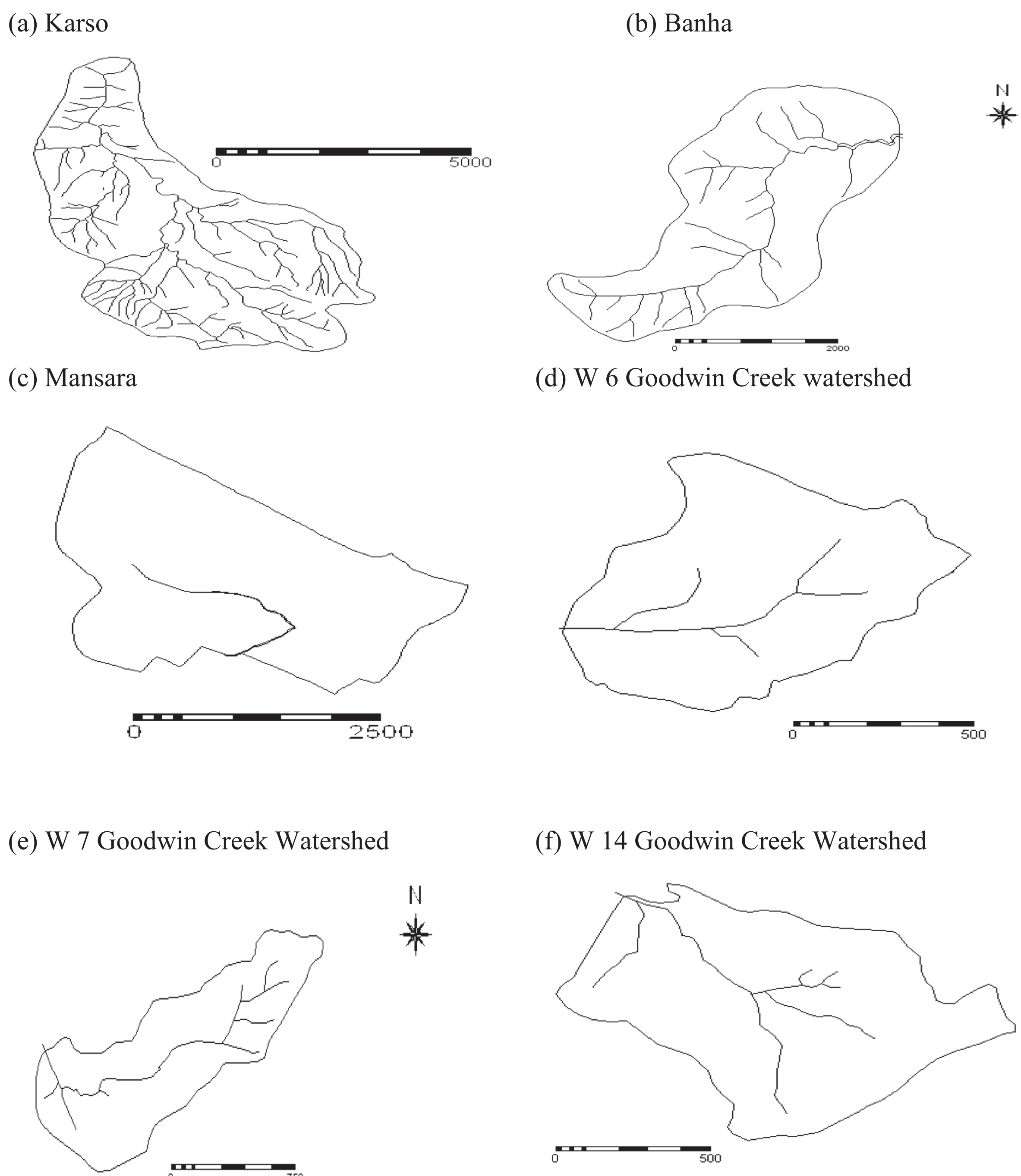


Fig. 1. Study watersheds (a) Karso; (b) Banha; (c) Mansara; (d) W6 Goodwin Creek; (e) W7 Goodwin Creek; (f) W14 Goodwin Creek.

Coupling of Eqs. (19) and (20) its can be analytically expressed as

$$Q_{sn_s}(t) = (n_s - 1)^{n_s}/t_{ps}\Gamma(n_s)[(t/t_{ps})\exp(-t/t_{ps})]^{n_s-1} \quad (21)$$

Eq. (21) shows that the IUSG ordinates at time t in units of h^{-1} (Singh et al., 2008)

From the experience on infiltration tests (Mein and Larson, 1971), $f_0 = i_0$, where i_0 is the uniform rainfall intensity, at time t = 0. The relationship between initial infiltration rate (LT^{-1}) at time t = 0, uniform rainfall intensity, Horton parameter and potential maximum retention can be mathematically expressed as

$$f_0 = i_0 = kS \quad (22)$$

We know that the rainfall is directly proportional to uniform rainfall intensity and time t, it is mathematically expressed as

$$P = i_0 t \quad (23)$$

which is a valid and reasonable assumption of usually derived infiltration rates from field/laboratory tests (Mishra and Singh, 2004). Substituting the value of i_0 into Eq. (22) yield

$$P = kSt \quad (24)$$

where k is Horton parameter, S is potential maximum retention

2.3. Power law

Novotny and Olem (1994) related the runoff coefficient (C) with sediment delivery ratio DR in the power form as below (Singh et al., 2008):

$$DR = \alpha C^{\beta} \quad (25)$$

where α and β are, respectively, the coefficient and exponent of the power relationship, and DR, is a dimensionless ratio of the sediment yield Y to the potential maximum erosion A

$$DR = \frac{Y}{A} \quad (26)$$

The runoff coefficient is defined as the ratio of runoff to rainfall, it is mathematically expressed as

$$C = \frac{Q}{P} \quad (27)$$

A substitution of the expression of Eq. (26) and Eq. (27) into Eq. (25) yields

$$Y = \alpha A\left(\frac{Q}{P}\right)^{\beta} \quad (28)$$

Now, the three sub-models, i.e., SMA-based SCS-CN model (Eq. (15)), Nash IUSG model (Eq. (21)) and Power law (Eq. (28)) will be used to develop proposed sediment graph models for estimation of time distributed sediment yield during a storm event as follows.

3. Formulation of SMA inspired sediment graph models (SMA-SGMs)

Case-I: Substituting initial soil moisture (V_0) = 0 and initial abstraction (I_a) = 0 into Eq. (15) yields

$$\frac{Q}{P} = \left(\frac{P}{P + S}\right)^2 \quad (29)$$

Coupling Eqs. (28) and (29) yields, it is mathematically express for Y as

$$Y = \alpha A[(P/P + s)^2]^{\beta} \quad (30)$$

Substituting the value of P from Eq. (24) into Eq. (30) yield

$$Y = \alpha A[(kts/kts + s)^2]^{\beta} \quad (31)$$

On simplification of Eq. (31) yields

$$Y = \alpha A[((kt)/(kt + 1))^2]^{\beta} \quad (32)$$

Eq. (32) compute the amount of mobilized sediment due to an individual storm event occurring equally over the watershed. Multiplication of Eq. (32) with watershed area Aw gives the expression for total mobilized sediment yield Y_T as:

$$Y_T = \alpha A A_w[((kt)/(kt + 1))^2]^{\beta} \quad (33)$$

The total amount of suspended sediment is routed by using the IUSG concept as discussed above to get the time distribution of sediment at the outlet of the basin. Coupling Eqs. (21) and Eq. (33) results the expression for proposed SMA-sediment graph model (SMA-SGM$_1$) $Q_s(t)$ as:

$$Q_s(t) = [\alpha A A_w[[(kt)/(kt + 1)]^2]^{\beta}(n_s - 1)^{n_s} / t_{ps}\Gamma(n_s)[(t/t_{ps})exp(-t/t_{ps})]^{n_s-1}] \quad (34)$$

Case-II Substituting initial soil moisture (V_0) $\neq 0$ and initial abstraction $I_a = 0$ into Eq. (15) yields, after

Table 2
Characteristics of the storm events.

Name of watershed	Events	q_{ps}(kN/h/kN)	t_{ps}(h)	β_s	Q_s(kN)	Q_{ps}(kN/h)
	August 17, 1991	0.22	6.0	1.36	2868.53	650.81
Karso	July 28, 1991	0.34	2.0	0.67	3180.34	1076.44
	June 14, 1994	0.62	2.0	1.24	1218.74	761.57
	August 30, 1993	0.30	4.0	1.20	9815.50	2970.88
Banha	August 31, 1993	0.62	2.0	1.24	1229.8	759.05
	July 17, 1996	0.72	1.0	0.72	1509.87	1093.42
	June 14, 1994	0.39	2.0	0.78	3053.44	1191.44
	August 20, 1996	0.19	3.0	0.57	1256.03	244.00
	August 30, 1996	0.40	1.0	0.80	2882.62	1159.63
Mansara	August 10, 1994	0.30	3.0	0.90	182.65	54.96
	July 19, 1994	0.40	3.0	1.22	154.78	63.11
	July 25, 1994	0.52	2.0	1.03	183.58	95.46
	August 16, 1994	0.31	2.0	0.63	368.64	117.34
W 6	January 2, 1982	0.84	1.0	0.84	183.82	155.78
	March 15, 1982	0.51	1.0	0.51	20.26	10.45
W 7	May 25, 1982	0.74	1.0	0.74	517.07	383.45
	June 3, 1982	0.76	1.0	0.76	612.86	470.09
W 14	June 16, 1982	0.42	1.0	0.42	4.01	1.72
	Sep 12, 1982	0.58	2.0	1.17	73.4	43.03

Note: q_{ps} = peak sediment flow rate, t_{ps} = time to peak sediment flow rat, β_s = shape factor, Q_s = observed total sediment outflow, Q_{ps} = observed peak sediment flow rate.

Table 3
Optimized parameters of calibration of the proposed SMA-SGMs from six watersheds.

Event	Model	Optimized parameters of the proposed models						
		α	β	k	θ	λ	S	A (kN/km^2)
Karso								
17.08.1991	SMA-SGM_1	0.400	0.317	0.1E−07	–	–	–	121.337
	SMA-SGM_2	0.009	1.00	0.5E−05	0.039	–	73.628	85.400
	SMA-SGM_3	0.300	0.918	0.079	–	0.23	75.199	10000.0
	SMA-SGM_4	0.003	0.890	0.2E−04	0.070	0.04	60.400	50.299
28.07.1991	SMA-SGM_1	0.684	0.303	0.070	–	–	–	188.124
	SMA-SGM_2	0.301	0.261	0.043	0.039	–	34.117	86.282
	SMA-SGM_3	0.003	0.986	0.079	–	0.03	60.00	1134.679
	SMA-SGM_4	0.815	0.500	0.002	0.070	0.04	34.258	185.662
Banha								
31.08.1993	SMA-SGM_1	0.400	0.300	0.4E−04	–	–	–	110.00
	SMA-SGM_2	0.002	0.016	0.079	0.029	–	65.099	68.400
	SMA-SGM_3	0.001	0.029	0.079	–	0.009	20.310	158.085
	SMA-SGM_4	0.001	0.069	0.079	0.004	0.02	56.778	121.684
17.07.1996	SMA-SGM_1	1.00	0.300	0.070	–	–	–	688.219
	SMA-SGM_2	0.077	0.003	0.033	0.050	–	4.349	2328.235
	SMA-SGM_3	0.171	0.029	0.041	–	0.009	10.614	1086.496
	SMA-SGM_4	0.054	0.004	0.079	0.004	0.02	85.099	3251.242
14.06.1994	SMA-SGM_1	1.00	0.512	0.070	–	–	–	590.273
	SMA-SGM_2	0.020	1.00	0.052	0.039	–	65.099	618.301
	SMA-SGM_3	0.042	0.631	0.079	–	0.009	30.651	265.149
	SMA-SGM_4	0.009	0.533	0.079	0.004	0.03	84.821	554.035
Mansara								
10.08.1994	SMA-SGM_1	0.511	0.300	0.7E−03	–	–	–	140.663
	SMA-SGM_2	0.279	0.317	0.2E−04	0.041	–	58.633	522.129
	SMA-SGM_3	0.342	0.400	0.1E−03	–	0.050	37.832	117.918
	SMA-SGM_4	0.332	0.818	0.2E−03	0.050	0.03	2.244	824.331
19.07.1994	SMA-SGM_1	0.400	0.302	0.1E−05	–	–	–	110.00
	SMA-SGM_2	0.051	0.754	0.00	0.049	–	11.943	50.717
	SMA-SGM_3	0.100	0.400	0.5E−05	–	0.050	16.172	184.314
	SMA-SGM_4	0.052	0.994	0.000	0.050	0.03	22.699	217.779
W 6								
02.01.1982	SMA-SGM_1	1.00	0.009	0.059	–	–	–	90.199
	SMA-SGM_2	0.044	0.267	0.079	0.050	–	68.122	155.542
	SMA-SGM_3	0.155	0.039	0.004	–	0.020	54.077	3312.374
	SMA-SGM_4	0.021	0.050	0.079	0.050	0.03	60.200	7164.00
W 7								
25.05.1982	SMA-SGM_1	1.00	0.300	0.070	–	–	–	246.221
	SMA-SGM_2	0.399	0.122	0.079	0.050	–	48.299	1068.076
	SMA-SGM_3	0.586	0.039	0.009	–	0.050	84.600	1247.307
	SMA-SGM_4	0.323	0.500	0.800	0.059	0.30	26.316	151.935
W 14								
16.06.1982	SMA-SGM_1	0.645	0.200	0.8E−04	–	–	–	175.321
	SMA-SGM_2	0.263	0.145	0.079	0.050	–	13.492	112.159
	SMA-SGM_3	0.242	0.200	0.2E−05	–	0.039	28.086	535.146
	SMA-SGM_4	0.423	0.969	0.3E−04	0.070	0.03	18.348	1171.517

simplification of Eq. (15) yields

$$Y = \alpha A[[V_0(P + S) + PS/(P + s)(S + V_0)]^2]^\beta \quad (35)$$

Substituting the value of P from Eq. (24) into Eq. (35) it derived sediment yield

$$Y = \alpha A[[V_0(kst + S) + ks^2t/(kst + s)(S + V_0)]^2]^\beta \quad (36)$$

On simplification of Eq. (36) yield

$$Y = \alpha A\left[\left[\frac{V_0}{S}(kst + S) + ks^2t/(kst + s)\left(1 + \frac{V_0}{S}\right)\right]^2\right]^\beta \quad (37)$$

For a given watershed and storm event, the ratio (θ) for V_0 and S is constant and it varies from 0 to 1 (Michel et al., 2005). Hence the substitution of θ (V_0/S) into Eq. (36) for computation of sediment yield it is expressed as

$$Y = \alpha A[[\theta(1 + kt) + kst/(1 + kt)(1 + \theta)]^2]^\beta \quad (38)$$

Multiplication of watershed area Aw in Eq. (38), Y_T can be an analytically expressed as

$$Y_T = \alpha AA_W[[\theta(1 + kt) + kst/(1 + kt)(1 + \theta)]^2]^\beta \quad (39)$$

The total amount of suspended sediment is routed by using the IUSG concept to get the time distribution of sediment at the basin outlet. Coupling Eq. (21) and Eq. (39) results the expression for proposed SMA-sediment graph model (SMA-SGM_1) $Q_s(t)$ as:

$$Q_S(t) = \left[\begin{array}{c}\alpha AA_W[[\theta(1 + kt) + kst/(1 + Kt)(1 + \theta)]^2]^\beta(n_s - 1)^{n_s} \\ / \ t_{ps}\Gamma(n_s)[(t/t_{ps})\exp(-t/t_{ps})]^{n_s-1}\end{array}\right] \quad (40)$$

Eq. (40) is the proposed sediment graph model (SMA-SGM_2)

Case-III Substituting initial soil moisture $(V_0) = 0$ and $(I_a) \neq 0$ into Eq. (15) yields

$$Y = \alpha A[[PS/(P + S)(S + I_a)]^2]^\beta \quad (41)$$

Substituting the value of P from Eq. (24) and the value of I_a from Eq. (3) into Eq. (41) yield

$$Y = \alpha A[[ks^2t/(kst + s)(S + \lambda S)]^2]^\beta \quad (42)$$

Simplification of Eq. (42) yield

$$Y = \alpha A[[kst/(1 + kt)(1 + \lambda)]^2]^\beta \quad (43)$$

Eq. (43) computes the amount of mobilized sediment. Now multiplication of Eq. (43) with watershed area $A_W$yields, it is an analytically expressed for total mobilized sediment Y_T as

$$Y_T = \alpha AA_w[[kst/(1 + kt)(1 + \lambda)]^2]^\beta \quad (44)$$

The total amount of suspended sediment is routed by using the IUSG concept to get the time distribution of sediment at the basin outlet. Coupling of Eq. (21) and Eq. (44) yields the proposed sediment graph model (SMA-SGM$_3$)$Q_S(t)$ as:

$$Q_s(t) = [\alpha AA_w[((kst)/(1 + kt)(1 + \lambda))^2]^\beta (n_s - 1)^{n_s} / t_{ps}\Gamma(n_s)[(t/t_{ps})\exp(-t/t_{ps})]^{n_s-1}] \quad (45)$$

Eq. (45) is the proposed sediment graph model (SMA-SGM$_3$)

Case-IV Substituting initial soil moisture $(V_0) \neq 0$ *and* initial abstraction $(I_a) \neq 0$ into Eq. (15) yields

$$Y = \alpha A[[V_0(P + S) + PS/(P + S)(S + V_0 + I_a)]^2]^\beta \quad (46)$$

Substituting the value of I_a and P from Eqs. (24) and (3) respectively into Eq. (46) yield

$$Y = \alpha A[[V_0(kst + S) + ks^2t/(kst + S)(S + V_0 + \lambda S)]^2]^\beta \quad (47)$$

Simplification of Eq. (47) yields

$$Y = \alpha A[[\theta(1 + kt) + kst/(1 + kt)(1 + \theta + \lambda)]^2]^\beta \quad (48)$$

Hence the total amount of mobilized sediment $Y_T$can be analytically expressed as

$$Y_T = \alpha AA_w[[\theta(1 + kt) + (kst)/(1 + kt)(1 + \theta + \lambda)]^2]^\beta \quad (49)$$

Coupling of Eq. (21) and Eq. (49) yields

$$Q_S(t) = \left[\begin{array}{c} \alpha AA_W[[\theta(1 + kt) + (kst)/(1 + kt)(1 + \theta + \lambda)]^2]^\beta (n_s - 1)^{n_s} \\ / \, t_{ps}\Gamma(n_s)[(t/t_{ps})exp(-t/t_{ps})]^{n_s-1} \end{array} \right] \quad (50)$$

Eq. (50) is the proposed sediment graph model (SMA-SGM$_4$)

4. Models application

4.1. Study areas

The workability of the proposed SMA-sediment graph models (SMA-SGMs) is tested using the data from six watersheds (Table 1 and Fig. 1). These dataset include three Indian watersheds of Indo-German Bilateral Project (IGBP) on Watershed Management, i.e. Karso watershed (27.93 km^2), Banha watershed (17.51 km^2) in Hazaribagh district, Bihar, India; and Mansara watershed (8.70 km^2) in Barabanki district, Uttar Pradesh, India; and three watersheds of the US Department of Agriculture-Agricultural Research Service (USDA-ARS) such as Treynor, IA, USA; sub-watersheds W 6 (1.25 km^2), W 7 (1.66 km^2) and W 14 (1.66 km^2) Goodwin Creek (GC) Experimental watershed, MS, USA. As shown in Table 1, the study watersheds have varying land use such as

Table 4
Characteristics of observed and computed sediment graph of proposed SMA-SGMs for calibration events from six watersheds.

Name of Watershed	Event	Model	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S(c)	RE (%)	Q_{ps}	Q_{ps}(c)	RE (%)	t_{ps}	t_{ps}(c)	RE (%)	
Karso	17.8.1991 (C)	SMA-SGM$_1$	2868.53	2174.87	24.18	650.81	472.68	27.37	6.0	6.0	0.00	83.44
		SMA-SGM$_2$	2868.53	2295.09	19.99	650.81	515.51	20.79	6.0	6.0	0.00	80.20
		SMA-SGM$_3$	2868.53	1595.76	44.37	650.81	342.62	47.35	6.0	7.0	−16.67	75.47
		SMA-SGM$_4$	2868.53	2239.72	21.92	650.81	501.15	23.00	6.0	6.0	0.00	80.95
	28.7.1991 (C)	SMA-SGM$_1$	3180.34	2005.77	36.93	1076.44	607.29	43.58	2.0	2.0	0.00	70.37
		SMA-SGM$_2$	3180.34	2384.69	25.02	1076.44	729.91	32.19	2.0	2.0	0.00	73.19
		SMA-SGM$_3$	3180.34	2163.59	31.97	1076.44	618.08	42.58	2.0	3.0	−50.00	57.73
		SMA-SGM$_4$	3180.34	2016.01	36.61	1076.44	560.79	47.90	2.0	3.0	−50.00	68.39
Banha	31.8.1993 (C)	SMA-SGM$_1$	1229.08	1121.25	8.77	759.05	663.10	12.64	2.0	2.0	0.00	85.26
		SMA-SGM$_2$	1229.08	1076.94	12.38	759.05	670.86	11.62	2.0	2.0	0.00	88.01
		SMA-SGM$_3$	1229.08	1182.80	3.77	759.05	735.11	3.15	2.0	2.0	0.00	84.75
		SMA-SGM$_4$	1229.08	1094.80	10.93	759.05	677.69	10.72	2.0	2.0	0.00	88.57
	17.7.1996 (C)	SMA-SGM$_1$	1509.87	1289.07	14.62	1093.42	808.27	26.08	1.0	1.0	0.00	92.42
		SMA-SGM$_2$	1509.87	1508.52	0.09	1093.42	1080.40	1.19	1.0	1.0	0.00	99.81
		SMA-SGM$_3$	1509.87	1505.03	0.32	1093.42	1065.38	2.56	1.0	1.0	0.00	87.24
		SMA-SGM$_4$	1509.87	1509.03	0.06	1093.42	1079.20	1.30	1.0	1.0	0.00	99.86
	14.6.1994 (C)	SMA-SGM$_1$	1191.44	3245.77	−6.30	1191.44	1038.40	12.84	2.0	2.0	0.00	95.53
		SMA-SGM$_2$	1191.44	2997.61	1.83	1191.44	1015.58	14.76	2.0	2.0	0.00	93.98
		SMA-SGM$_3$	1191.44	3388.45	−10.97	1191.44	1106.78	7.11	2.0	3.0	−50.00	95.79
		SMA-SGM$_4$	1191.44	3322.37	−8.81	1191.44	1082.22	9.17	2.0	2.0	0.00	95.76
Mansara	10.8.1994 (C)	SMA-SGM$_1$	182.65	162.18	11.21	54.96	44.83	18.43	3.0	3.0	0.00	91.15
		SMA-SGM$_2$	182.65	173.39	5.07	54.96	51.65	6.02	3.0	3.0	0.00	96.08
		SMA-SGM$_3$	182.65	149.28	18.27	54.96	39.59	27.97	3.0	3.0	0.00	85.47
		SMA-SGM$_4$	182.65	173.11	5.22	54.96	51.54	6.22	3.0	3.0	0.00	96.08
	19.7.1994 (C)	SMA-SGM$_1$	154.78	150.02	3.08	63.11	58.16	7.84	3.0	3.0	0.00	78.48
		SMA-SGM$_2$	154.78	154.07	0.46	63.11	62.72	0.62	3.0	3.0	0.00	89.77
		SMA-SGM$_3$	154.78	145.09	6.26	63.11	54.96	12.91	3.0	3.0	0.00	74.13
		SMA-SGM$_4$	154.78	155.56	−0.50	63.11	63.33	−0.35	3.0	3.0	0.00	89.74
W 6	2.1.1982 (C)	SMA-SGM$_1$	183.82	86.59	52.89	155.78	68.87	55.79	1.0	1.0	0.00	65.67
		SMA-SGM$_2$	183.82	176.81	3.81	155.78	130.22	16.41	1.0	1.0	0.00	94.57
		SMA-SGM$_3$	183.82	181.40	1.32	155.78	148.82	4.47	1.0	1.0	0.00	99.27
		SMA-SGM$_4$	183.82	182.98	0.46	155.78	144.00	7.56	1.0	1.0	0.00	98.08
W 7	25.5.1982 (C)	SMA-SGM$_1$	517.07	461.53	10.74	383.45	296.26	22.74	1.0	1.0	0.00	93.76
		SMA-SGM$_2$	517.07	513.27	0.73	383.45	357.16	6.86	1.0	1.0	0.00	99.21
		SMA-SGM$_3$	517.07	513.85	0.62	383.45	368.49	3.90	1.0	1.0	0.00	99.75
		SMA-SGM$_4$	517.07	512.84	0.82	383.45	336.66	12.20	1.0	1.0	0.00	97.39
W 14	16.6.1982 (C)	SMA-SGM$_1$	4.01	3.65	8.98	1.72	1.36	20.93	1.0	1.0	0.00	78.53
		SMA-SGM$_2$	4.01	3.81	4.99	1.72	1.55	9.88	1.0	1.0	0.00	80.29
		SMA-SGM$_3$	4.01	3.83	4.49	1.72	1.43	16.86	1.0	1.0	0.00	78.13
		SMA-SGM$_4$	4.01	3.78	5.74	1.72	1.54	10.47	1.0	1.0	0.00	81.84

agriculture, forest, open scrub, grass/pasture and waste land with varying soil type such as light sandy loam, sandy loam, loam, clay loam, silty, and silt loam. The Karso, Mansara and W6 Goodwin Creek, watersheds are agriculture dominated, whereas, Banha is forest dominated watershed. The watersheds such as W7 Goodwin Creek, and W14 are grass lands/pastures dominated in nature. These watersheds also represent different climate such as sub-humid tropical, semi-humid tropical, semi-arid, sub-tropical and humid.

4.2. Data availability and use

In IGBP watersheds, the USDH-48 sampler and Punjab bottle sampler were used to collect the sediment samples. The rainfall-runoff-sediment data of these watersheds, at time intervals varying from 10 to 60 min for individual events, are available in SWCD (1991, 1993, 1994, 1995 and 1996). The Goodwin Creek Experimental watershed, operated by the National Sedimentation Laboratory (NSL), is organized and instrumented for conducting extensive research on upstream erosion, in stream sediment transport, and watershed hydrology (Blackmarr, 1995). The watershed is divided into fourteen nested sub-watersheds with a flow measuring flume constructed at each of the drainage outlets. Twenty-nine standard recording rain gauges are located within and adjust outside the watersheds. Measurements collected at each site include water stage, accounting of automatically pumped sediment samples, air and water temperature, precipitation and climatological parameters. The runoff, sediment, and precipitation data of Goodwin Creek sub-watersheds are available on WWW at URL: http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/Goodwin.html. In this study, several storms are selected for model calibration and validation of proposed SMA-SGMs. In this study, the selected watersheds fall under different climatic conditions such as sub-humid tropical, semi-arid, sub-tropical and humid climate region of India and USA. It is observed from Table 2 that the watersheds falling under the sub-humid tropical region produced higher total sediment outflow and peak sediment flow rate as compared to semi-arid, sub-tropical and humid climate regions. The characteristics of the storm events of the present study are presented in Table 2.

5. Application, results and discussion

All the four models were calibrated and validated using large data set as discussed above. In this study, ten events were used for calibration and other nine events were used for model validation. The performance of the models was also compared with the existing Bhunya et al. (2010) sediment graph model (hereafter referred as BSGM). The proposed SMA-SGMs parameters are optimized using calibration data set from six watersheds (Table 2)

5.1. Calibration of the sediment graph model

5.1.1. Parameter estimation

The shape parameter (n_s) of Nash based IUSG sub-model was estimated by the relationship given by Bhunya et al. (2003) as

$$n_s = 5.53\beta_s^{1.75} + 1.04 \text{for} 0.01 < \beta_s < 0.35$$

$$n_s = 6.29\beta_s^{1.998} + 1.157 \text{for} \beta_s \geq 0.35 \quad (51)$$

where β_s is an non dimensional parameter defined as the multiplication of peak sediment flow rate (q_{ps}) [kN/h/kN] and time to peak sediment flow rate (t_{ps}) [h]. β_s is also defined as shape factor (Singh, 2000; Singh et al., 2008; Bhunya et al., 2003). Depending upon the hydrologic conditions, the first sediment graph model (SMA-SGM$_1$) has four parameters, viz., α, β, kand n_s; the second sediment graph model (SMA-SGM$_2$) has six parameters, viz., α, β, k, n_s, θ and S; the third sediment graph model (SMA-SGM$_3$) has six parameters, viz., α, β, k, n_s, λ and S; and the fourth sediment graph model (SMA-SGM$_4$) has seven parameters α, β, k, n_s, λ, θ and S, respectively. The model parameters were optimized using the non-linear Marquardt algorithm (Marquardat, 1963) of the least square procedure and given in Table 3.

5.2. Performance evaluation criteria

The performance of the proposed SMA inspired sediment graph models (SMA-SGMs) was evaluated using Nash Sutcliffe efficiency (NSE) and relative error (RE). The analytical expression of NSE can be expressed as (Nash and Sutcliffe, 1970):

$$\left(1 - \frac{\sum_{j=1}^{N}(Q_S - Q_{S(C)})}{\sum_{j=1}^{N}(Q_S - Q_{S(mean)})}\right) \times 100 \quad (52)$$

where NSE is the Nash Sutcliffe Efficiency, N is the number of an event, j is an integer varying from 1 to N, Q_S and$Q_{S(C)}$ are the observed and computed total sediment outflow, respectively, $Q_{S(mean)}$ is the mean of observed sediment outflow rate. Similarly, the expression for RE can be expressed as:

$$RE_{(QS)} = \frac{Q_{S(C)} - Q_S}{Q_{S(C)}} \times 100 \quad (53)$$

$$RE_{(QPS)} = \frac{Q_{PS(C)} - Q_{PS}}{Q_{PS(C)}} \times 100 \quad (54)$$

$$RE(t_{ps}) = \frac{t_{PS(C)} - t_{PS}}{t_{PS(C)}} \times 100 \quad (55)$$

where Q_{PS} and $Q_{PS(C)}$ are observed and computed peak sediment flow rate, respectively; $t_{PS}$and $t_{PS(C)}$ are observed and computed time to peak sediment flow rate, respectively; and RE(t_{ps}), RE$_{(QS)}$, andRE$_{(QPS)}$ are relative error in time to peak sediment flow rate, relative error in peak sediment flow rates and relative error in total sediment outflow rate respectively. The computed values of NSE and RE for SMA-SGM$_1$ to SMA-SGM$_4$ models for all the six watersheds during calibration are given in Table 4.

The computed sediment graphs were found to exhibit a close agreement with the observed sediment graphs for all the storm events as shown in Fig. 2.

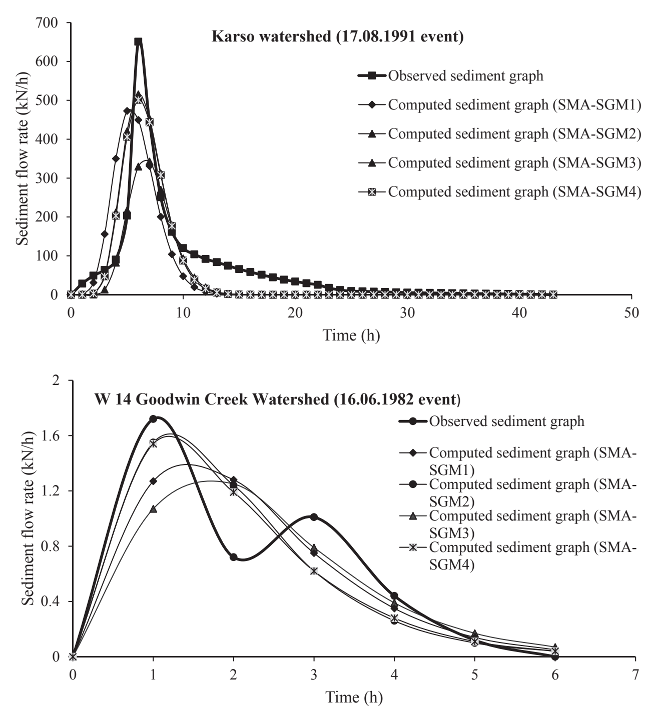


Fig. 2. Comparison of observed and computed sediment graphs for calibration of the models for Karso and W 14 Goodwin Creek watersheds.

Table 5
Optimized parameters of validation of the proposed SMA-SGMs from six watersheds.

Event	Model	Optimized parameters of the proposed models						
		α	β	k	θ	λ	S	A (kN/km^2)
Karso								
14.06.1994	SMA-SGM$_1$	0.520	0.300	0.1E − 05	–	–	–	143.050
	SMA-SGM$_2$	0.012	0.924	0.9E − 05	0.039	–	75.400	2498.782
	SMA-SGM$_3$	0.849	0.654	0.079	–	0.133	75.199	4616.198
	SMA-SGM$_4$	0.020	0.500	0.7E − 04	0.070	0.04	48.135	54.303
14.10.1993	SMA-SGM$_1$	0.400	0.995	0.070	–	–	–	110.00
	SMA-SGM$_2$	0.013	0.243	0.014	0.039	–	21.052	119.571
	SMA-SGM$_3$	0.003	0.808	0.079	–	0.03	10.955	1181.980
	SMA-SGM$_4$	0.320	0.724	0.8E − 03	0.070	0.04	60.400	80.299
Banha								
20.08.1996	SMA-SGM$_1$	0.503	0.553	0.070	–	–	–	137.331
	SMA-SGM$_2$	0.006	0.989	0.067	0.039	–	65.099	198.960
	SMA-SGM$_3$	0.026	0.529	0.053	–	0.009	16.746	162.996
	SMA-SGM$_4$	0.005	0.406	0.045	0.004	0.03	74.362	325.053
30.08.1996	SMA-SGM$_1$	0.837	0.306	0.070	–	–	–	229.673
	SMA-SGM$_2$	0.015	0.954	0.079	0.039	–	65.099	467.828
	SMA-SGM$_3$	0.058	0.313	0.057	–	0.009	40.464	372.886
	SMA-SGM$_4$	0.011	0.384	0.079	0.005	0.03	85.099	667.297
Mansara								
25.07.1994	SMA-SGM$_1$	0.429	0.300	0.4E − 03	–	–	–	135.454
	SMA-SGM$_2$	0.823	0.576	0.000	0.049	–	60.00	50.000
	SMA-SGM$_3$	0.241	0.400	0.3E − 03	–	0.050	26.785	89.351
	SMA-SGM$_4$	0.109	0.580	0.000	0.050	0.03	27.524	384.055
16.08.1994	SMA-SGM$_1$	0.518	0.300	0.043	–	–	–	142.125
	SMA-SGM$_2$	0.256	0.032	0.079	0.040	–	10.001	90.145
	SMA-SGM$_3$	0.284	0.400	0.007	–	0.050	28.204	99.270
	SMA-SGM$_4$	0.980	0.501	0.000	0.050	0.03	32.585	420.236
W 6								
15.03.1982	SMA-SGM$_1$	0.377	0.019	0.059	–	–	–	90.199
	SMA-SGM$_2$	0.029	0.013	0.069	0.004	–	70.897	1012.855
	SMA-SGM$_3$	0.030	0.039	0.057	–	0.020	9.150	1050.478
	SMA-SGM$_4$	0.008	0.050	0.079	0.050	0.03	59.880	2958.733
W 7								
0.3.06.1982	SMA-SGM$_1$	0.917	0.300	0.069	–	–	–	3263.790
	SMA-SGM$_2$	0.452	0.020	0.079	0.050	–	48.299	1209.369
	SMA-SGM$_3$	0.595	0.039	0.019	–	0.050	6.522	1263.593
	SMA-SGM$_4$	0.313	0.500	0.800	0.059	0.30	25.108	157.152
W 14								
12.09.1982	SMA-SGM$_1$	0.402	0.200	0.4E − 05	–	–	–	90.688
	SMA-SGM$_2$	0.020	0.264	0.000	0.050	–	13.361	86.923
	SMA-SGM$_3$	0.203	0.230	0.4E − 06	–	0.039	5.189	509.544
	SMA-SGM$_4$	0.135	0.500	0.000	0.070	0.03	11.942	4096.266

It can be observed from Table 4 that the resulting NSE values vary from 65.67 to 99.56% for SMA-SGM$_1$; from 73.19 to 99.81% for SMA-SGM$_2$, from 57.73% to 99.75% for SMA-SGM$_3$; and from 66.39 to 99.86% for SMA-SGM$_4$, respectively for Karso, Banha, Mansara, W 6, W 7, W 14 watersheds. Similarly, the RE values for total sediment outflow varies from −6.30 to 52.89% for SMA-SGM$_1$; from 0.09 to 27.19% for SMA-SGM$_2$; from −10.97 to 44.37% for SMA-SGM$_3$; and from −8.81 to 36.61% for SMA-SGM$_4$, respectively for Karso, Banha, Mansara, W 6, W 7, W 14 watersheds. The RE values of peak sediment outflow rate varies from −0.29 to 55.79% for SMA-SGM$_1$, from −0.57 to 32.19% for SMA-SGM$_2$, from 1.72 to 47.35% for SMA-SGM$_3$ and from −0.35 to 47.90% for SMA-SGM$_4$, respectively for Karso, Banha, Mansara, W 6, W 7 and W 14 watersheds. The RE values of time to peak sediment outflow varies from –33.33 to 0.00% for SMA-SGM$_1$, from –33.33 to 0.00% for SMA-GM$_2$, from −50.00 to 0.00% for SMA-SGM$_3$ and from −50.00 to 0.00% for SMA-SGM$_4$, respectively for Karso, Banha, Mansara, W 6, W 7 and W 14 watersheds.

5.3. Validation of the model

For validation of the proposed SMA-SGMs models, the parametersα, β, k, n_s, θ, λ and S which depend on land use/land cover, soil characteristics, individual storm events and climatic conditions were estimated for all the six watersheds. It can be observed from Table 5, the parameter α varies from 0.377 to 0.917, from 0.006 to 0.823, from 0.003 to 0.849 and from 0.005 to 0.98 for SMA-SGM$_1$ to SMA-SGM$_4$, respectively. Accordingly, βvaries from 0.019 to 0.995, from 0.013 to 0.989, from 0.039 to 0.808 and from 0.05 to 0.724 for SMA-SGM$_1$ to SMA-SGM$_4$. Similarly k varies from 0.01E to 04 to 0.07, from 0.00 to 0.079, from 4E to 07 to 0.079 and from 0.00 to 0.80 for SMA-SGM$_1$ to SMA-SGM$_4$ respective models. Parameter θ varies from 0.004 to 0.05 and from 0.004 to 0.070 for SMA-SGM$_2$ to SMA-SGM$_4$ each of the models. The computed parameters values are good agreement with Mishra et al. (2006a, 2006b), Singh et al. (2008) and BSGM models. The parameterλ varies from 0.009 to 0.133 and from 0.03 to 0.3 for SMA-SGM$_3$ to SMA-SGM$_4$, respective models, a value of $\lambda = 0.05$ has also been supported for field use (Hawkins et al., 2001), which can, however, vary from 0 to ∞ (Mishra and Singh, 1999, 2003, 2004).

The optimized value of parameter S vary from 10.001 to 75.4 mm, from 5.189 to 75.199 mm and from 11.942 to 85.099 mm, respectively for SMA-SGM2 to SMA-SGM$_4$ models as shown in Table 5. During validation of the proposed models, the NSE varies from 67.89 to 99.56%, 67.11 to 99.56%, 67.57 to 99.52% and 66.81 to 99.53% for SMA-SGM$_1$ to SMA-SGM$_4$ respectively as shown in Table 6. The validation of the models RE of total sediment outflow (kN) it varies from 0.75 to 24.11% for SMA-SGM$_1$, from 0.89 to 27.19% for SMA-SGM$_2$, from 2.82 to 23.81% for SMA-SGM$_3$, from 0.93 to 26.34% for SMA-SGM$_4$ respectively. Therefore the RE of peak sediment outflow rate (kN/h) it varies from −0.29 to 32.93% for SMA-SGM$_1$, from −0.57 to 31.56% for SMA-

Table 6
Characteristics of observed and computed sediment graph for validation of the proposed SMA-SGMs from six watersheds.

Name of Watershed	Event	Models	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S(c)	RE (%)	Q_{ps}	Q_{ps}(c)	RE (%)	t_{ps}	t_{ps}(c)	RE (%)	
Karso	14.6.1994 (V)	SMA-SGM$_1$	1218.74	1209.59	0.75	761.57	687.84	9.68	2.0	2.0	0.00	96.52
		SMASGM$_2$	1218.74	1166.85	4.26	761.57	731.03	4.01	2.0	2.0	0.00	97.12
		SMA-SGM$_3$	1218.74	1125.59	7.64	761.57	633.03	16.88	2.0	2.0	0.00	93.47
		SMA-SGM$_4$	1218.74	1149.16	5.71	761.57	717.62	5.77	2.0	2.0	0.00	97.08
	14.10.1994 (V)	SMA-SGM$_1$	1058.56	939.17	11.28	344.57	274.99	20.19	3.0	4.0	−33.3	83.95
		SMA-SGM$_2$	1058.56	868.23	17.98	344.57	268.86	21.97	3.0	3.0	0.00	79.54
		SMA-SGM$_3$	1058.56	902.35	14.76	344.57	262.04	23.95	3.0	4.0	−33.3	85.11
		SMA-SGM$_4$	1058.56	1016.84	3.96	344.57	278.11	19.29	3.0	3.0	0.00	83.29
Banha	20.8.1996 (V)	SMA-SGM$_1$	1256.03	953.26	24.11	244.00	163.65	32.93	3.0	4.0	−33.3	67.89
		SMA-SGM$_2$	1256.03	914.54	27.19	244.00	167.00	31.56	3.0	4.0	−33.3	67.11
		SMA-SGM$_3$	1256.03	970.71	22.72	244.00	165.49	32.18	3.0	4.0	−33.3	67.57
		SMA-SGM$_4$	1256.03	925.23	26.34	244.00	161.20	33.93	3.0	4.0	−33.3	66.81
	30.8.1996 (V)	SMA-SGM$_1$	2882.62	2502.36	13.19	1159.63	926.27	20.12	2.0	2.0	0.00	89.75
		SMA-SGM$_2$	2882.62	2272.72	21.16	1159.63	830.63	28.37	2.0	2.0	0.00	88.85
		SMA-SGM$_3$	2882.62	2535.95	12.03	1159.63	932.60	19.58	2.0	2.0	0.00	89.77
		SMA-SGM$_4$	2882.62	2365.99	17.92	1159.63	854.15	26.34	2.0	2.0	0.00	89.08
Mansara	25.7.1994 (V)	SMA-SGM$_1$	183.58	164.32	10.49	95.46	80.29	15.89	2.0	2.0	0.00	90.49
		SMA-SGM$_2$	183.58	181.34	0.89	95.46	94.89	0.60	2.0	2.0	0.00	98.18
		SMA-SGM$_3$	183.58	149.56	18.53	95.46	70.76	25.87	2.0	2.0	0.00	84.24
		SMA-SGM$_4$	183.58	181.88	0.93	95.46	94.86	0.63	2.0	2.0	0.00	98.18
	16.8.1994 (V)	SMA-SGM$_1$	368.64	288.25	21.81	117.34	80.39	31.49	2.0	2.0	0.00	80.10
		SMA-SGM$_2$	368.64	291.25	20.99	117.34	92.52	21.15	2.0	2.0	0.00	87.79
		SMA-SGM$_3$	368.64	280.87	23.81	117.34	71.48	39.08	2.0	2.0	0.00	73.96
		SMA-SGM$_4$	368.64	301.63	18.18	117.34	95.82	18.34	2.0	2.0	0.00	87.80
W 6	15.3.1982 (V)	SMA-SGM$_1$	20.26	19.45	4.00	10.45	10.48	−0.29	1.0	1.0	0.00	99.56
		SMA-SGM$_2$	20.26	19.42	4.15	10.45	10.51	−0.57	1.0	1.0	0.00	99.56
		SMA-SGM$_3$	20.26	19.35	4.49	10.45	10.27	1.72	1.0	1.0	0.00	99.52
		SMA-SGM$_4$	20.26	19.80	2.27	10.45	10.45	0.00	1.0	1.0	0.00	99.53
W 7	3.6.1982 (V)	SMA-SGM$_1$	612.86	604.08	1.43	470.09	400.58	14.79	1.0	1.0	0.00	89.09
		SMA-SGM$_2$	612.86	533.42	12.96	470.09	395.41	15.89	1.0	1.0	0.00	93.92
		SMA-SGM$_3$	612.86	595.56	2.82	470.09	437.89	6.85	1.0	1.0	0.00	94.85
		SMA-SGM$_4$	612.86	530.05	13.51	470.09	358.84	23.67	1.0	1.0	0.00	88.33
W 14	12.9.1982 (V)	SMA-SGM$_1$	73.4	68.40	6.81	43.03	39.13	9.06	2.0	2.0	0.00	82.14
		SMA-SGM$_2$	73.4	69.59	5.19	43.03	41.15	4.37	2.0	2.0	0.00	88.32
		SMA-SGM$_3$	73.4	69.04	5.94	43.03	39.24	8.81	2.0	2.0	0.00	81.23
		SMA-SGM$_4$	73.4	71.31	2.85	43.03	42.16	2.02	2.0	2.0	0.00	88.62

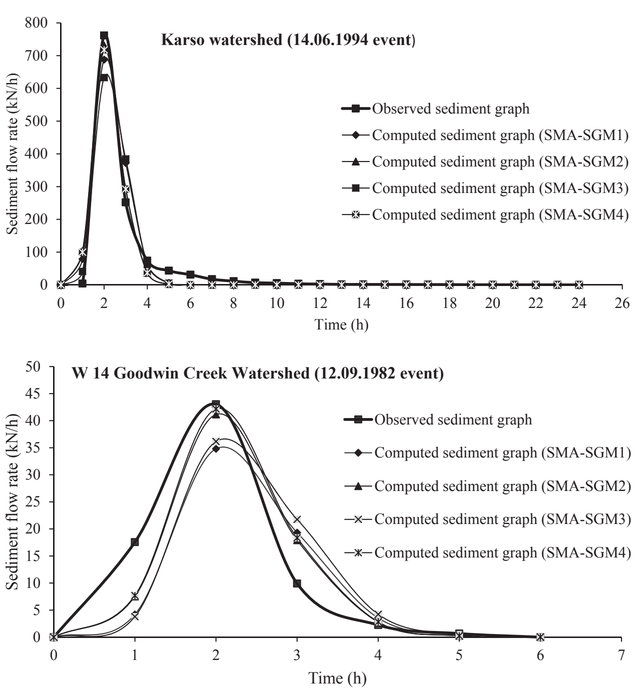


Fig. 3. Comparison of observed and computed sediment graphs for validation of the models for Karso and W 14 watersheds.

SGM$_{2,}$ from 1.72 to 39.08% for SMA-SGM$_3$, from 0.0 to 33.93% for SMA-SGM$_4$ respectively. Similarly the RE of time to peak sediment outflow (h) it varies from −33.33 to 0.0% for SMA-SGM$_1$ to SMA-SGM$_4$ respectively.

The RE of the proposed model and BSGM model it varies from similar to calibration events from all application of the watersheds. It can be observed that a graphical representation of the observed sediment graph and computed sediment graphs also indicated a good agreement between the proposed model and observed sediment graph for the validation events (Fig. 3). Form the computed and observed sediment graphs results are discussed above, it is evident that the proposed sediment graph models for all the events the resulting NSE in both model calibration and validation were reasonably high to indicate the satisfactorily model performance. To demonstrate the applicability of the proposed model to the ungauged watershed, sediment graph were computed for the nineteen storm events with all model parameters are predicted.

It is seen in Table 6, the total computed sediment flow rate and observed sediment flow rate, computed peak sediment flow rate and observed sediment flow rate, computed time to peak and observed time to peak are more accurate results of the observed and computed of the proposed SMA-SGMs. Therefore both calibration and validation events are plotted between line of perfect fit (LPF) of computed sediment yield and observed sediment yield. The closeness of data point in calibration and validation of the model it indicate the good agreement of all applications of the models performance as shown in Fig. 4 (Appendix B, Fig. 4b).

The sediment producing characteristics of the watersheds have been subjected to change by the land use treatments and soil conservation measures taken in the watershed. In sequence to estimate the effect of soil conservation measures on sediment flow. The proposed SMA-SGMs shows in calibration and validation of the models in definite trend in attenuation of crest segments and peak ordinates during the nineteen storm events for successive years. In the present study, several types of SMA-SGMs were developed for the India watershed and USDA-ARS watershed and their efficacies were evaluated using various statistical indices and the corresponding results were then interpreted. The proposed SMA-SGMs have substantial potential for computing sediment graphs (temporal sediment flow rate distribution) as well as total sediment yield from the both gauged and ungauged watersheds. Furthermore, these models will be very useful in those cases, where the

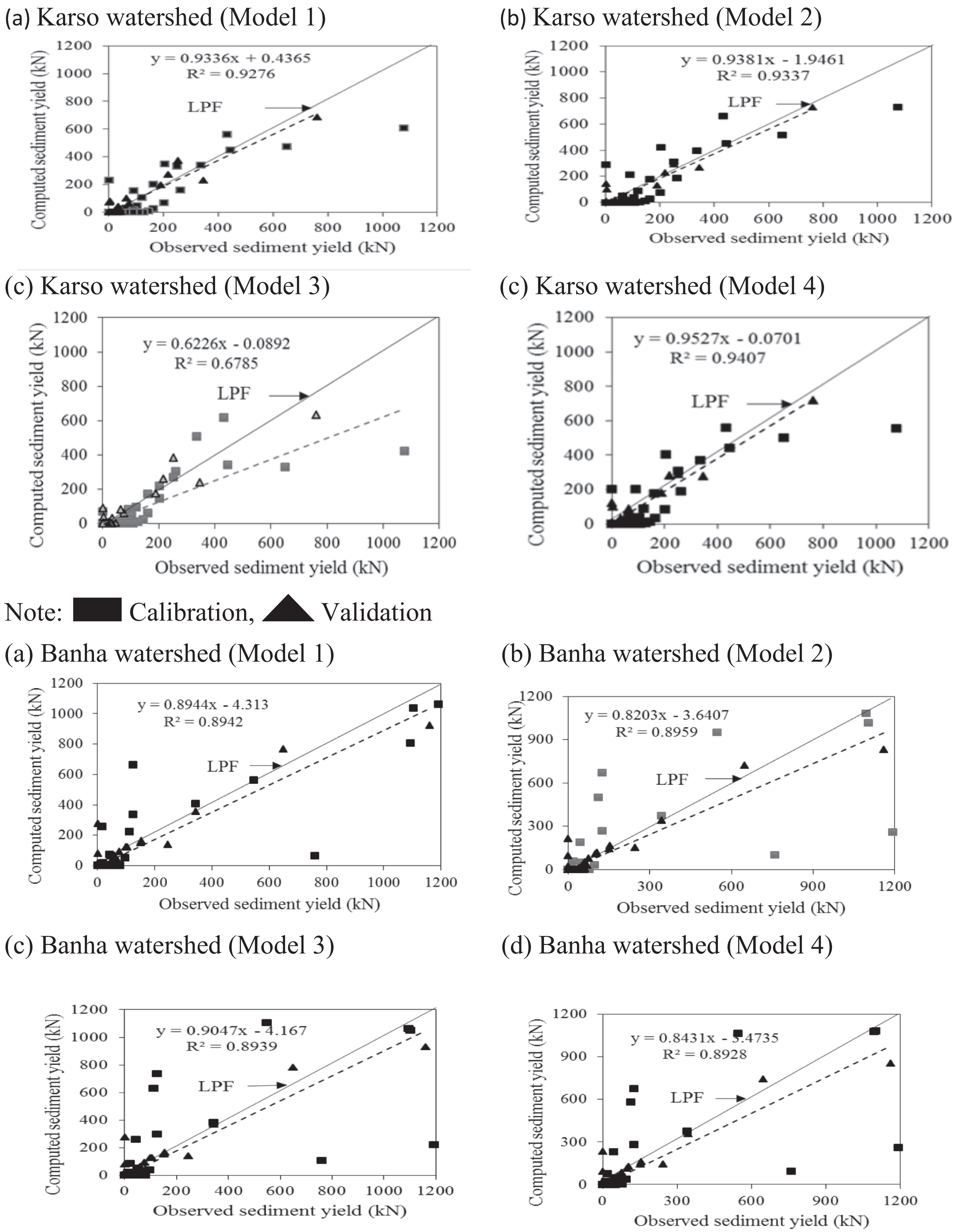
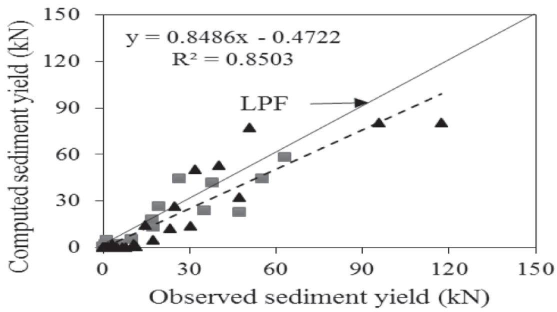
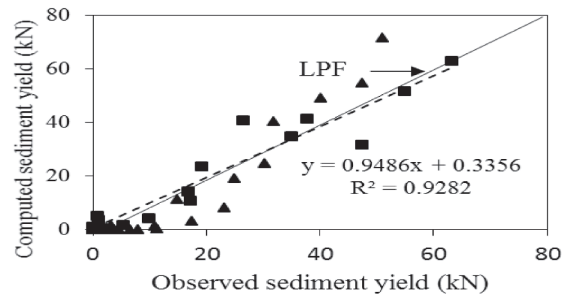


Fig. 4. Comparison of computed and observed sediment yield for calibration and validation of proposed SMA-SGMs.

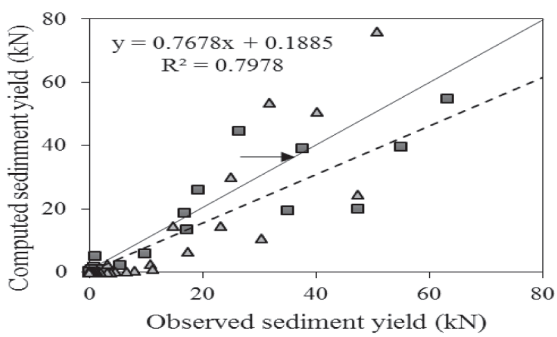
(a) Mansara watershed (Model 1)



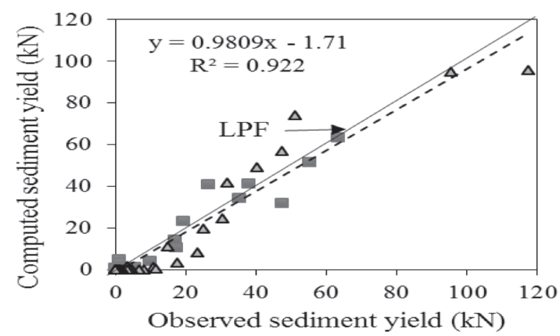
(b) Mansara watershed (Model 2)



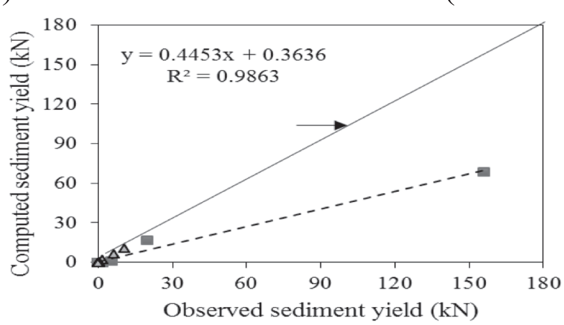
(c) Mansara watershed (Model 3)



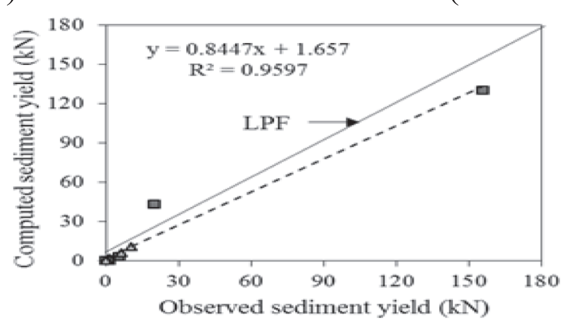
(d) Mansara watershed (Model 4)



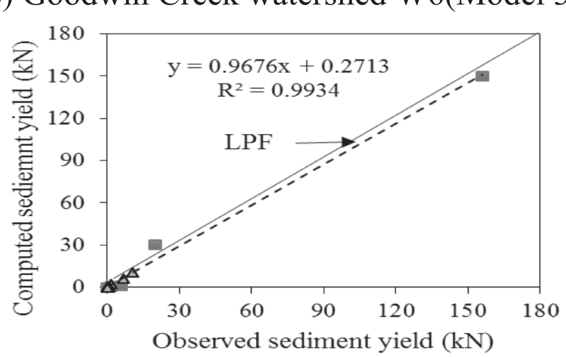
(a) Goodwin Creek watershed W6(Model 1)



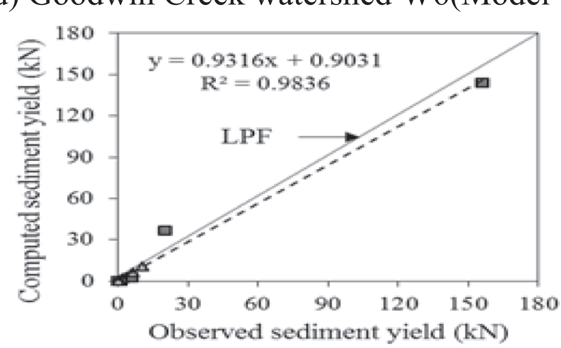
(b) Goodwin Creek watershed W6(Model 2)



(c) Goodwin Creek watershed W6(Model 3)



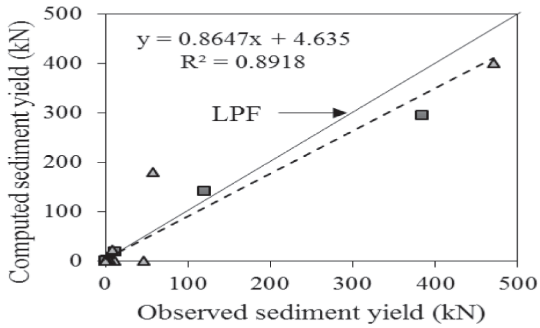
(d) Goodwin Creek watershed W6(Model 4)

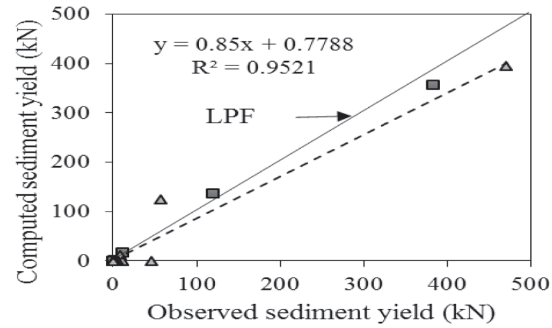


(a) Goodwin Creek watershed W7(Model 1)

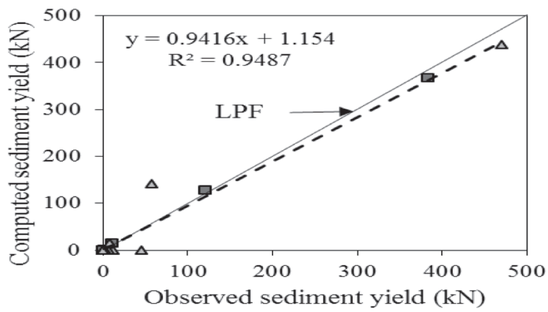
(b) Goodwin Creek watershed W7(Model 2)

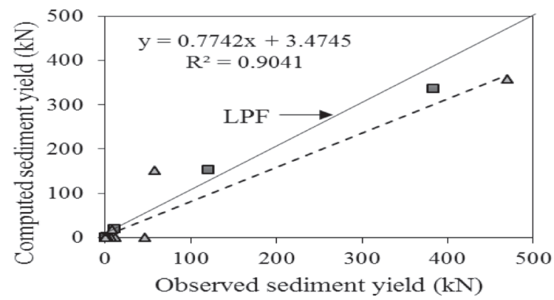
Fig. 4. (*continued*)



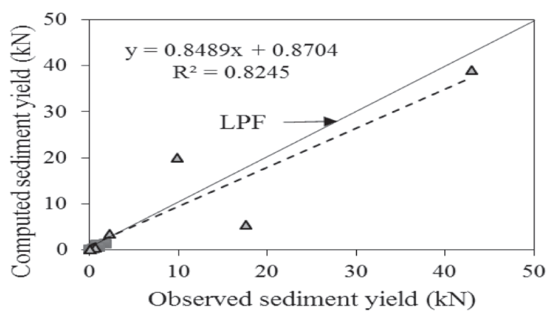


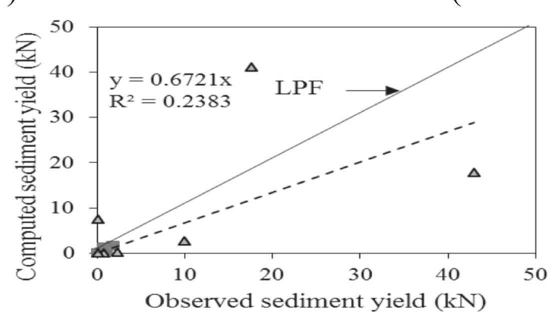
(d) Goodwin Creek watershed W7(Model 3) (d) Goodwin Creek watershed W7(Model 4)



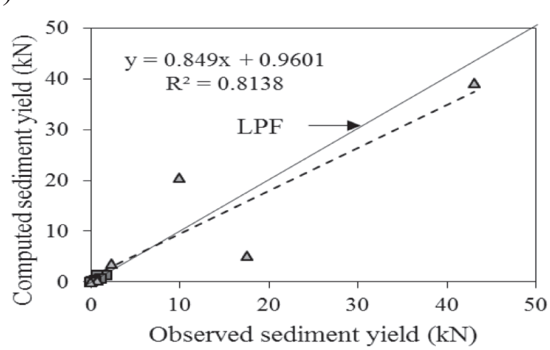


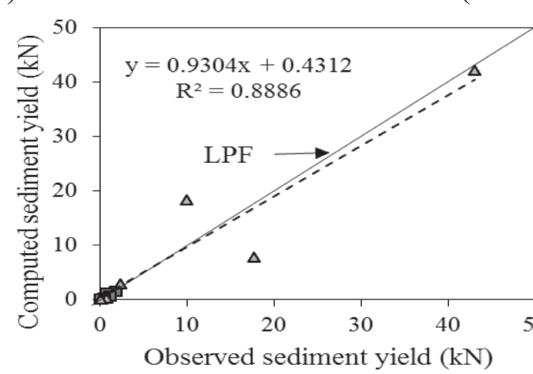
(a) Goodwin Creek watershed W14(Model 1) (b) Goodwin Creek watershedW14(Model 2)





(c) Goodwin Creek watershed W14(Model 3) (d) Goodwin Creek watershed W14(Model 4)





Note: ■ Calibration, ▲ Validation

Fig. 4. (*continued*)

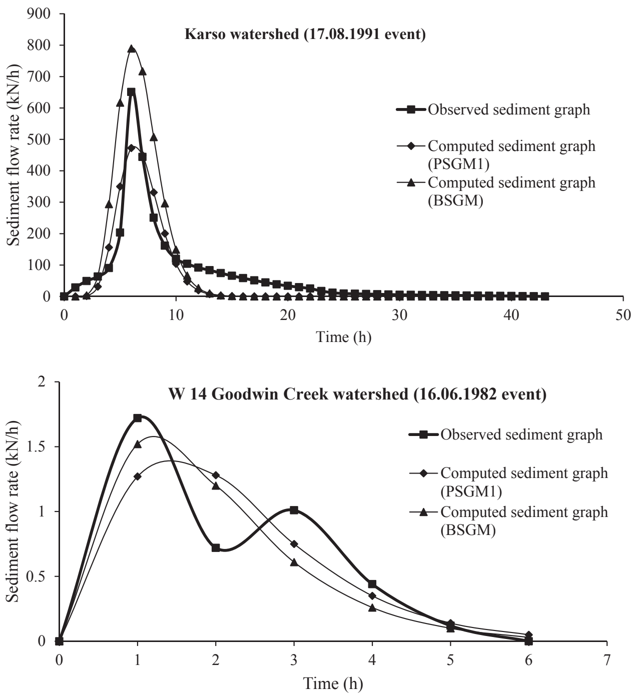


Fig. 5. Comparison between SMA-SGM$_1$ and BSGM models for calibration of the models for Karso and W 14 Goodwin Creek watersheds.

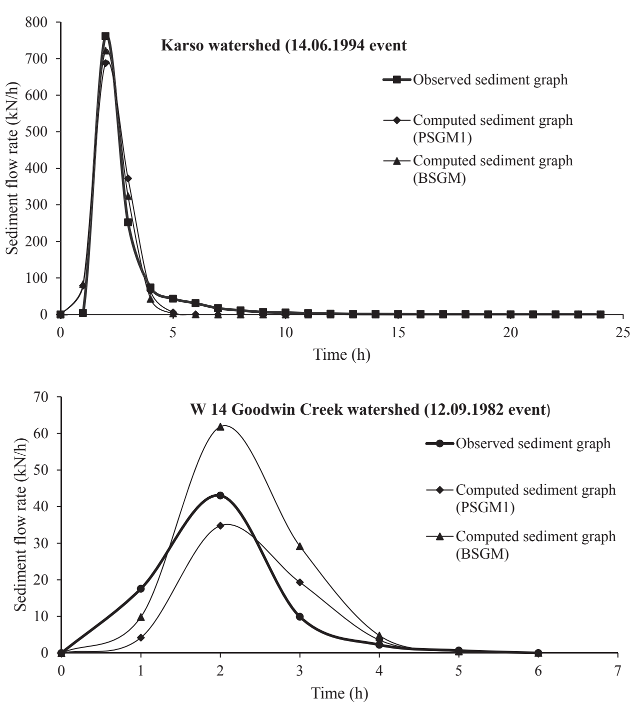


Fig. 6. Comparison between SMA-SGM$_1$ and BSGM models for validation of the models for Karso and W 14 Goodwin Creek watersheds.

larger part of the sediment is generated by few high storm events which are difficult to measure in field conditions. In case of un-gauged watersheds, these models require only the salient points of the sediment graph (in terms of q_{ps} and t_{ps}) which can be derived using the shape factor (βs), n_s and K_s (Singh et al., 2013).

5.4. Comparative analysis between proposed SMA-SGM and BSGM models

The comparative analysis between SMA-SGM and BSGM models the calibration and validation of the models of observed and computed total sediment outflow (kN), observed and computed peak sediment flow rate (kN/h) and observed and computed time to peak sediment outflow (h) is shown in Appendix A (Table 7). It is seen from the computation results of both calibration and validation event (Appendix A, Table 7) the BSGM overestimate the total sediment flow rate and peak sediment flow rate for the Karso, Banha and Mansara watersheds and rest of underestimate for all applications of the watersheds. Therefore visual representation between computed sediment flow rate (kN/h) and observed sediment flow rate from nineteen storm events are plotted as shown in Figs. 5 and 6 (Appendix B, Figs. 5b and 6b).

It can be observed that the proposed SMA-SGMs in calibration events (Fig. 2) it compute higher sediment flow rate (kN/h) as compared to calibration events (Fig. 5) of BSGM. The results obtained from the proposed SMA-SGMs show that these models are more efficient as compared to BSGM. The model performance of calibration and validation events of proposed SMA-SGMs and BSGM are presented in Appendix A (Tables 7A and 8A), therefore it observed that from Appendix A (Table 7A) the proposed SMA-SGM performs consistently better than BSGM for all applications of the storm events. On the basis of statistical indices, the NSE of BSGM is lower than proposed SMA-SGM, similarly the RE of BSGM is higher than proposed SMA-SGMs as shown in Appendix A (Table 8A). Further as can be observed that from Appendix A (Table 8A) the average NSE of proposed SMA-SGMs of Karso, Banha and Mansara watersheds are 83.57%, 86.17% and 85.05% comprising land uses such as forest, agriculture waste land, grass/pasture and open scrub. Similarly, the average NSE of proposed SMA-SGMs of W6, W7 and W14 Goodwin Creek watersheds are 82.16%, 91.42% and 80.33% comprising forest, agriculture, grass/pasture and fallow. Hence it can be observed that in W7 Goodwin Creek watershed, the model performance is higher as compared to other watersheds, it is reason that the W7 Goodwin Creek watershed have maximum grass/ pasture land use cover as compared to other watersheds. The sediment flow rate is varying according to several types of slopes, soil types, landuse/ landcover and hydrological condition of the watershed. The proposed SMA-SGMs produce the higher sediment graphs as well as sediment yield as compare to BSGM. Clay soil have higher resistance to the sediment yield that covers maximum area than the other types of the soil, therefore the clay soil have the more porosity. The above discussion of the soil and land use and hydrological condition of the watershed it evidence of the proposed SMA-SGMs is higher sediment flow rate predict or sediment yield from watersheds as compare to BSGM. It can be observed that from Table 3 (Appendix A, Table 3A), Table 4 (Appendix A, Table 4a) and Fig. 2 (Appendix B, Fig. 2b) that the initial soil moisture (V_0) has major impact and the initial abstraction 'I_a' has the lowest impact on computation of sediment graph as compared to the other parameters of all the four SMA-SGM$_1$ to SMA-SGM$_4$ models.

6. Conclusions

The following conclusions can be drawn from the proposed SMA-SGMs as given below:

1. The analytical development of the sediment graph models is proposed by incorporating simple and highly used models such as SMA, SCS-CN, Nash's, IUSG and Power law for computation of sediment graphs.
2. The proposed model is conceptually and hydrologically sound for computation of sediment graphs as well as the total sediment yield from the small watershed.
3. In validation of the model the resulting NSE of improved sediment graph models it varies from 67.89 to 99.56%, 67.11 to 99.56%, 67.57 to 99.52% and 66.81 to 99.53% for SGM$_1$ to SMA-SGM$_4$respective models and therefore calibration of the model the resulting NSE it varies from 65.67 to 99.56%, 73.19 to 99.81%, 57.73% to 99.75% and 66.39 to 99.86% for SMA-SGM$_1$ to SMA-SGM$_4$.

4. The proposed model performs consistently better than BSGM from all twenty events, the basis of statistical indices the NSE of BSGM is lower than proposed models, and similarly the RE of BSGM is higher than proposed models.

Conflict of interest

We have no conflicts of interest to disclose.

Appendix A

See Tables 7A and 8A.

Acknowledgements

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Table 7A
Comparison between proposed SMA-SGM and Bhunya et al. (2010) models.

Name of Watershed	Event	Model	Proposed SMA-SGMs						Existing Bhunya et al. (2010) model		
			Total sediment out flow (kN)		Peak sediment out flow rate (kN/h)		Time to peak sediment outflow (h)		Total sediment out flow (kN)	Peak sediment out flow rate (kN/h)	Time to peak sediment outflow (h)
			Q_S	$Q_S(c)$	Q_{ps}	$Q_{ps}(c)$	t_{ps}	$t_{ps}(c)$	$Q_S(c)$	$Q_{ps}(c)$	$t_{ps}(c)$
Karso	17.8.1991 (C)	SMA-SGM$_1$	2868.53	2174.87	650.81	472.68	6.0	6.0	3544.92	789.16	6.0
	28.7.1991 (C)	SMA-SGM$_1$	3180.34	2005.77	1076.44	607.29	2.0	2.0	2426.26	743.94	2.0
	14.6.1994 (V)	SMA-SGM$_1$	1218.74	1209.59	761.57	687.84	2.0	2.0	1174.41	721.86	2.0
	14.10.1994 (V)	SMA-SGM$_1$	1058.56	939.17	344.57	274.99	3.0	4.0	1294.59	367.74	3.0
Banha	31.8.1993 (C)	SMA-SGM$_1$	1229.08	1121.25	759.05	663.10	2.0	2.0	1083.13	660.36	2.0
	17.7.1996 (C)	SMA-SGM$_1$	1509.87	1289.07	1093.42	808.27	1.0	1.0	664.63	447.63	1.0
	14.6.1994 (C)	SMA-SGM$_1$	1191.44	3245.77	1191.44	1038.40	2.0	2.0	3245.77	1061.00	2.0
	20.8.1996 (V)	SMA-SGM$_1$	1256.03	953.26	244.00	163.65	3.0	4.0	953.26	163.65	4.0
	30.8.1996 (V)	SMA-SGM$_1$	2882.62	2502.36	1159.63	926.27	2.0	2.0	2497.35	926.55	2.0
Mansara	10.8.1994 (C)	SMA-SGM$_1$	182.65	162.18	54.96	44.83	3.0	3.0	173.69	50.45	3.0
	19.7.1994 (C)	SMA-SGM$_1$	154.78	150.02	63.11	58.16	3.0	3.0	239.21	95.06	3.0
	25.7.1994 (V)	SMA-SGM$_1$	183.58	164.32	95.46	80.29	2.0	2.0	173.90	88.32	2.0
	16.8.1994 (V)	SMA-SGM$_1$	368.64	288.25	117.34	80.39	2.0	2.0	265.61	79.38	2.0
W 6	2.1.1982 (C)	SMA-SGM$_1$	183.82	86.59	155.78	68.87	1.0	1.0	85.94	68.44	1.0
	15.3.1982 (V)	SMA-SGM$_1$	20.26	19.45	10.45	10.48	1.0	1.0	19.48	10.49	1.0
W 7	25.5.1982 (C)	SMA-SGM$_1$	517.07	461.53	383.45	296.26	1.0	1.0	278.84	191.61	1.0
	3.6.1982 (V)	SMA-SGM$_1$	612.86	604.08	470.09	400.58	1.0	1.0	472.87	334.09	1.0
W 14	16.6.1982 (C)	SMA-SGM$_1$	4.01	3.65	1.72	1.36	1.0	1.0	3.72	1.52	1.0
	12.9.1982 (V)	SMA-SGM$_1$	73.4	68.40	43.03	39.13	2.0	2.0	106.12	61.85	2.0

Table 8A
Model performance of the calibration and validation of proposed model and existing Bhunya et al (2010) model from six watersheds.

Name of WS	Event	Model	Proposed SMA-SGMs			NSE (%)	Bhunya et al. (2010) model			NSE (%)
			RE of total sediment outflow (kN)	RE of peak sediment outflow rate (kN/h)	RE of time to peak sediment outflow (h)		RE of total sediment outflow (kN)	RE of sediment outflow rate (kN/h	RE of time to peak sediment outflow (h)	
Karso	17.8.1991 (C)	SMA-SGM$_1$	24.18	27.37	0.00	83.44	−23.58	−66.95	0.0	33.55
	28.7.1991 (C)	SMA-SGM$_1$	36.93	43.58	0.00	70.37	23.71	−22.50	0.0	73.31
	14.6.1994 (V)	SMA-SGM$_1$	0.75	9.68	0.00	96.52	3.64	−4.95	0.0	97.12
	14.10.1994 (V)	SMA-SGM$_1$	11.28	20.19	−33.33	83.95	−22.30	−33.73	0.0	67.52
Banha	31.8.1993 (C)	SMA-SGM$_1$	8.77	12.64	0.00	85.26	11.87	0.41	0.0	87.15
	17.7.1996 (C)	SMA-SGM$_1$	14.62	26.08	0.00	92.42	55.98	44.62	0.0	61.26
	14.6.1994 (C)	SMA-SGM$_1$	−6.30	12.84	0.00	95.53	−6.30	−2.18	0.0	95.69
	20.8.1996 (V)	SMA-SGM$_1$	24.11	32.93	−33.33	67.89	24.11	0.00	−33.33	67.32
	30.8.1996 (V)	SMA-SGM$_1$	13.19	20.12	0.00	89.75	13.37	−0.03	0.0	89.73
Mansara	10.8.1994 (C)	SMA-SGM$_1$	11.21	18.43	0.00	91.15	4.91	−12.54	0.0	95.18
	19.7.1994 (C)	SMA-SGM$_1$	3.08	7.84	0.00	78.48	−54.55	−63.45	0.0	35.93
	25.7.1994 (V)	SMA-SGM$_1$	10.49	15.89	0.00	90.49	5.27	−10.00	0.0	95.40
	16.8.1994 (V)	SMA-SGM$_1$	21.81	31.49	0.00	80.10	27.95	1.26	0.0	83.50
W 6	2.1.19982 (C)	SMA-SGM$_1$	52.89	55.79	0.00	65.67	53.25	0.62	0.0	65.32
	15.3.1982 (V)	SMA-SGM$_1$	4.00	−0.29	0.00	99.56	3.85	−0.10	0.0	99.56
W 7	25.5.1982 (C)	SMA-SGM$_1$	10.74	22.74	0.00	93.76	46.07	35.32	0.0	70.65
	3.6.1982 (V)	SMA-SGM$_1$	1.43	14.79	0.00	89.09	22.84	16.60	0.0	87.59
W 14	16.6.1982 (C)	SMA-SGM$_1$	8.98	20.93	0.00	78.53	7.23	−11.76	0.0	80.53
	12.9.1982 (V)	SMA-SGM$_1$	6.81	9.06	0.00	82.14	−44.58	−58.06	0.0	46.95

Appendix B

See Figs. 2B, 3B, 4B, 5B and 6B .

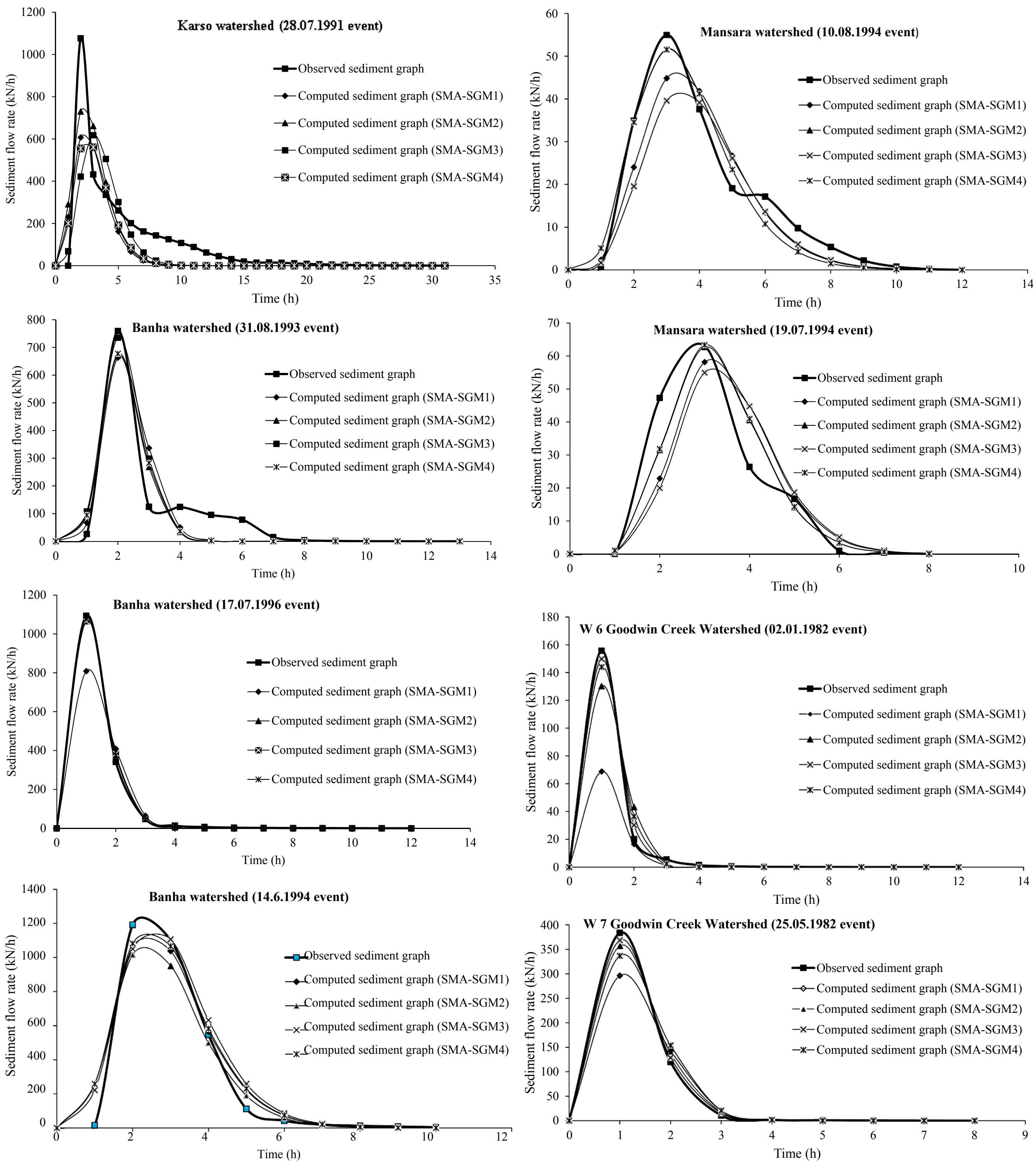

Fig. 2B. Comparison of observed and computed sediment graphs for calibration of the models for Karso, Banha, Mansara, W 6, W 7 and W 14 Goodwin Creek watershed.

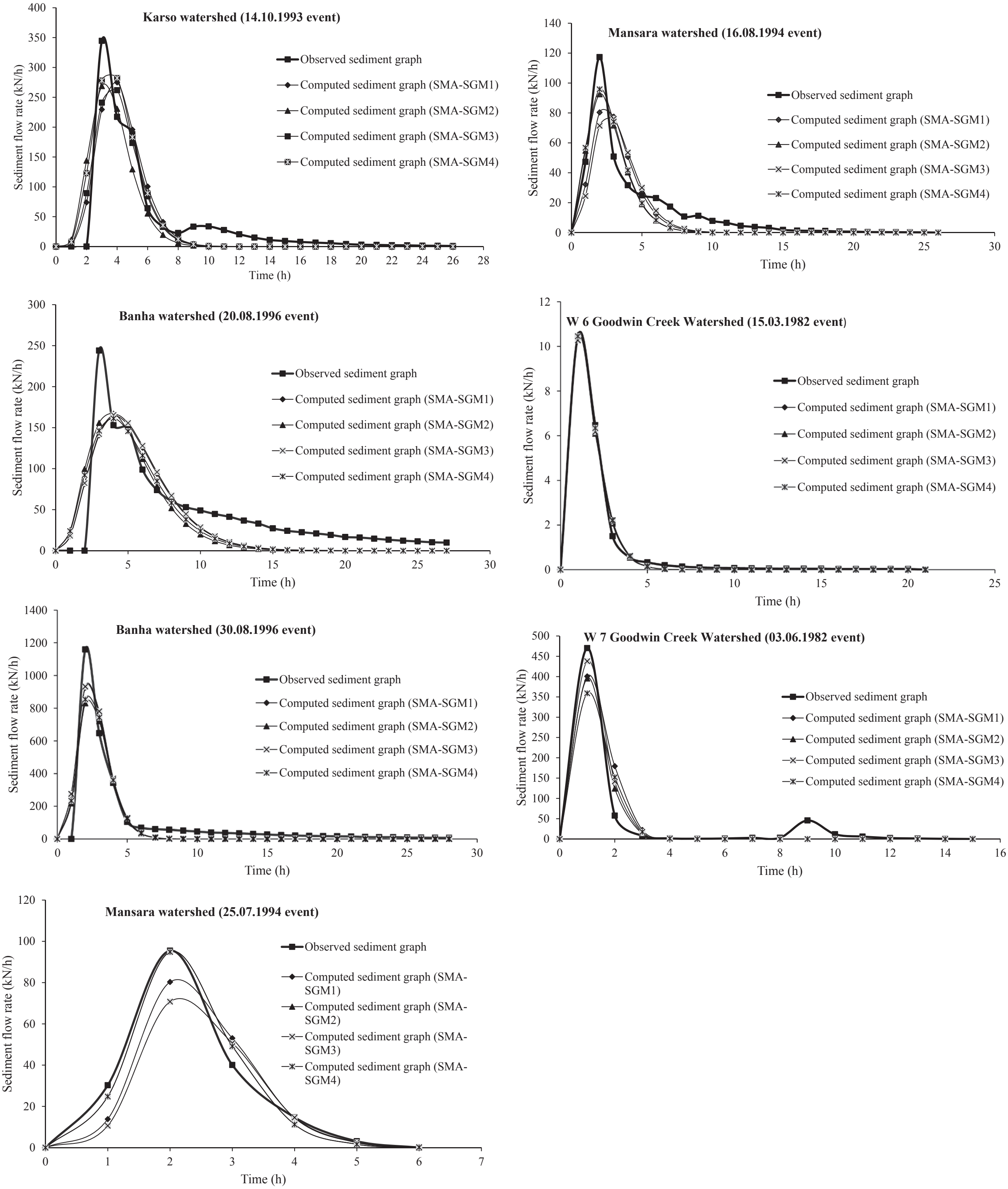

Fig. 3B. Comparison of observed and computed sediment graphs for validation of the models for Karso, Banha, Mansara, W 6, W 7 and W 14 watersheds.

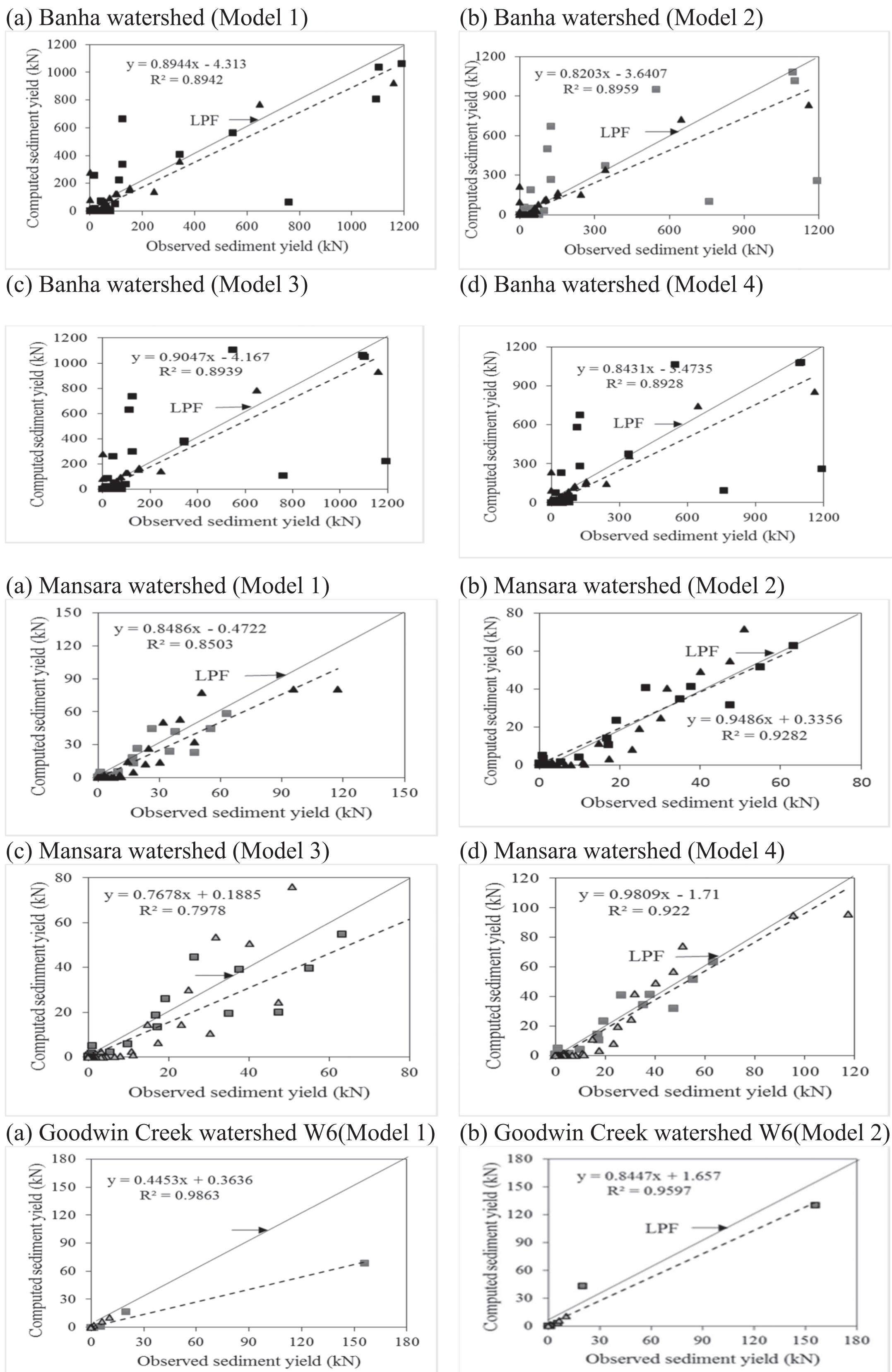

Fig. 4B. Comparison of computed and observed sediment yield for calibration and validation of proposed SMA-SGMs.

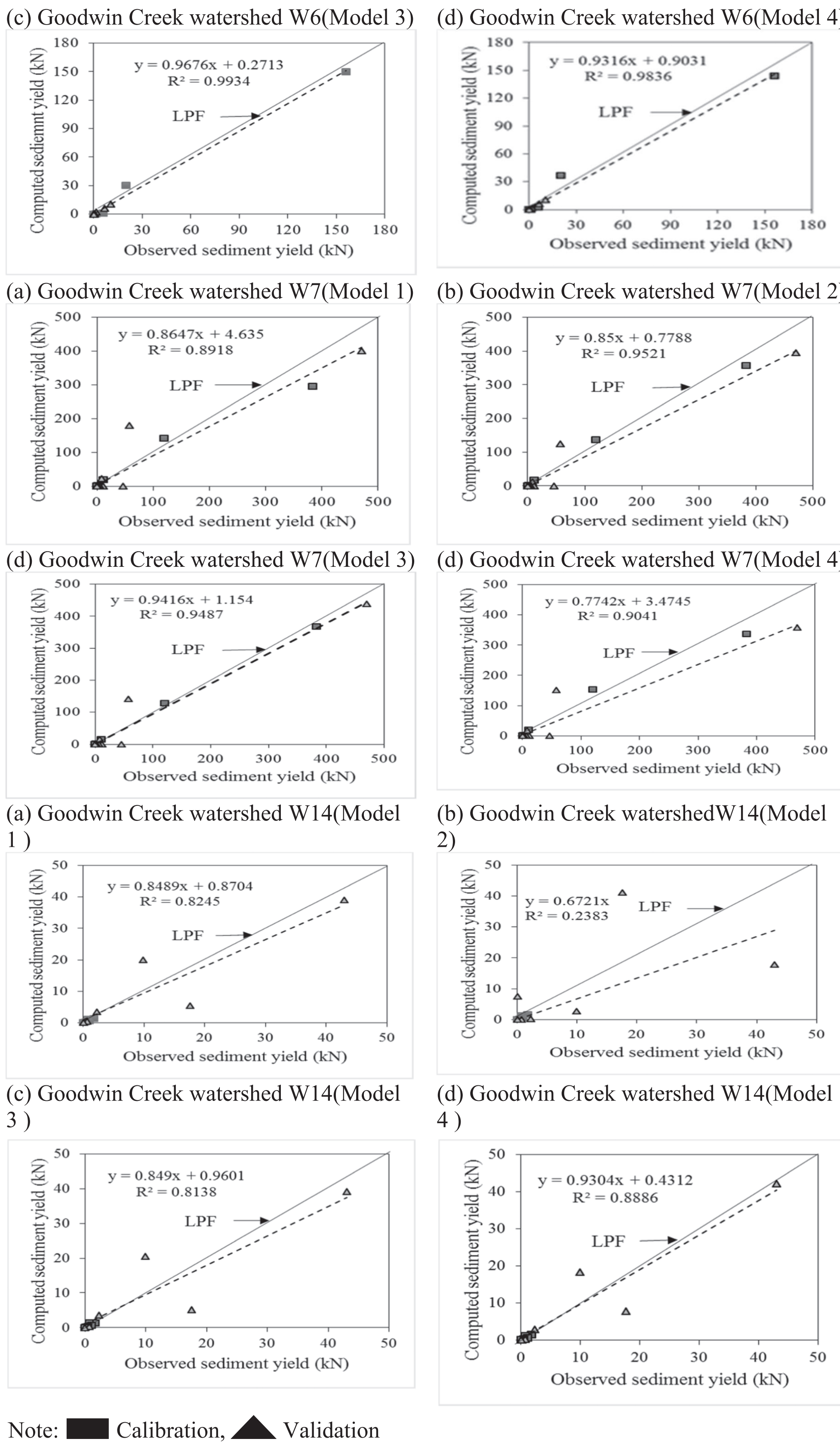

Fig. 4B. (*continued*)

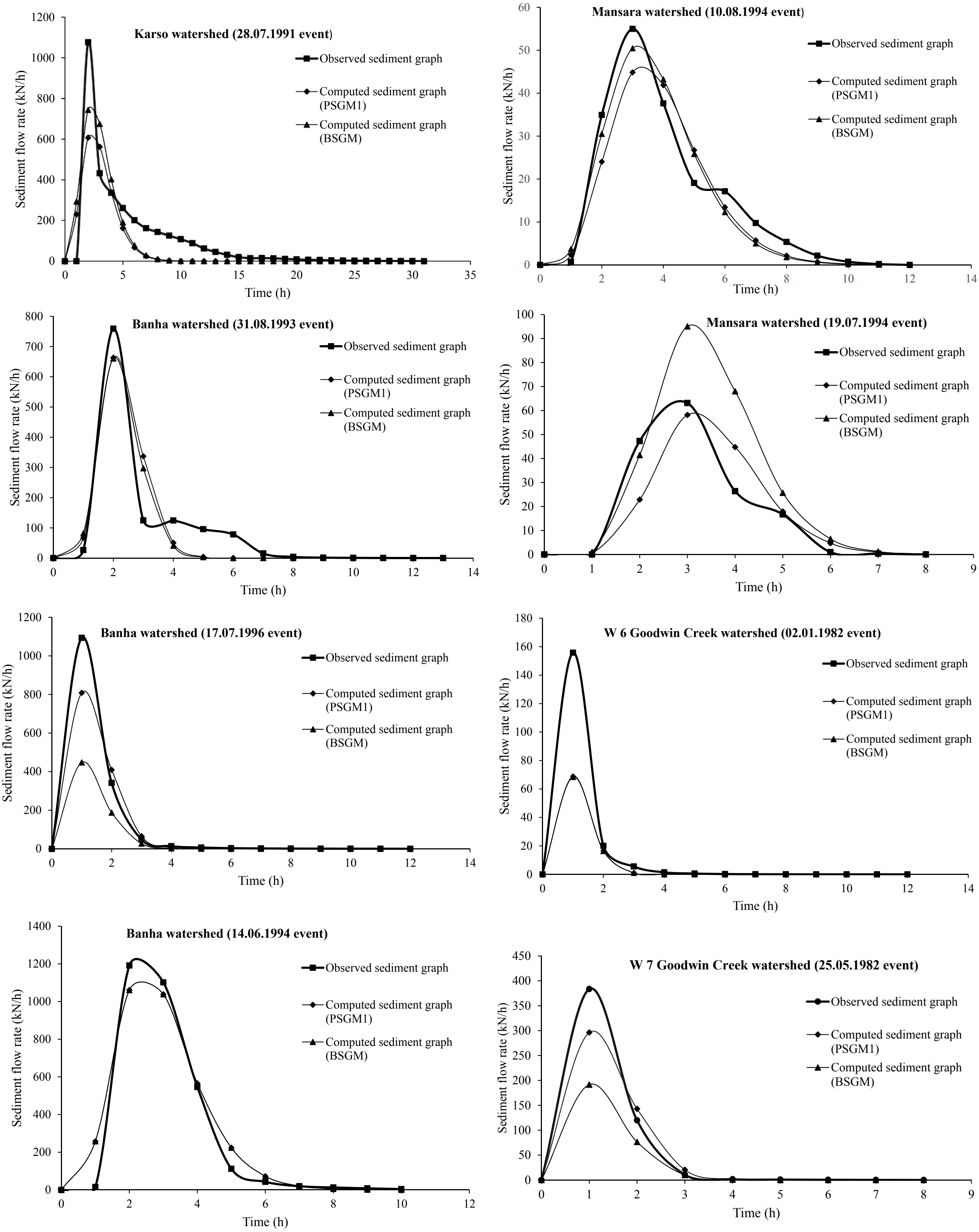

Fig. 5B. Comparison between SMA-SGM_1 and BSGM for calibration of the models for Karso, Banha, Mansara, W 6, W 7 and W 14 Goodwin Creek watersheds.

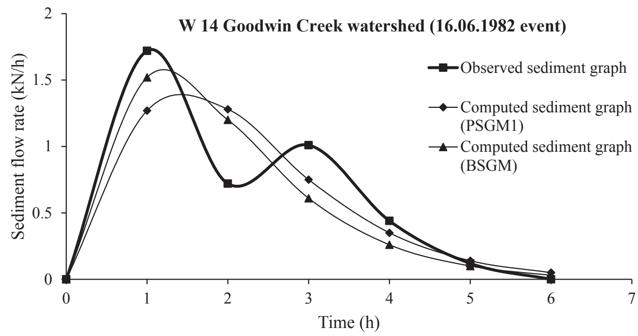

Fig. 5B. (*continued*)

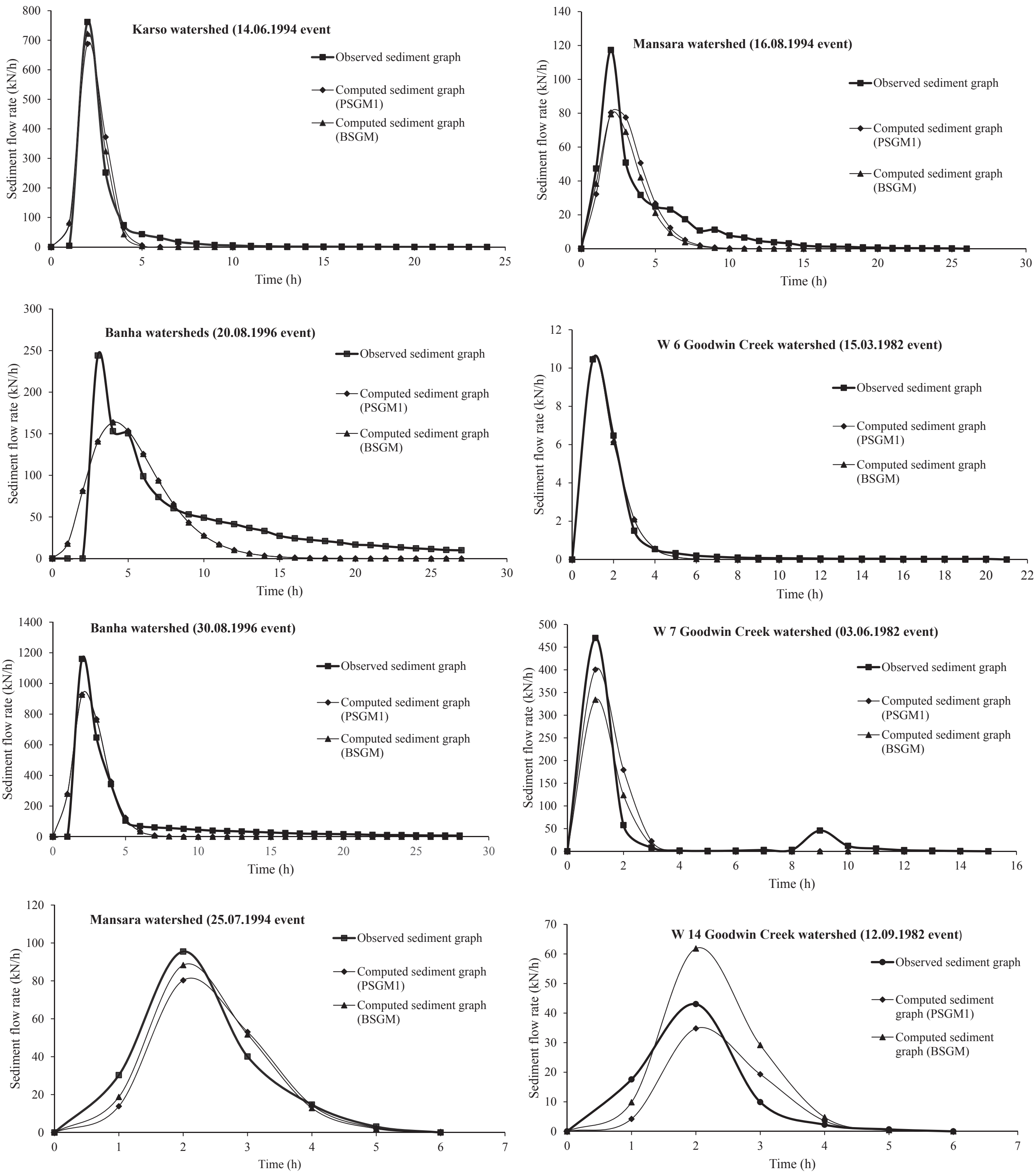

Fig. 6B. Comparison between SMA-SGM$_1$ and BSGM for validation of the models for Karso, Banha, Mansara, W 6, W 7 and W 14 Goodwin Creek watershed.

Appendix C. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.04.077.

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