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Effect of the accuracy of spatial rainfall information on the modeling of water, sediment, and NO_3–N loads at the watershed level

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Abstract

In a given watershed, the accuracy of models in predicting the hydrologic and erosion behavior depends, to a large extent, on the quality of the knowledge in respect of the spatial rainfall. The hydrologic and erosion aspects of rainfall are often discussed without due regard to any resulting improvement in watershed modeling. Thus, there is a real need for streamlining raingauge networks in order to reflect rainfall variability and its effect on the prediction of water, sediment and nutrient fluxes at the watershed scale. In this study, such an impact was analyzed using 9-year data collected at the outlets of two watersheds encompassing a range of climates, surface areas and environmental conditions. The Soil and Water Assessment Tool (SWAT) was applied using as input data that collected from 1 to 15 precipitation gauges per watershed. At both sites the highest densities of raingauges were used for SWAT calibration. The differences between the highest gauge concentration and lower concentrations used for the estimation of sediment loads led to the conclusion that a high gauge concentration is necessary. At both watersheds, predictions using rainfall records from the national service stations produced inaccurate estimations. This was probably because the gauge concentration was too sparse. Finally, the general applicability of these results is proposed by displaying the possibilities of extrapolation to other watersheds or models.

Keywords: Hydrologic modeling; SWAT; Spatial input data; Rainfall

1. Introduction

Predicting water availability, water quality and sediment delivery at the watershed scale have become challenging issues for food supply, food security, human health and natural ecosystems. The ability of environmental models to accurately predict these outputs at a catchment outlet depends to a great extent on how well spatial data describe the relevant characteristics.

For this reason, proper implementation of environmental models require decisions to be made about not

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only the size of the spatial grids such as DEMs, land use and soil map but also the raingauge density.

Several references exist on the impact of the accuracy of the topographical description on the quality of the prediction quality of models. Zhang and Montgomery (1994) suggested a spatial resolution of 10 m to represent hydrologic processes based on simulations with TOPMODEL (Beven and Kirkby, 1979). Blöschl and Sivapalan (1995) stated that high resolution DEMs are required when small-scale processes are dominant. Such an impact of topographic accuracy on the prediction quality of runoff production and sediment yields is due to misestimations of crucial terrain attributes involved in the NRCS curve number technique (USDA, 1972) and Universal Soil Loss Equation (MUSLE) (Williams, 1975).

Land-use resolution was also shown to greatly affect water and sediment outputs. Brown et al. (1993) indicated that predictions using the ANSWERS model exhibited drift anomalies at map resolutions greater than 120-m. Thus, the sensitivity of watershed models to inaccurate rainfall input data is becoming a key issue. Prediction errors due to a necessarily imperfect knowledge of the temporal and spatial distribution of rainfall have already been investigated both theoretically and experimentally. But the hydrological aspects of rainfall are often discussed without reference to the eventual improvement of predictions from watershed models. In the design of raingauge networks, rainfall is also considered independently of watershed modeling. A few recent attempts have been performed to evaluate the impact of raingauge network density on modeling prediction (Faurès et al., 1995; Andréassian et al., 2001; Muttiah and Wurbs, 2002).

Any decision regarding the optimal quantity of raingauges cannot be made without a consideration of the output variables, i.e. water, sediment or nutrients. It is also important to understand not only the level to which model prediction errors are affected by the precision of the input data, but also the mechanisms involved in these errors, which occur under several environmental conditions such as climate and watershed size. Finally, from a practical point of view, the sensitivity analysis of watershed (rainfall-runoff) models based on an imperfect knowledge of rainfall input will allow: (i) the judgment of whether or not they are reliable and robust and; (ii) the optimization of the effort required for data collection and preparation. In particular, we believe that a reliance of high concentrations of gauges (i.e. precise areal rainfall estimates) could unnecessarily increase the effort required for data collection above a given threshold and preparation without any significant benefit in the models accuracy.

Several approaches are proposed for the evaluation of the sensitivity of hydrologic models outputs in relation to the raingauge density. Rainfall data may be first artificially generated at several selected points and afterwards inputted to hydrologic models (e.g. Duncan et al., 1993). The impact of the gauge density is then tested through the comparison of an optimal synthetic output from all raingauge fields to estimations performed with a decreasing number of gauges. Secondly, observed rainfall and observed fluxes may also be used to evaluate the impact of raingauge concentration. The authors' belief is working only with observed data is preferable. Indeed, Andréassian et al. (2001) argued that for practical purposes observed data is preferred: 'sensitivity analysis must be based on the analysis of how rainfall in a specific area is transformed into runoff'. But, in some cases, the differences between scenarios could be of the second order regarding absolute prediction errors leading to interpretation difficulties (Lopez, 1996). Thus, in this study and because the selected hydrological model was previously calibrated at study sites using real data (Chaplot et al., 2004; Saleh et al., 2000), the impact of imperfect rainfall knowledge on the modeling accuracy is evaluated through a semi-empirical approach, consisting of the comparison between a perfect synthetic output and estimations generated using sampled rainfall fields (e.g. Lopez 1996). This approach is considered semi-empirical, in the sense that real data from raingauge networks and estimated watershed outputs are involved.

There is a real need for streamlining raingauge networks in order to capture enough rainfall variability in order to predict water, sediment and nutrient fluxes at the watershed level. The authors' belief is that such results will help to design cost-effective strategies for climatic data collection.

In this study, our main objective was to evaluate the impact of the spatial accuracy of rainfall knowledge by using from 1 to 15 gauges on the simulation of runoff, sediment, and NO_3–N loads. This impact was analyzed using data collected from two different 9-year periods over two watersheds covering a range of climate, rainfall depth, initial soil moisture as well as geologic, soil, vegetation, and land-form conditions. The Soil and Water Assessment Tool (SWAT, Neitsch et al., 2000), an agricultural non-point source pollution model, designed to predict the impact of agricultural management practices on water outflow, sediment, nutrients and pesticides loads for large ungauged sub-basins was applied here since it was previously validated at these two watersheds (Saleh et al., 2000; Chaplot et al., 2004). Over the study periods, synthetic outputs for runoff, NO_3–N and sediment generated from the highest raingauge concentration were compared with estimations from sampled rainfall fields.

2. Materials and methods

2.1. Description of the study sites

Both study watersheds are located in the USA. The first watershed, Walnut Creek (WAC), is located in central Iowa, 5 km to the South-East of Ames (Fig. 1). It is a 51 km^2 area with smooth hillslopes developed in till and loess materials (Table 1). Maximum slope gradients are observed in the Eastern part, close to the outlet, whereas flat areas with numerous closed depressions or potholes characterize the Western part (Fig. 1A). WAC was artificially drained since early 1900 to support corn–soybean rotation. Soils within the watershed varied in their degree of excess of water from well drained to poorly drained and saturated by water. They comprise the familiar Clarion-Nicollet-Webster soil association (Typic Hapludolls-Aquic Hapludolls-Typic Endoaquolls) found throughout Central and North Central Iowa (Hatfield et al., 1999). Cold and dry winters and warm and rainy summers characterize the climate in the region (Table 1). The second watershed, the Bosque upper river watershed (BUR), is located in central Texas. It is a 918 km^2 area stretched out along a North/North-West and South/South-East axis. Composed of shales and limestones, the steepest slopes are observed downstream as a response of the regressive erosion of the Bosque river (Fig. 2A). In 1998, 45% of the surface area of BUR was used as a cattle range and 10% was used for crops (McFarland and Rauck, 1999). Fine sandy loams with sandy clay subsoils dominate soils in the Western part, while elsewhere calcareous clays and clay loams are the predominant soils (Ward et al., 1992). Relatively cold winters and warm summers mark the climate in the region (Table 1). Winter and fall rainfalls are induced by low-intensity, long-duration storms whereas in spring and summer, the majority of rainfall events are thunderstorms.

2.2. The climatic data input for SWAT and the tested scenarios for raingauge concentration

At both watersheds, climatic data over a 9-year period were recorded from one automatic weather station and some additional automatic precipitation gauges, numbered randomly (Figs. 1 and 2). At both catchments we used all the raingauges available, the quantity of which was defined by expert judgment according to USGS standards. Mean areal rainfall was computed according to the Thiessen method. At Walnut Creek, the weather station (gauge number 1) was located to the West of the center of the catchment (Fig. 1). The rainfall amount and intensity were recorded at 30-min intervals. In addition, 14 automatic raingauges were installed throughout the watershed to evaluate the spatial variability of rainfall. Similar equipment was available at the Bosque watershed but only 13 additional automatic raingauges were installed (Fig. 2).

Eight scenarios of gauge concentration were tested within SWAT. These included the use per basin of 1, 2, 3, 5, 7, 9, 11, 13 and 14 or 15 (in the case of WAC only) raingauges. The density of gauges varied from 0.02 to 0.3 km^{-2} at Walnut Creek and from 0.001 to 0.02 km^{-2} at Bosque. In both cases, the scenario involving a single gauge included the gauge number 1. Subsequent scenarios sequentially numbered gauges. Thus, for instance, the scenario taking into account 7 gauges included gauges 1–7. The final scenario used the data from the closest national weather service station, either at Des Moines, 50 km South of WAC or at Waco, 90 km South of BUR.

The spatial distribution of rainfall was determined in SWAT from all precipitation gauges weighted by Thiessen area. Additional input climate variables of maximum and minimum temperatures, solar

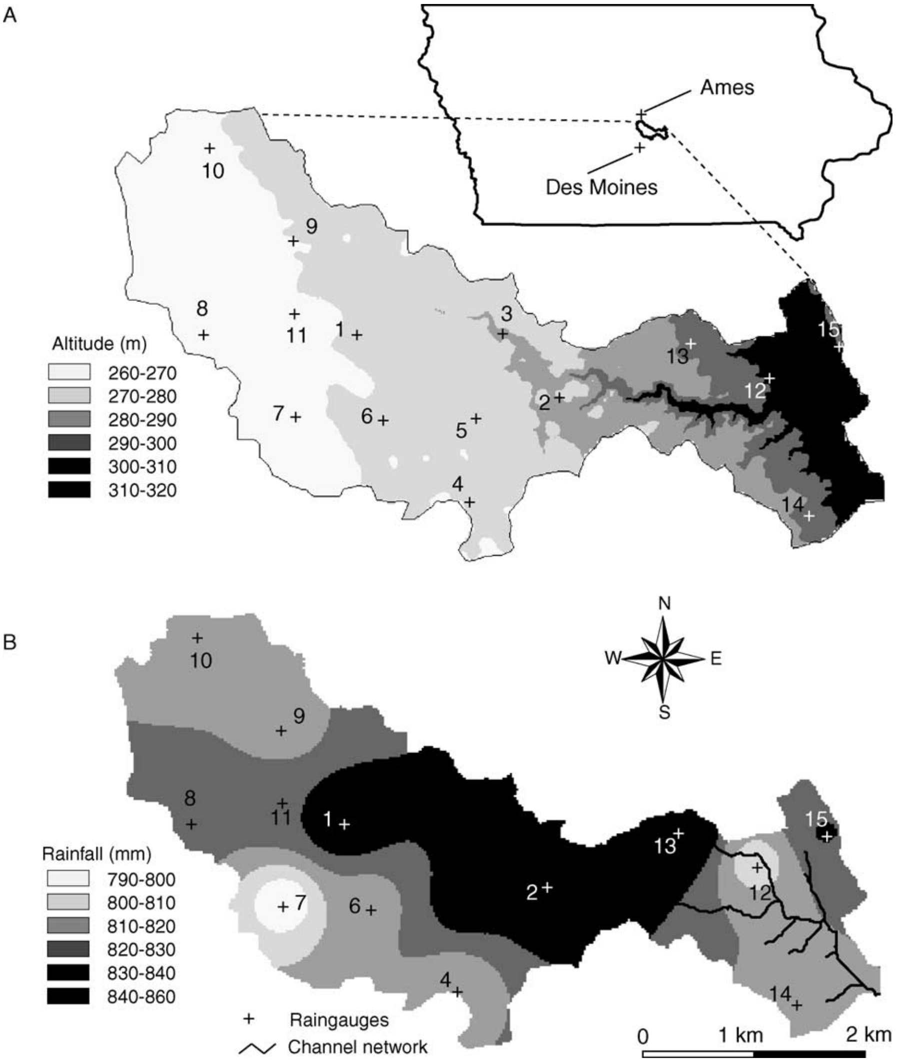

Fig. 1. Digital elevation models with a 30-m mesh of the Walnut Creek watershed, central Iowa (A). Spatial distribution of yearly average rainfall amount over 1991–1998 (B). Position of raingauges and channel network.

Table 1
Main characteristics of the two study catchments: name; location; surface area; main bedrock and surficial material; minimum and maximum altitude; mean slope and its standard deviation; mean annual precipitation, maximum monthly precipitation, and standard deviation of monthly amounts over the last 30 years period; minimum and maximum monthly temperatures

Name	Location	Surface area (km^2)	Bedrock	Altitude (m)		Slope (%)		Precipitation (mm)			Temperature (°C)	
				Min.	Max.	Mean	SD	Mean	Max.	SD	Min.	Max.
Walnut Creek	Iowa	51.3	Tills, loess	263	323	1.5	2.0	818	130	36	−13	29
Bosque	Texas	918.6	Shales, limestones	308	496	4.3	3.5	738	75	30	0	33

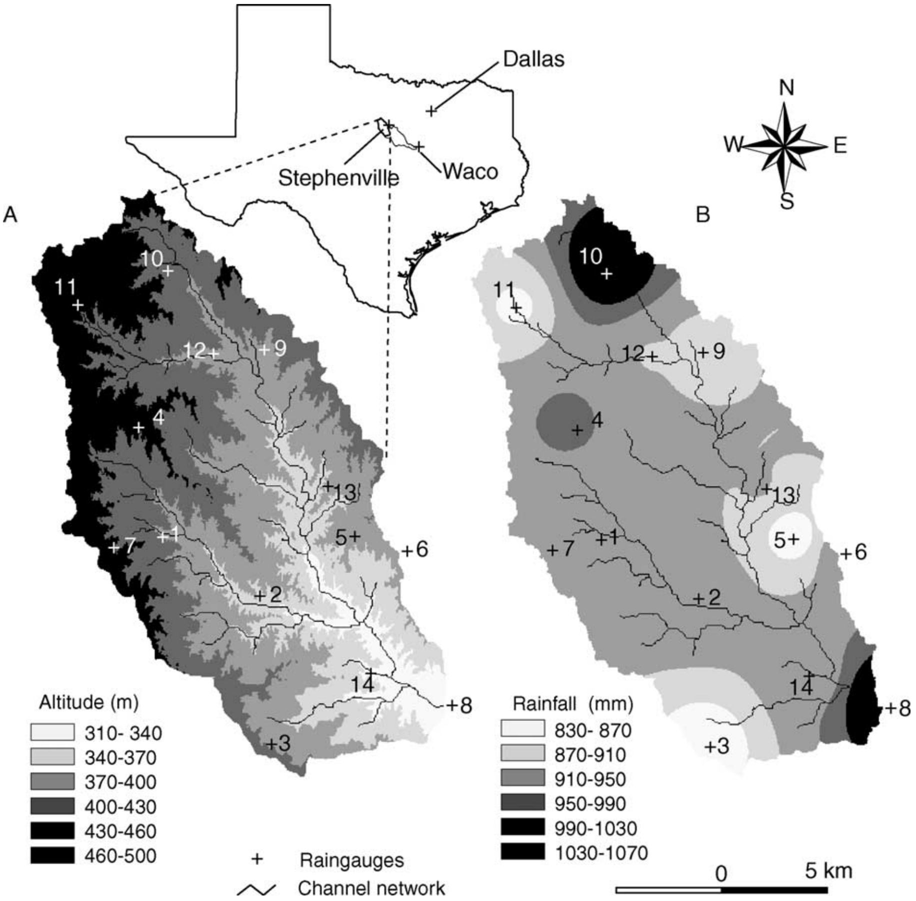

Fig. 2. Digital elevation models with a 30-m mesh of the Bosque watershed, central Texas (A). Spatial distribution of yearly average rainfall amount over 1988–1996 (B). Position of raingauges and channel network.

radiation, relative humidity, and wind speed were provided by the weather station. Since SWAT is based on the concept of hydrologic response units (HRUs) which are portions of a sub-basin that possess unique land use/land management/soil attributes, the input data are estimated at the HRU level. Output loads from each SWAT HRU were calculated separately and then summed together to determine the total loadings from the sub-basin.

2.3. The other spatial input data for SWAT

For each of the watersheds, other input data in SWAT consisted of: (i) a Digital Elevation Model, DEM; (ii) a land use map and, (iii) a soil map. In both cases, the DEM with a 30-m mesh was interpolated from the contour lines of available USGS 7 1/2-min topographic maps. The watersheds were afterwards delineated using the flow direction and the flow accumulation grids computed by Basin3 software (EPA, 2000).

At the Walnut Creek watershed, the land-use map was derived from 1992 aerial photographs. A precise soil map at a 1/50,000 scale generated by the Soil Conservation Service (1984) was used. 1/50,000 maps show units comprising only one soil type. The associated database recorded for each map unit the soil type and its main characteristics (e.g. texture, CEC). At the Bosque catchment, the land use characterization was performed from supervised classification of Landsat Thematic Mapper images of 28 August 1992. The soil map at 1/50,000 was provided by the USDA Natural Resources Conservation Service.

In both cases, a hydrologic response unit (HRU) threshold of 10% was set for the inclusion of each land use type for the SWAT analysis. The two watersheds were subdivided into smaller sub-watersheds, based on the land use categories and the dominant soil types associated with each land use. In addition, SWAT was run at a monthly step by using daily input rainfall.

2.4. Quality assessment of runoff, sediment and NO_3–N predictions

At the two watersheds studied, SWAT was previously calibrated and validated using 9-year records for rainfall at all available gauges and for observed runoff and NO_3–N loads at the outlet. As seen on Fig. 3, the monthly estimated stream water at WAC and BUR matched observed values reasonably well with a coefficient of determination of 0.75 and 0.68, respectively. However, SWAT systematically over-estimated low and medium water discharges at WAC and showed a greater spot scattering over 2 $m^3 s^{-1}$ at BUR. At both catchments SWAT was also shown to accurately predict the monthly outputs of NO_3–N (Saleh et al., 2000; Chaplot et al., 2004).

Assuming accurate estimations of runoff, sediment and NO_3–N at the two watersheds, estimated loads using the regional weather stations and decreasing gauge densities were compared to a reference output generated from all available gauges (15 in the case of WAC catchment and 14 in the case of BUR watershed). The quality assessment for each study variable (Var) such as runoff or sediment loads was performed using several statistical parameters: the mean difference (MD), the mean absolute difference (MAD), the root mean standard difference (RMSD) between estimations $(\mathrm{Var})^*$ and observations (Var) (Eqs. (1)–(3)). In addition, we considered p (Eq. (4)), the standard deviation of MAD

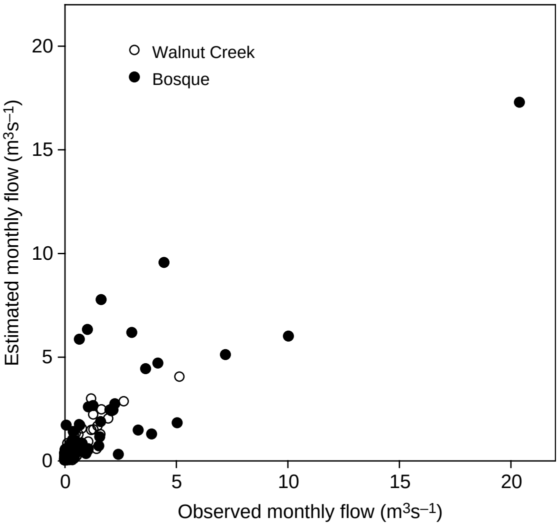

Fig. 3. Monthly predicted versus observed water fluxes at the outlet of the Bosque and the Walnut Creek watersheds.

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}[(\mathrm{Var})^* - \mathrm{Var}] \quad (1)$$

$$\mathrm{MAD} = \frac{\sum_{i=1}^{n} |(\mathrm{Var})^* - \mathrm{Var}|}{n} \quad (2)$$

$$\mathrm{RMSD} = \left\{\frac{1}{n}\sum_{i=1}^{n}[(\mathrm{Var})^* - \mathrm{Var}]^2\right\}^{0.5} \quad (3)$$

$$p = \sqrt{\frac{\sum_{i=1}^{n}(|(\mathrm{Var})^* - \mathrm{Var}| - \mathrm{MAD})^2}{n}} \quad (4)$$

MAD, MD and RMSD decrease with increasing regression model accuracy. The RMSD expresses the degree to which the interpolated value differs from the reference value. The parameter p evaluates the extent to which errors are normally distributed around the zero value.

3. Results

3.1. The spatial variability of rainfall at the two watersheds

Yearly rainfalls over 1991–1998 period for the 15 study raingauges (w1–w15) of Walnut Creek watershed are presented in Table 2. The average yearly rainfall amount over the period was 828 mm with values from 706 in 1995 to 1278 in 1993. The mean annual rainfall amount ranged from 792 mm for w7 to 854 for w13. As shown in Fig. 1B, maximum average yearly amounts computed from the 15 gauges occurred in the central part of the catchment.

Table 2
Yearly rainfall amount (mm) over the 1991–1998 period for the 15 study raingauges of the Walnut Creek watershed, central Iowa

	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	w11	w12	w13	w14	w15	Mean	SD
1991	941	903	876	838	850	864	855	881	856	825	859	900	901	903	902	877	32
1992	784	805	825	815	806	820	775	800	777	797	756	818	826	798	823	802	21
1993	1244	1231	1245	1201	1235	1334	1224	1293	1319	1276	1340	1257	1340	1321	1310	1278	47
1994	607	595	690	668	707	613	588	666	642	675	642	553	675	629	629	639	42
1995	710	754	699	709	745	649	671	713	696	732	693	688	734	705	695	706	28
1996	873	898	846	814	861	720	798	825	780	887	779	792	849	783	821	822	48
1997	670	644	622	611	650	559	595	645	620	651	616	581	576	527	547	607	42
1998	1038	1021	981	917	947	993	890	875	853	808	856	870	931	919	944	923	66
1999	800	800	781	752	759	798	729	769	796	851	800	799	855	776	838	793	35
Mean	852	850	840	814	840	817	792	830	815	833	816	807	854	818	834	828	39
SD	199	194	187	173	173	236	193	193	207	184	215	208	215	226	220		

At the BUR watershed, the mean rainfall amount over the 9-year period was much higher with 943 mm and with a greater standard deviation (Table 3). Yearly amounts ranged from 732 mm in 1988 to 1135 in 1994 with average yearly amounts of 829 mm at b14 and 1075 mm at b7. Maximum average yearly rainfall amounts characterized the watershed outlet and Northern upper limit (Fig. 2B). Greater differences between raingauges existed at the BUR watershed than at the WAC (Tables 2 and 3).

3.2. Impact of the spatial variability of rainfall knowledge on SWAT prediction accuracy

Assuming realistic estimations of water quantity and quality, SWAT is used here as a decision tool to test the impact of the raingauge concentration on the prediction accuracy of water, sediment and NO_3–N loads. At Walnut Creek, simulated runoff fluxes ranged from 0 to 2.7 $m^3 s^{-1}$. From the highest raingauge density, two runoff peaks of more than 1.5 $m^3 s^{-1}$ were simulated during the study period, in July 2003 and June 1998 (Fig. 4). Flow discharge peaks of the second order (between 0.4 and 1.2 $m^3 s^{-1}$) are observed in late spring and occasionally in summer during rainy periods. Minimum discharge (<0.02 $m^3 s^{-1}$) each year mostly occurred in summer or in fall under low rainfall conditions. At Bosque upper river, estimated runoff fluxes ranged between 1.5 $m^3 s^{-1}$ in winter 1995–1996 and 34 $m^3 s^{-1}$ in May 1994 (Fig. 5).

The mean runoff flux using the highest gauge density was 0.36 $m^3 s^{-1}$ at the outlet of WAC and 8.1 $m^3 s^{-1}$ at BUR mouth (Tables 4 and 5). At both sites, mean values varied only slightly with decreasing raingauge concentration. At Walnut Creek, the mean monthly runoff flux over 1991–1998 ranged from 0.36 $m^3 s^{-1}$ with 15 gauges to 0.43 $m^3 s^{-1}$ with 2 or

Table 3
Yearly rainfall amount (mm) over the 1988–1996 period for the 14 study raingauges of the Bosque watershed, central Texas

	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	Mean	SD
1988	742	736	723	732	741	741	721	734	729	688	729	722	802	715	732	24
1989	1024	1016	1000	1011	1023	1023	998	1013	1008	985	1008	999	1099	990	1014	27
1990	1021	1013	997	1008	1020	1020	995	1010	1005	944	1005	996	1096	987	1008	32
1991	1108	1100	1084	1095	1107	1107	1082	1097	1092	1072	1192	1185	1183	1074	1113	42
1992	802	794	778	789	1029	801	776	791	786	781	1010	882	877	768	833	86
1993	753	757	729	844	908	740	838	729	859	872	717	591	747	735	773	83
1994	1154	1119	1164	995	1190	996	1307	1138	1243	1299	1128	957	1163	1030	1135	109
1995	939	859	955	676	1127	903	1278	920	820	753	1016	751	1010	571	898	183
1996	842	889	747	796	992	842	1167	1034	916	970	812	877	995	794	905	115
Mean	933	920	910	866	1059	898	1075	952	953	958	979	874	996	829	943	70
SD	166	154	186	153	102	135	223	167	178	205	182	199	167	190		

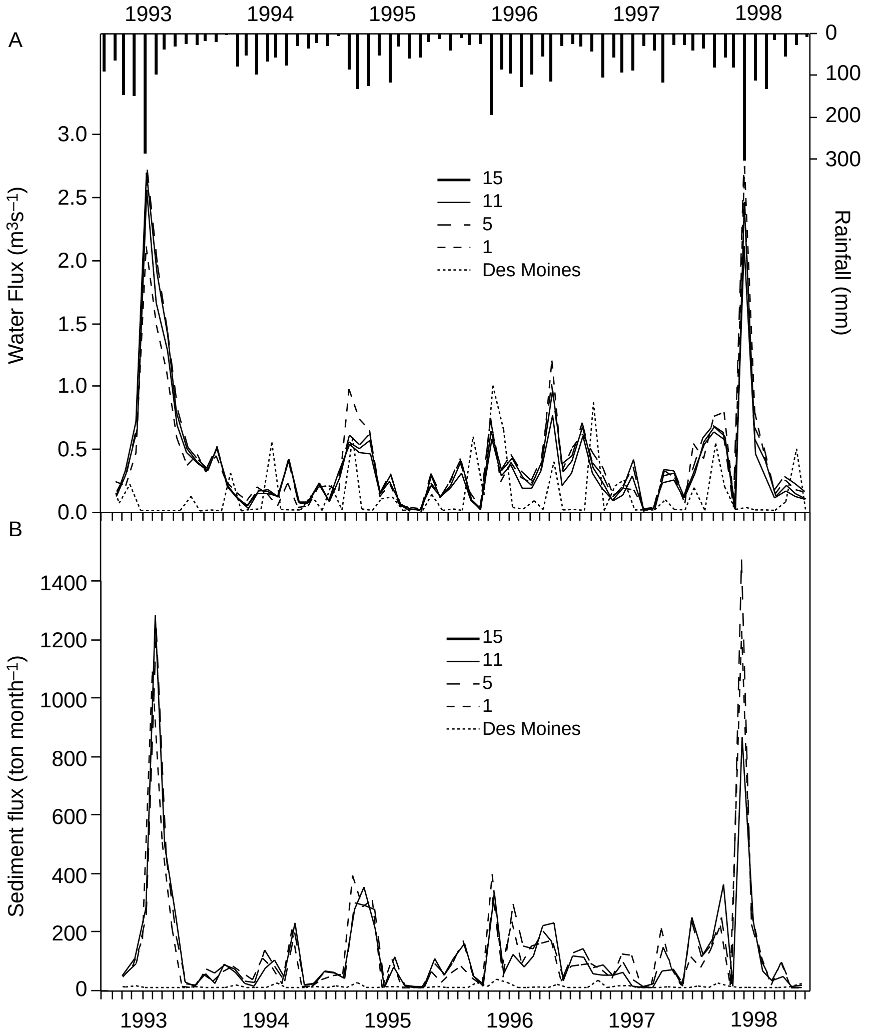

Fig. 4. Monthly rainfall (mm) at the Walnut Creek watershed. Temporal variations of estimated water (A) and sediment (B) loads using 15, 11, 5 and 1 precipitation gauge as well as information from the national weather station of Des Moines.

5 gauges. Similarly, values at BUR increased from 6.5 $m^3 s^{-1}$ with 2 or 3 gauges to around 8 $m^3 s^{-1}$ with either 1, 7 or 13 gauges. However, greater RMSD and *p* occurred below 7 raingauges revealing greater and more skewed errors. Finally, at both watersheds the use of climatic data from the National Weather Service stations produced accurate estimations of the mean monthly water fluxes but misestimated the monthly loads as indicated by MD, RMSD and *p*.

At Walnut Creek, differences were more pronounced during periods of low runoff and at secondary peaks (January 1993, July 1996). There were no differences for the large peaks of 1993 and 1998 (Fig. 4A). At BUR, differences between scenarios were more acute except during spring 1994 and fall 1996 following rainy periods (Fig. 5A). Scenarios differed irrespective of the flow discharge level, i.e. whether either under low runoff conditions or for runoff peaks. Similarly, the computed mean nitrogen varied only slightly with the decrease of the raingauge density. At WAC, NO_3–ton loads ranged from 10.2 to 11.5 N $month^{-1}$ with a mean value of 10.7 N $month^{-1}$ using 15 raingauges. At BUR, *N* loads showed a range of 6.4 ton $month^{-1}$

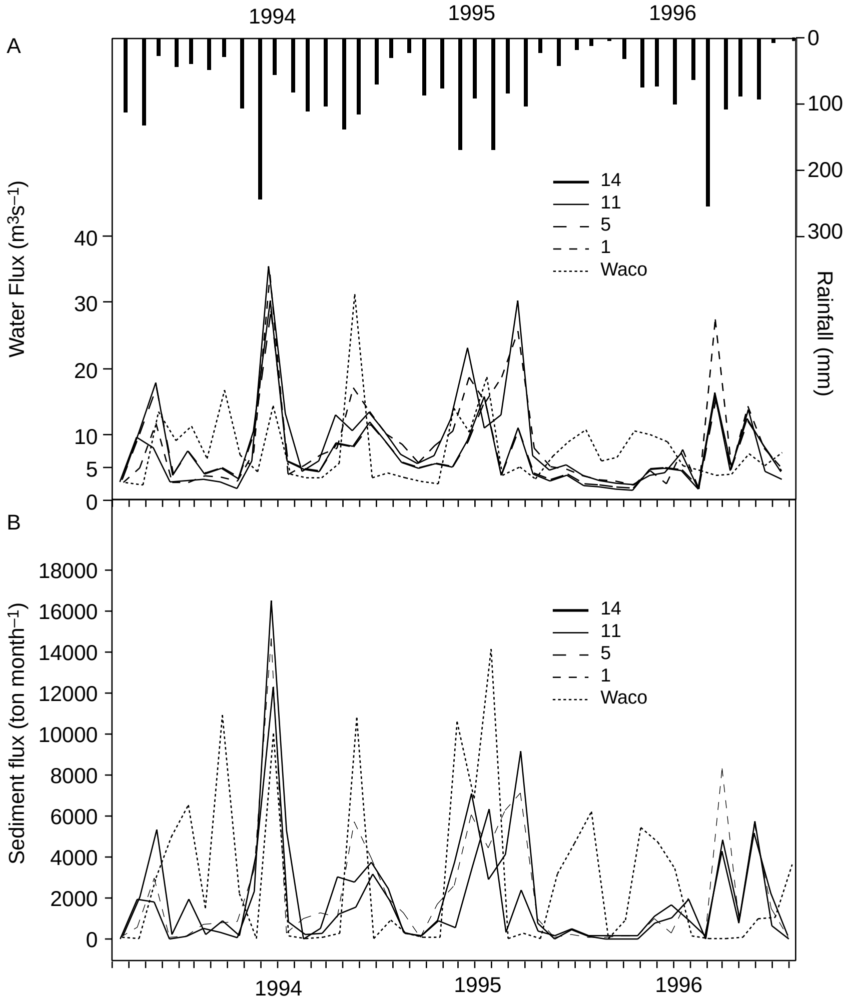

Fig. 5. Monthly rainfall (mm) at the Bosque watershed. Temporal variations of estimated water (A) and sediment (B) loads using 15, 11, 5 and 1 precipitation gauge as well as information from the national weather station of Waco.

with a mean value of 29.8 ton month^{-1} using 14 raingauges. But in both cases, climatic data from the National Weather Service stations generated inaccurate estimations (Tables 4 and 5). Average NO_3–N fluxes were under-estimated by 60% at WAC and were over-estimated by 45% at BUR.

The temporal variations of estimated sediment loads at the outlet of the two watersheds are presented in Figs. 4B and 5B. At Walnut Creek, the sediment fluxes over 1991–1998 remained lower than 400 ton month^{-1} excluding July 1993 and May 1998 with 1230 and 800 ton month^{-1}, respectively. A high correlation is generally observed with runoff fluxes with the exception of winter 1993, summer 1997 with high runoff but low sediment loads. Sediment loads at BUR were much more regularly distributed over the study period with, however, a peak at 16,100 ton month^{-1} in May 1994 (Fig. 5B). The prediction accuracy for sediment outputs from these two watersheds greatly decreased with decreasing raingauge density (Tables 4 and 5). Indeed, even though the computed mean loads did not show significant variations at decreasing raingauge density, the statistical parameters of MD, RMSD, MAD, and especially p, revealed bias in the prediction. In the case of WAC, the predictions remained similar from

Table 4
Impact of the raingauge quantity (from 1 to 14 gauges) on the estimation of runoff, NO_3–N and sediment loads at the outlet of the Walnut Creek watershed (central Iowa) over the 1991–1998 period; comparison with data from closest national weather service station (NWSS) of Des Moines

	15	13	11	9	7	5	3	2	1	NWSS
Runoff ($m^3\ s^{-1}$)										
Mean	0.36	0.40	0.41	0.40	0.41	0.42	0.41	0.43	0.39	0.30
MD		0.04	0.05	0.04	0.05	0.06	0.05	0.07	0.03	−0.16
RMSD		0.06	0.07	0.07	0.08	0.09	0.11	0.14	0.16	0.24
MAD		0.04	0.05	0.04	0.05	0.06	0.07	0.08	0.10	0.12
p		0.04	0.06	0.06	0.06	0.07	0.10	0.12	0.17	0.35
Nitrogen (ton N $month^{-1}$)										
Mean	10.7	11.2	11.3	11.2	11.2	11.4	11.4	11.5	10.2	4.2
MD		0.4	0.6	0.4	0.5	0.6	0.7	0.8	−0.5	−6.6
RMSD		1.6	2.5	2.8	2.7	2.6	3.2	3.7	4.1	18.9
MAD		0.9	1.3	1.4	1.4	1.4	1.7	2.1	2.6	10.1
p		1.6	2.6	3.0	2.8	2.6	3.3	3.9	5.1	24.3
Sediment (ton $month^{-1}$)										
Mean	120.5	120.9	121.0	124.0	124.0	133.5	133.9	134.1	133.7	65.2
MD		0.4	0.5	3.5	3.5	13.0	13.4	13.6	13.2	−119.3
RMSD		0.7	0.9	69.3	69.2	78.7	71.5	71.6	71.4	227.6
MAD		0.4	0.5	26.1	26.1	24.2	34.2	34.3	34.2	119.5
p		0.5	0.7	72.8	72.8	78.4	73.2	73.3	73.3	307.5

15 to 11 raingauges (Table 5). At BUR, a general trend of decreasing accuracy occurred from 13 to 1 gauges. The assessment of prediction quality through the statistical parameter *p* revealed a large increase of SWAT results variability below 2 raingauges. At Walnut Creek, larger differences between scenarios occurred during the peak of 1998 where lower gauge concentrations highly over-estimated sediment fluxes. In addition, lower gauge densities also over-estimated lower peaks, especially in 1996 and 1997.

Table 5
Impact of the raingauge quantity (from 1 to 14 gauges) on the estimation of runoff, NO_3–N and sediment loads at the outlet of the Bosque watershed (central Texas) over the 1988–1996 period; comparison with data from closest national weather service station (NWSS) of Waco

	14	13	11	9	7	5	3	2	1	NWSS
Runoff ($m^3\ s^{-1}$)										
Mean	8.07	8.50	7.50	7.90	8.50	7.50	6.50	6.50	8.48	6.75
MD		−0.47	−1.26	−1.19	−0.45	−0.67	−1.57	−1.56	0.41	−1.32
RMSD		3.44	4.74	4.33	5.03	6.24	6.06	6.71	7.58	8.08
MAD		3.02	3.02	3.02	3.02	3.02	3.02	3.02	1.91	6.26
p		4.24	5.89	6.12	6.22	7.20	7.44	9.29	9.32	10.79
Nitrogen (ton N $month^{-1}$)										
Mean	29.8	25.2	25.4	26.1	25.3	25.7	26.1	29.6	31.6	43.0
MD		−4.6	−4.8	−3.6	−4.6	−3.9	−6.4	−7.3	1.8	13.2
RMSD		18.6	16.3	21.5	20.9	19.8	26.1	30.2	29.0	51.6
MAD		8.7	9.3	11.9	12.2	9.0	12.3	15.4	17.2	41.3
p		17.5	14.4	20.1	19.0	17.9	21.2	24.5	16.6	56.8
Sediment (ton $month^{-1}$)										
Mean	1995	1887	1831	1736	1644	1645	1773	2025	2119	3906
MD		100	−50	−75	−122	−132	46	211	325	1911
RMSD		862	765	831	1129	1002	923	1191	1895	5613
MAD		410	348	396	513	477	420	567	861	2673
p		768	879	921	867	921	1023	897	2344	4512

At BUR, the temporal variations of differences between scenarios exhibit similar trends for runoff, i.e. greater differences under low runoff conditions as well as for runoff peaks with, however, some rare exceptions (spring 1994; fall 1996, Fig. 5B). But the differences between the scenarios were more pronounced.

At both sites, sediment predictions using input data from the national weather stations generated inaccurate estimations.

4. Discussion

In this study of two medium scale watersheds of Iowa and Texas, under different climatic, soil, landform, and land use conditions, we evaluated the impact of a less detailed knowledge of the spatial variability of rainfall on the prediction quality of runoff, sediment, and NO_3–N outputs. The first watershed (Walnut Creek, central Iowa) was a flat 51 km^2 watershed with intensive agriculture and an average annual precipitation of 828 mm. The second (Bosque, central Texas) was larger (918 km^2) and shows a larger mean (1006 mm) and spatial variability precipitation of rainfall.

At both sites, runoff and nitrogen fluxes varied only slightly with decreasing gauge concentration (from 1 to 14 or 15 gauges per watershed). This result was unexpected since it differed from the previous studies of Faurès et al. (1995), and Andréassian et al. (2001) which showed that a single raingauge can lead to large uncertainties in runoff predictions due to the lessening of the rainfall spatial variability knowledge. Higher gauge concentrations are indeed expected to provide more compensation for spatial errors (Faurès et al., 1995) relying on precipitation data themselves (Larson and Peck, 1974; Winter, 1981). One explanation for the absence of decrease of the model's accuracy at lower gauges concentrations at both catchments could be the buffering of the variability of the rainfall by using monthly estimates. Among other possible explanations is the fact that the reference runoff was already synthetic.

Despite the slight differences observed on the mean runoff loads, a general trend to over-estimate the low and medium level peaks at lower raingauge density was observed at the two watersheds, leading in this case to the recommendation of the use of the highest gauge densities. In addition, at lower gauge densities, the greatest flow and nitrogen peaks were misestimated at Bosque whereas accurate predictions were observed at Walnut, where lower rainfall variability was observed.

SWAT benefited greatly from improved rainfall knowledge for sediment loads. This showed that the increased accuracy of rainfall knowledge greatly improved models predictions, confirming experimental results on the great impact of rainfall agressivity on sediment production (Uson and Ramos, 2001). These results suggested that the definition of an optimal raingauge concentration should consider modeling results not only for runoff but also for NO_3–N and sediment outputs.

A certain level of generality was conferred to the analysis by testing watersheds with different rainfall and environmental conditions. But only few situations were tested and a larger sample of catchment size is needed to draw more general conclusions.

Regarding the raingauge concentration threshold, generalizations do not seem to be possible since they should be defined on a case by case basis. Indeed, firstly runoff or sediment loads were shown to involve different thresholds. Secondly, a single raingauge at the smaller watershed provided a greater density per unit area than the 15 available at the larger basin but proved insufficient to ensure good modeling results. Finally, extrapolation of results to other models must also be considered carefully. Indeed, the conclusions were mainly driven by SWAT's specific formulation and implementation assumptions.

This new knowledge on the threshold of raingauge concentration required for runoff, nitrogen and sediment loads estimations should help scientists to optimize field surveys, input data preparation requirements as well as computational resources needed for effective utilization of the SWAT model. We believe that the methodology presented here based on the comparison of model efficiency not only for runoff but also for nitrogen and sediment loads will allow the consideration of models accuracy from a new perspective. Finally, the sensitivity analysis performed here by using the greatest raingauge density to calibrate the model remains theoretical. Indeed, because generally sparse rainfall data are only available, hydrologist are unable to first calibrate their models using detailed rainfall data and then use the parameters obtained with the information of a sparse network. Thus, in complement, further researches should be performed to evaluate the impact of limited raingauge information by performing a recalibration of the model using the limited data.

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