Hydrologic-Economic Analysis of Best Management Practices for Sediment Control in the Santa Fe Watershed, New Mexico

Heidi L. N. Moltz[1]; Vicente L. Lopes[2]; Walter Rast[3]; and Stephen J. Ventura[4]

Abstract: The Santa Fe River Watershed in Santa Fe County, New Mexico was identified as one of the top five high risk nonpoint source pollution areas out in the Rio Grande Basin. This watershed was selected to demonstrate the use of hydrologic modeling as a powerful tool for assessing the impacts of land management practices on erosion and sediment control at the watershed level. A method based on the Hydrologic Simulation Program-Fortran was used to address the local nonpoint sediment pollution concerns. The model was modified to reflect predicted future land uses related to expected urban expansion in the watershed. Six scenarios were created and the costs and benefits of each were weighed. The total estimated costs ranged from under $1 million to over $66 million. Total average annual sediment yields at the watershed outlet ranged from 3,441 to 4,111 tonnes/year, depending on management practices employed. These results indicate the magnitude of expected sediment reductions under various management strategies. Additionally, they provide an indication of the magnitude of expected sediment reductions in the Santa Fe Watershed and the estimated cost of each management practice.

DOI: 10.1061/(ASCE)HE.1943-5584.0000187

CE Database subject headings: Best Management Practice; Nonpoint pollution; Hydrologic models; Watersheds; Benefit cost ratios; Sediment transport; Urban development; New Mexico.

Author keywords: BMP; Nonpoint source pollution; Hydrologic models; Watersheds; Benefit-cost ratios; Sediment transport; Urban development.

Introduction

Sediment is a major pollution concern in many places in the world, threatening water supplies, recreation, and wildlife and associated habitat. The total cost of erosion and sedimentation in the United States is about $44 billion per year (1995 dollars) (Pimentel et al. 1995), making sediment management an economically important priority. Increases in suspended sediments cause a decrease in light penetration through the water column, a degradation of fish spawning habitat, and a decrease in dissolved oxygen. The movements of sediments also control the transport of nutrients, metals, and pathogens (Collins and Anthony 2008). Therefore, effectively reducing sediments can subsequently reduce these pollutants (Owens 2008). Pimentel et al. (1995) found that application of soil conservation practices can reduce erosion rates from 2 to 1,000 times relative to no management.

The Santa Fe River Watershed in Santa Fe County, New Mexico was identified as one of the top five high risk nonpoint source pollution areas out of 17 in the Rio Grande Basin. This watershed was selected to demonstrate the use of hydrologic modeling as a powerful tool for assessing the impacts of land management practices on erosion and sediment control at the watershed level. Hydrologic models provide quantitative and spatially explicit assessments of sediment generation and transport processes, develop pollutant loading estimates, and yield information on the efficacy of control practices and land uses changes applied at the field, farm, and watershed scale. Sediment was identified as the major nonpoint source pollutant in the Santa Fe Watershed based upon impairments for streambed sediment deposits, prioritizations of current management efforts (Grant 2002; Stephens and Associates, Inc. 2003), and a survey of local organizations. This study assessed the effectiveness of sediment management techniques at the watershed level both in terms of sediment load reductions and cost. Understanding the sources, overland-transport mechanisms, and instream transport processes at the watershed level is necessary to predict and manage sediment impact.

To address the need for sediment reduction in the Santa Fe Watershed, a watershed-specific model was developed using the Hydrologic Simulation Program-Fortran (HSPF) (Donigian 1995) to assess the magnitude of the sediment problem, evaluate potential solutions, and inform the decision-making process. Because the Santa Fe Watershed is expected to experience significant ur-

[1]Senior Water Resources Scientist, Interstate Commission on the Potomac River Basin, 51 Monroe St. PE-08, Rockville, MD 20850 (corresponding author). E-mail: hm1079@gmail.com

[2]Professor, Aquatic Resources Program, Texas State Univ., 601 Univ. Dr., San Marcos, TX 78666.

[3]Professor, Aquatic Resources Program, Texas State Univ., 601 Univ. Dr., San Marcos, TX 78666.

[4]Professor, and Chair, Dept. of Soil Science, Univ. of Wisconsin, 439 Soils, 1525 Observatory Dr., Madison, WI 53706.

Note. This manuscript was submitted on January 2, 2009; approved on September 20, 2009; published online on October 1, 2009. Discussion period open until September 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 15, No. 4, April 1, 2010. ©ASCE, ISSN 1084-0699/2010/4-308–317/$25.00.

banization in the next decades, this study used HSPF to model several scenarios to explore the impacts of urbanization on sediment and sediment-related pollution under current and future conditions. Management scenarios were developed on the basis of the regional water plan (Stephens and Associates, Inc. 2003), the Watershed Restoration Action Strategy (Grant 2002), and personal communication with agencies responsible for land management. Model results were used to evaluate the effectiveness of possible local sediment reduction programs to enhance water quality in the Santa Fe Watershed. Furthermore, typical costs for implementation of management practices were calculated and compared to simulated sediment load reductions as a means of assessing their cost effectiveness.

The primary purpose of this study was to predict: (1) the amount of sediment produced under current and future conditions; (2) the amount of produced sediment reaching the drainage network; (3) the effectiveness of local stakeholder-approved sediment management techniques in reducing the current and expected sediment problems; and (4) the costs of sediment management efforts. Results of this study provide relevant information to decision makers regarding sediment and sediment-related pollution abatement in the Santa Fe Watershed under current and future land use conditions.

Study Area

The city and surrounding urbanized area of Santa Fe, New Mexico, estimated population 72,056 in 2006 (U.S. Census Bureau 2008), depends on the Santa Fe River, a tributary to the Rio Grande, for drinking water and irrigation. The Santa Fe River was named the most endangered river in the United States in 2007 by American Rivers, a conservation group (DeVries 2007). The Santa Fe River is often dry in sections due to overallocation. In addition to frequent water shortages, several pollutants of concern have been identified including sediment, ash, nutrients, metals, and trash (Grant 2002). Water quality problems in the reach downstream of the city of Santa Fe have resulted in designation as an impaired stream reach and federal imposition of total maximum daily load (TMDL) standards for stream-bottom deposits, chlorine, dissolved oxygen, and pH. The reach is currently not in attainment of its designated uses as a marginal cold water fishery, a warm water fishery, and livestock watering.

Sediment is a primary pollutant of concern in the Santa Fe Watershed, as established through the TMDL designation, local planning documents, and ongoing management efforts by local, state, and federal agencies working in the watershed. According to the Santa Fe Watershed Restoration Action Strategy (Grant 2002), the major potential source of sediment would be from a fire in the eastern, forested portion of the watershed and the resulting soil erosion. This is a potential threat only actualized in the event of a fire. In the central portion of the watershed, the primary source of sediment is a result of erosion by urban development and stream bed and bank erosion. In the western portions of the watershed, sediment is predominantly from rangeland erosion.

The study area outlet is the USGS gaging station 08317200. The gauge is approximately 13 km (18 mi) by river upstream of the hydrologic Santa Fe Watershed outlet at the Rio Grande. The study area is approximately 54,122 ha (133,739 acres). According to the Western Regional Climate Center, the long-term average annual rainfall and snowfall are 350.52 and 655.32 mm, respectively. The average annual maximum and minimum temperatures are 16 and 3°C, respectively. The predominant land uses in the study area are grassland followed by forested areas. The upper portion of the watershed is Santa Fe National Forest. There are two municipal drinking water reservoirs, McClure and Nichols Reservoirs, in the upper portion of the watershed on the main stem of the Santa Fe River. Reservoir hydrology was not simulated in this study. Instead, the reservoir contribution to downstream hydrology was simulated as a point source input of water using USGS gauge 0831600 located at the reservoir outlet. The middle portion of the watershed is predominately a developed, urban area. Downstream of the urban area is the Santa Fe wastewater treatment plan. This point source was simulated in the model based on available discharge data. The lower portion is dominated by grassland and upland shrubland. Other land uses in the study area include cropland, barren, pasture, and water and wetlands. See Fig. 1 for a map of the study area.

Methods

Modeling Approach

The USEPA's Better Assessment Science Integrating Point and NonPoint Sources (BASINS) was selected for this project for its comprehensive suite of modeling tools. The BASINS environment makes it possible to assess large amounts of point and nonpoint source data by integrating environmental data, analytical tools, and modeling programs. Several hydrologic and water quality models are included in the BASINS suite of methods and models.

The HSPF was chosen for use in this study. HSPF can simulate a wide variety of stream and watershed conditions and it enables flexibility in scenario development to simulate alternative conditions (Donigian 1995). HSPF can also calculate pollutant reductions from best management practice (BMP) implemented from urban and rural land uses. Another important capability of HSPF is the many pollutants it is capable of simulating including pesticides, nitrogen, toxics, sediment, or other user-defined pollutants (Bicknell et al. 1993, 2001). To date, HSPF has been used in numerous sediment modeling studies (Bao et al. 1996; Fontaine and Jacomino 1997; Chesapeake Bay Program Modeling Subcommittee 1998; Hayashi et al. 2004).

The HSPF model simulates water movement through and across impervious (IMPLND module) and pervious (PERLND module) land to the atmosphere, ground water, or surface runoff. The flow of water between the storage zones, stream, and atmosphere is affected by many process related model parameters. Process related hydrologic parameters and calibrated values for the Santa Fe Watershed are shown in Table 1. The HSPF model also simulates sediment contribution rates from PERLND and IMPLND land segments to a stream reach (RCHRES module) and instream sediment transport processes. Process based sediment transport and delivery parameters and calibrated values for the Santa Fe Watershed are shown in Table 2. The HSPF user's manual (Bicknell et al. 2001) provides a complete description of each parameter.

Modeling a watershed with HSPF requires several steps including characterization of the watershed, preparation of meteorological and hydrological time series, and the calibration and validation process.

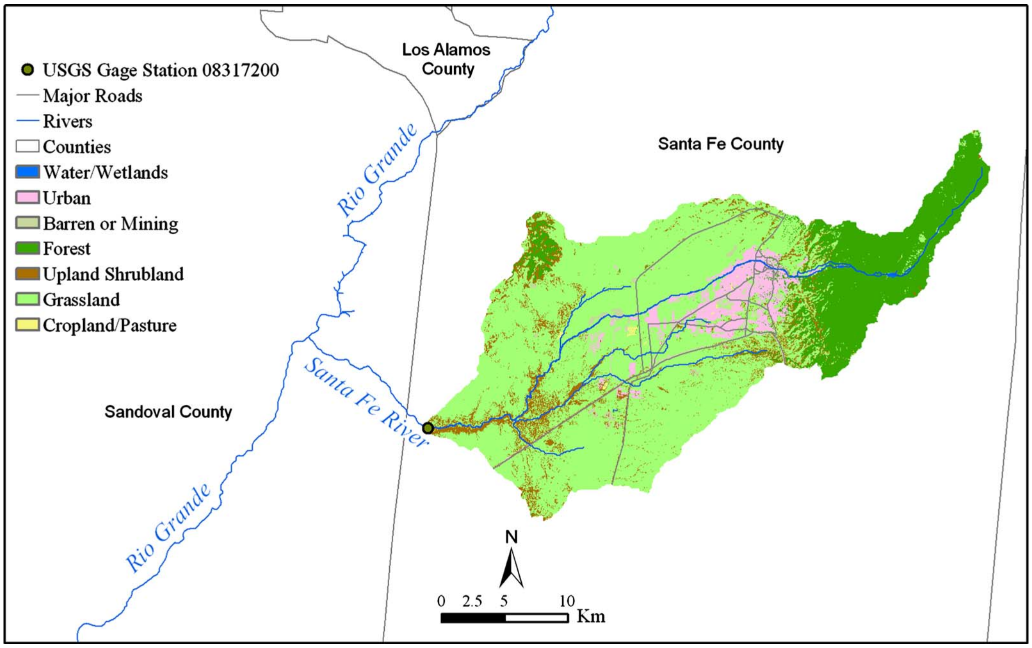

Fig. 1. Santa Fe Watershed study area

Model Development

The Santa Fe River HSPF model was characterized by defining subwatersheds and determining initial values of model parameters. Initial parameter values were determined from default values, previous studies, and observed data. Calibration of these values to obtain Santa Fe watershed-specific parameters will be described in a subsequent section. Subwatershed delineation resulted in the creation of 14 subwatersheds based on hydrology (National Hydrography Data set) and topography (30-m National Elevation Data set DEM) using the BASINS automatic delineation routine (Fig. 2). These subwatersheds are associated with HSPF stream reaches by the RCHRES module. Subwatershed development assumed that each reach has homogeneous channel properties, such as slope, and that reach outlets are located at important points such as gaging stations and tributary confluences.

The BASINS software provided an interface to download various data sets needed by the HSPF model. Input data for the HSPF

Table 1. Calibrated Hydrologic Parameters for HSPF [Modified from Environmental Protection Agency (USEPA) 2000]

Parameter	Description	Land segment	Value[a]
AGWETP	Fraction of remaining evapotranspiration from active ground water	PERLND[b]	0
AGWRC	Base ground-water recession	PERLND[b]	0.98
BASETP	Fraction of remaining evapotranspiration from base flow	PERLND[b]	0–02
CEPSC	Interception storage capacity	PERLND[b]	2.5 mm
DEEPFR	Fraction of ground-water inflow to deep recharge	PERLND[b]	0
INFEXP	Infiltration equation exponent	PERLND[b]	2
INFILD	Ratio of maximum and mean infiltration capacities	PERLND[b]	2
INFILT	Index to infiltration capacity of soil	PERLND[b]	4.8 mm/hr
INTFW	Interflow index	PERLND[b]	1
IRC	Interflow recession coefficient	PERLND[b]	0.3 1/day
KVARY	Ground-water outflow modifier	PERLND[b]	0.6/in
LSUR	Length of assumed overland flow plane	PERLND[b] or IMPLND[c]	45.7 m
LZETP	Lower zone evapotranspiration	PERLND[b]	0.1–0.7
LZSN	Lower zone nominal storage	PERLND[b]	101.6–177.8 mm
NSUR	Manning's n for assumed overland flow plane	PERLND[b] or IMPLND[c]	0.1–0.3
RETSC	Impervious retention storage capacity	IMPLND[c]	2.5 mm
SLSUR	Slope of assumed overland flow plane	PERLND[b] or IMPLND[c]	0.05–0.3
UZSN	Upper zone nominal storage	PERLND[b]	7.6 mm

[a]Calibrated values differ based on land use, stream reach, and for pervious/impervious areas. Parameters are dimensionless unless otherwise indicated.
[b]PRLNDs are pervious land segments.
[c]IMPLNDs are impervious land segments.

Table 2. Calibrated Sediment Transport and Delivery Parameters for HSPF [Modified from Environmental Protection Agency (USEPA) 2006]

Parameter	Description	Segment	Value[a]
KSER	Coefficient in the soil washoff or transport equation	PERLND[b]	5–10
JSER	Exponent in the soil washoff equation	PERLND[b]	1
KRER	Coefficient in the soil detachment equation	PERLND[b]	0.45
JRER	Exponent in the soil detachment equation	PERLND[b]	2
KGER	Coefficient in the matrix soil equation, which simulates gully erosion	PERLND[b]	0.5–9
JGER	Exponent in the matrix soil equation, which simulates gully erosion	PERLND[b]	1
KEIM	Coefficient in the solids washoff equation	IMPLND[c]	0.1
JEIM	Exponent in the solids washoff equation	IMPLND[c]	2
ACCSDP	The rate solids accumulate on the impervious land surface	IMPLND[c]	0.0006 (tonne/ha/day)
KSAND	Coefficient in the sandload power function, based on velocity	RCHRES[d]	0.4
EXPND	Exponent in the sandload power function	RCHRES[d]	1.5
TAUCD	Critical bed shear stress for deposition	RCHRES[d]	1.0–31.1 (N/sq m)
TAUCS	Critical bed shear stress for scour	RCHRES[d]	4.4–47.4 (N/sq m)
M	Erodibility coefficient of the sediment	RCHRES[d]	0.001

[a]Calibrated values differ based on land use and stream reach. Parameters dimensionless unless otherwise indicated.

[b]PRLNDs are pervious land segments.

[c]IMPLNDs are impervious land segments.

[d]RCHRES are stream reaches.

model included spatial data like land use, topography, and hydrography as well as meteorological time series data. 30-m resolution National Land Cover Dataset (NLCD) data were used to characterize land cover in the study area during calibration and verification and during current scenario runs. Data from 2001 were used for the entire period due to the limited availability of detailed development history and land use changes in the region. Percent impervious cover for each land use was estimated based on EPA guidance and was assumed to be the same under current and future conditions.

Meteorological data, including precipitation, solar radiation, wind, pan evaporation, air temperature, dew point, and cloud cover, were compiled through BASINS. Data from National Oceanic and Atmospheric Administration's National Climactic Data Center monitoring station "Santa Fe 2" (NM298085) were used for precipitation, air temperature, and pan evaporation. At the time of data download, data were available for this station from 1972 through 2005. Station "NM Albuquerque" (NM290234) was used to obtain dew point, wind speed, solar radiation, and cloud cover data. The Albuquerque station is the closest station with these required data sets. The station is 87 km (54 mi) to the southwest of "Santa Fe 2" in Bernalillo County. During calibration, the Albuquerque data were adjusted within HSPF based on elevation differences. Data were available for this station from 1970 through 2005.

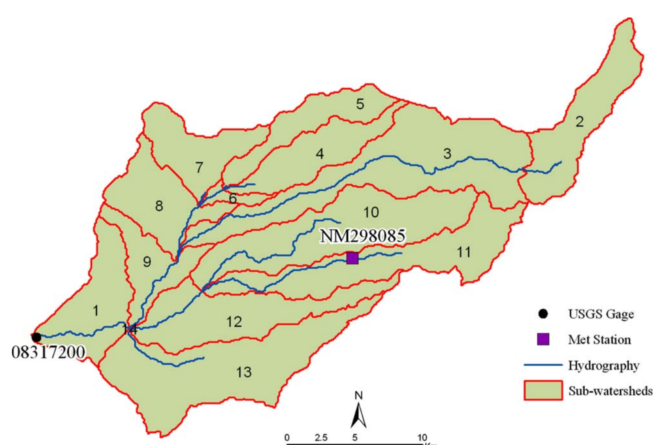

Fig. 2. USGS outlet gauge and meteorological data stations in the study area and HSPF delineated subwatersheds

Daily streamflow data for calibrating simulated instream flow was available from USGS gauge 08317200 at the study area outlet for 1970 through 2006. Observed sediment data were obtained through the National Water Quality Assessment Program (NAWQA) for the study area outlet sampling location 08317200. Fig. 2 shows USGS gauges and meteorological data stations in the study area. Surface water losses to ground water in the region were measured in a 2000 USGS report (Thomas et al. 2000) and used to estimate ground-water losses in this study.

Model Calibration and Validation

The Santa Fe River HSPF model was calibrated for hydrology and sediment. The goal of model calibration was to match simulated streamflow and sediment load values with observed values. Several assumptions perhaps responsible for variation between simulated and measured values include (1) precipitation was evenly distributed across the watershed, except as adjusted for elevation to account for snow accumulation and melt; (2) percent imperviousness for each land use remained constant throughout the simulation period; (3) land uses remained constant throughout the 24-year simulation period for model testing purposes (but were adjusted during scenario development); (4) dimensions of stream reaches remained constant throughout the analysis; and (5) percent impervious cover associated with each land use remained constant.

Hydrology calibration criteria included total streamflow volume for the calibration period, low flow and high flow volume errors, and error in peak flows. The model was run on an hourly time step and evaluated to determine how well simulated streamflow correlated with observed streamflow on an hourly, daily, and

Table 3. Differences between Current and Future Land Uses

Santa Fe Watershed land uses							
		2001 land use			Post-2001 buildout		
Land use	Avg. tonnes/ha/yr	Hectares	% of total	Avg. tonnes/yr	Hectares	% of total	Avg. tonnes/yr
Cropland	5.34	111	0.21	594	40	0.07	214
Barren or mining	3.99	369	0.68	1471	176	0.33	702
Pasture	2.4	28	0.05	66	23	0.04	55
Urban	0.49	3786	7	1867	17472	32.29	8561
Grass land	0.31	38786	71.66	12173	27972	51.69	8671
Upland shrub Land	0.2	4670	8.63	942	3767	6.96	753
Forest	0.11	6356	11.74	712	4662	8.62	513
Water/wetlands	0.07	15	0.03	1	0	0	0
Total	—	54122	100	17827	54112	100	19470

annual basis. Model results were also evaluated to ensure simulation of a realistic water balance including evaporation, infiltration, runoff, and groundwater recharge. Model efficiency was determined using the Nash Sutcliffe coefficient (NSE) (Nash and Sutcliffe 1970). The NSE is used to assess the predictive power of hydrological models by determining a model's ability to predict about the 1:1 line between observed and simulated data. According to Gassman et al. (2007), the NSE is the most widely used statistic for model calibration and verification.

After calibrated for hydrology, sediment transport and delivery parameters were optimized. The objective was to represent sediment behavior in the watershed taking into consideration four factors: (1) local stream characteristics; (2) sediment loading rates that are consistent with calibration targets; (3) modeled suspended sediment concentrations that provide a reasonable match with locally observed data; and (4) modeled sand, silt, and clay bed load fractions that provide a reasonable match with locally observed data [Environmental Protection Agency (USEPA) 2006]. Expected sediment load ranges by land use were estimated using the Universal Soil Loss Equation. Values were then adjusted for delivery to the stream with estimated sediment delivery ratios since not all eroded soil makes it to the drainage network. The estimated delivery ratio was calculated using Eq. (1) as recommended by Hummel et al. (2000), where W=subwatershed area; R/L=relief to length ratio; BR=bifurcation ratio; and DR =delivery ratio. R/L and BR were estimated using the 30-m National Elevation Data set DEM and the National Hydrography Data set in ArcGIS

$$\log \mathrm{DR} = 3.59253 - 0.230\,43 \log \mathrm{W} + 0.510\,22 \log \mathrm{R/L} - 2.785\,94 \log \mathrm{BR} \quad (1)$$

The estimated loading rates were used as calibration targets for the watershed model. Model parameters were then adjusted so simulated sediment loadings were consistent with the estimated calibration targets. Simulated suspended sediment concentration values were calibrated using observed NAWQA sediment concentration data from the watershed outlet USGS gauge. 33 instantaneous sediment concentration values were available from March 1993 to October 1995. Due to the limited availability of observed data, the entire three year time period was used for calibration.

Parameters affecting bed sand, silt, and clay transport were also calibrated using 19 observed values collected at the watershed outlet from 1981 to 1993. Transportation of particles as bed load or suspended load is typically distinguished by particle size. Silts and clays that are less than 2 mm in diameter are primarily transported as suspended materials in the water column. Bed load, transported close to the channel bed, consists of particles greater than 2 mm in diameter (Owens 2008). Optimization of parameters that affect these processes was based on the amount of sheer stress of scour and deposition of bed sediments (Table 2). This process ensured that a plausible proportion of bed load was deposited and removed from each stream reach during each rainfall event [Environmental Protection Agency (USEPA) 2006]. Suspended sediment transport was also calibrated by adjusting parameters in Table 2. Observed data on the percentage of suspended sediment that is silt or clay were obtained through the NAWQA program for the outlet gauge.

After the model was calibrated and verified under current conditions, future land use data were used to create a second version of the model. The availability of a future land use model allowed for simulation of the impacts of sediment management under projected land use conditions. Future land use data were obtained from the City of Santa Fe (GIS Department 2008). The data layer represents Santa Fe's land use characteristics upon complete buildout. The projected expansion may be complete as early as 2020 but may take much longer, according to the City of Santa Fe. Based on this information, a spatially explicit future land use layer was created using ESRI's ArcGIS by combining 2001 30-m NLCD data with the city's future data. The current and future land use layers were combined using the Spatial Analyst "Merge" function in ArcGIS. Urban areas as defined by the Santa Fe planning data set were given preference over 2001 NLCD data during the merge. Areas outside of the city were not defined in the city's data set; therefore, 2001 data remained in rural areas and urban expansion was captured based on the city's projected urban areas. Table 3 shows the resulting land use differences. Using the created layer, a second version of the calibrated model was created by adjusting the model's land uses for each reach. Scenarios were then developed to assess the effectiveness of land use practices to control sediment as the city reaches the projected growth.

Results and Discussion

Model Calibration and Validation

For hydrologic parameter optimization, the model calibration time period was January 1, 1977 through December 30, 1988. The verification time period was January 1, 1989 through December 30, 1998. The year 1992 was not considered during the verifica-

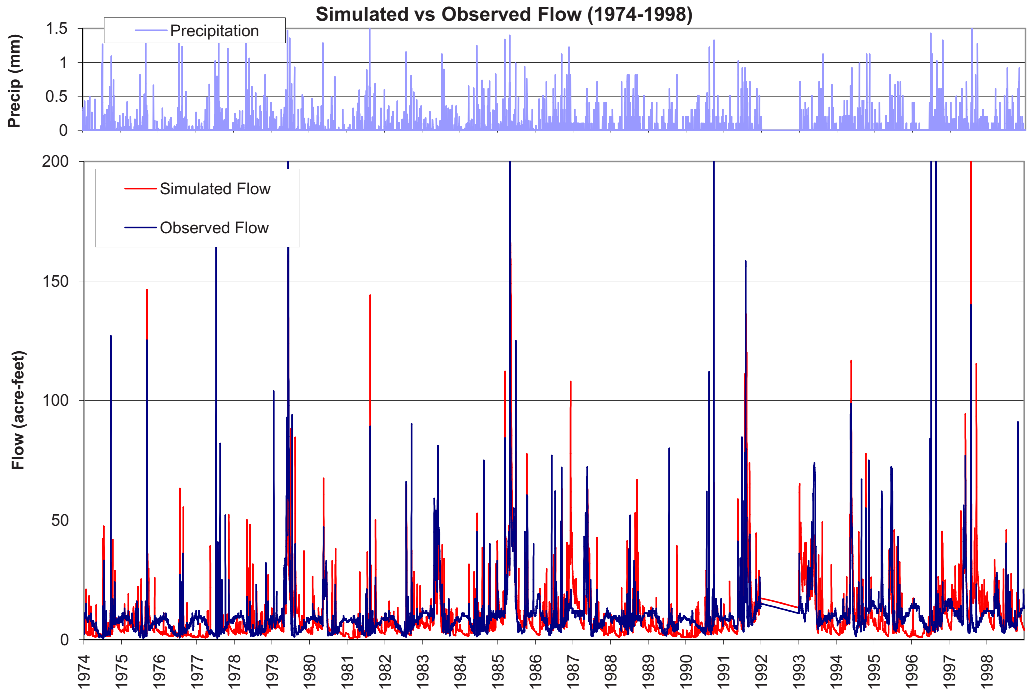

Fig. 3. Simulated and observed flows (1974–1998). Note: Observed flows from USGS gaging station 08137200, Santa Fe River above Cochiti Lake. Data from 1992 was not included in analysis due to inadequate precipitation records.

tion process due to inadequate precipitation records. Calibration focused on optimizing storm-flow values to ensure optimal simulation of pollutant transport during storm events. This process included calibration of snow accumulation and melt to simulate winter hydrographs using the SNOW module in HSPF. The average model efficiency, using the Nash Sutcliffe method, for optimized storm events during the calibration period was 0.81 and the coefficient of determination was 0.89. During the validation period, model efficiency was 0.78 and the coefficient of determination was 0.84. Fig. 3 shows simulated and observed flows for the entire simulation period. Fig. 4 shows the exceedance-probability curve for the entire period of 1974–1998. Agreement between the measured and simulated exceedance-probability curve is an indicator of calibration over the range of flow conditions (Ockerman 2007). This model had the highest error rates for extreme, both high and low, flows; however, there is general agreement between measured and simulated curves for across the range of flows. The error in total simulated streamflow volume (difference between simulated and gauged streamflow) at the outlet of the study area for 1974–1998 was −9%. Simulation errors were within acceptable limits categorized by Lumb et al. (1994) and Donigian (2002). Table 4 describes the simulation errors and acceptable limits.

Fig. 5 provides simulated and observed suspended sediment concentrations at the study area outlet after calibration. Overall, simulated suspended sediment values were lower than observed values. This was due to sediment transport via surface runoff and instream flow in HSPF. The Santa Fe Watershed model underestimated flow by 9%. On average, the percent difference of simulated to observed suspended silt and clay loadings was −6%, categorized by Donigian (2002) as "very good" for sediment calibration. Model efficiency was not calculated for sediment calibration due to the limited number of observed values. Further, model calibration was considered successful using the "weight of evidence" approach described by the Environmental Protection Agency (USEPA) (2006).

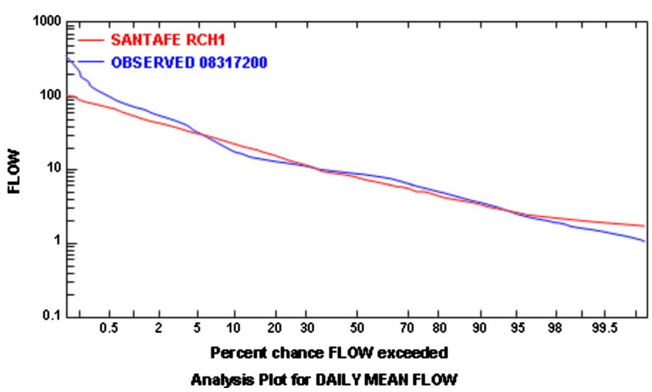

Fig. 4. Exceedance probability curve (1974–1998). SANTAFE RCH1 represents the simulated flows at the study area outlet.

Sediment Modeling

Sediment loading rates were calculated for the eight land uses. Croplands had the highest unit area load followed by barren lands, pasture, and urban areas as expected by the Environmental Protection Agency (USEPA) (2006) sediment calibration guid-

Table 4. Simulation Errors and Acceptable Limits

Comparison of streamflow volumes and peaks	Error (%)	Criteria (%)
(1974–1998)	—	—
Total flow volume	−9.38	10
Total of highest 10% of daily flows	−6.8	15
Total of lowest 50% of daily flows	4.98	10

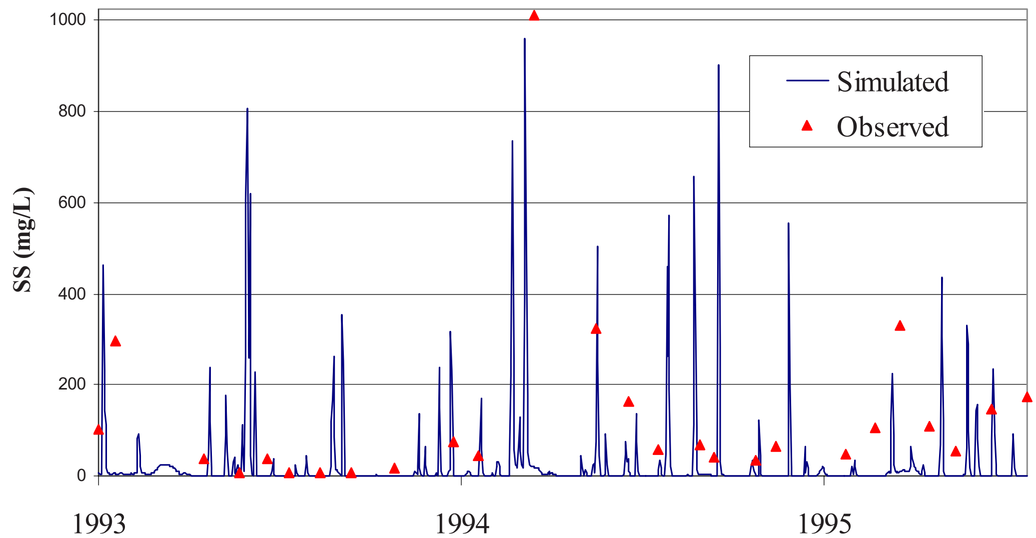

Fig. 5. Simulated and observed suspended sediment concentrations at the study area outlet

ance. Grasslands had the highest average tonnes/year sediment yield due to occupying almost three quarters of the study area; although, grasslands had a relatively low unit area load. The average annual suspended sediment concentration at the watershed outlet under current conditions was 50 mg/L. The average flow was 0.46 m^3/s (16 cfs), while the total average annual sediment yield, including bedload and suspended sediment, was 3,818 tonnes/year. Based on the projected urban expansion, the City of Santa Fe will gain almost 13,800 developed ha (34,000 acres). Under future conditions, there was an increase in average flow to 0.74 m^3/s (26 cfs) resulting in a reduced average annual suspended sediment concentration of 26 mg/L at the watershed outlet. The total average annual sediment yield, including bedload and suspended sediment, increased slightly to 3,956 tonnes/year. These results suggest a 62% increase in flow and a 3.5% increase in sediment yield as a result of urbanization in the Santa Fe Watershed.

Sediment yields might be expected to increase drastically with such a large area of urban expansion; however, the only slight increase may be due to an increase in impervious areas and the reduction in pervious, erodible areas such as croplands and barren land within the study area. The simulated yields do not take into account the effects of increased erosion during the construction phase of urban expansion. Erosion from construction sites during urban expansion can be massive. Urban development increases sediment yield by stream channelization and land clearing (Schoonover et al. 2007) and runoff from impervious surfaces in urban areas can cause bank erosion downstream (Morgan 1995). Moreover, urbanization was shown to increase hydrologic response to precipitation in this study by increasing hydrograph peaks, further increasing the threat of erosion downstream of the study area. Imposed regulatory limits to impervious cover during urban development in Santa Fe could lessen these impacts.

Several structural and nonstructural land management practices were assessed using the current and future models. Model scenarios were developed by contacting local, state, and federal agencies and reviewing Santa Fe Watershed management documents and plans. Scenarios were developed using the BMPRAC module in HSPF. This module allows for application of management techniques on a user-specified percentage of each land use. Where management is implemented, a sediment removal fraction is designated for the management practice. USEPA recommended removal fractions are available within the module based on literature values. Sediment removal fractions used in this study for filter strips, grassed waterways, sediment basins, and dry detention basins were 70, 75, 95, and 85%, respectively. Livestock exclusion and revegetation were simulated by converting a percentage of the land use to grasslands in the HSPF Land Use Editor.

The effectiveness of selected land management practices on reducing the sediment unit/area loads, without consideration of cost, is shown in Table 5. For comparison purposes, the contributing area to the management practice was an equal area (50% contributing area) for all practices. Grassed waterways were shown to be most effective on croplands. Revegetation was shown to be most effective on barren or mining areas. Pasture

Table 5. Effectiveness of Land Management Practices on Reducing Sediment Yield

	Sediment removal rates by land-use type (1974–1998)						
	(Average tonnes/ha/year)						
Land use	No BMP	Filter strips	Grass waterways	Dry detention	Sediment basin	Revegetation	Livestock exclusion
Cropland	5.34	3.47	**3.34**	NA	NA	NA	NA
Barren/mining	3.99	2.60	2.49	NA	NA	**2.15**	NA
Pasture	2.40	1.57	1.50	NA	NA	NA	**1.36**
Urban	0.49	0.40	0.40	0.39	**0.37**	0.43	NA

Note: Structural and nonstructural practices were evaluated on appropriate land uses to determine their effectiveness using HSPF; a value of "NA" signifies management practice was not appropriate for the respective land use; the optimal management practice is shown in bold for each land use.

Table 6. Scenario Names, Descriptions, and Rationale

Scenario	Name	Description	Rationale
1	Minimum structural	10% detention pond, 5% sediment basin	10% urban drainage to detention ponds requires only retrofitting existing detention ponds in the basin (Stephens and Associates, Inc. 2003). 5% urban drainage to sediment basins is a low end estimate of watershed area under construction at any given time.
2	Minimum nonstructural	5% urban and bare revegetation	5% represents minimal efforts to revegetate along streambanks and in open spaces.
3	Maximum structural	50% detention ponds, 15% sediment basin	50% urban drainage to detention ponds would require construction of new ponds and retrofitting of old ones. 15% sedimentation basins represent a high estimate of watershed area under construction at any given time.
4	Maximum nonstructural	50% urban and bare revegetation	50% represents the aggressive revegetation identified as a priority in the regional water plan (Stephens and Associates, Inc. 2003).
5	Minimum combination	10% detention ponds, 5% sediment basin, 5% urban and bare revegetation	Combination of Scenarios 1 and 2
6	Maximum combination	50% detention ponds, 15% sediment basin, 50% urban and bare revegetation	Combination of Scenarios 3 and 4

sediment loads were smallest in areas where livestock were excluded, a common management technique for riparian pasturelands. In urban areas, sediment basins were most effective at reducing sediment yield.

Management practices were not simulated on grasslands, shrublands, or wetlands because those land uses were not identified as management targets by local stakeholders. Management practices were not simulated on forested areas because these areas were predominately upstream of the drinking water reservoirs and were not calibrated. Forested areas are actively managed in the watershed. Almost $1 million have been spent on upper watershed management to reduce fire danger by the United States Forest Service and the City of Santa Fe (Stephens and Associates, Inc. 2003). Over 2,428 ha (6,000 acres) of forest management was complete as of 2005.

Based on the simulated effectiveness of the management techniques previously described, six scenarios were created under future conditions. Scenario development focused on urban areas due to the expected extensive urbanization. Management techniques are classified into two categories, structural and nonstructural. Recommended structural techniques include detention ponds and sedimentation basins. Nonstructural techniques include revegetation of urban pervious areas and bare lands. The six scenarios are minimal structural, maximum structural, minimum nonstructural, maximum nonstructural, minimum combination of both structural and nonstructural techniques, and maximum combinations. Table 6 describes each scenario.

The simulated sediment reduction associated with Scenarios 1–6 are shown in Table 7. The maximum combination of structural and nonstructural measures (Scenario 6) was most effective at reducing sediment yield and suspended sediment concentrations followed by the maximum application of structural measures alone (Scenario 3). The maximum nonstructural (Scenario 4) and minimum combination (Scenario 5) scenarios were significantly less at around 4% reduction in suspended sediment. The minimum structural (Scenario 1) and the minimum nonstructural (Scenario 2) were the two least effective management options. Revegetation in urban and bare areas had a lower impact on percent suspended sediment reduction than the structural options.

Cost and Benefits

Costs for each of the scenarios were calculated in dollars using estimates from the USEPA BMP Cost guide (1999 dollars) [Environmental Protection Agency (USEPA) (1999)] and watershed-specific implementation procedures documented in the regional water plan (Stephens and Associates, Inc. 2003). The cost of revegetation was estimated at $900 per acre because of the expressed need to reseed as part of revegetation in the Santa Fe Watershed. The costs of detention basins depended on the ability to retrofit existing structures or the need to construct new ones. Existing detention basins in the watershed were designed for the 100-year flood. Retrofitting these basins to capture sediment from typical run-off events would be cheaper than constructing new basins. Retrofitting was estimated at $1,000 per detention basin but was only available in the areas, where detention ponds already exist. For retrofits, costs would also be minimized because no permits would be required. Where construction of new detention

Table 7. Total Estimated Costs and Load Reductions Associated with Each of the Six Scenarios (Based on 1999 Dollars)

Scenario	Sediment reduction (%)	Sediment conserved (tonne/year)	Cost revegetation ($)	Cost detention basin ($)	Cost sediment basin ($)	Total cost ($)	Cost/tonne sediment Conserved
1	3.3	137	0	8,634,000	4,318,000	12,952,000	94,540
2	0.4	15.5	990,900	0	0	990,900	63,929
3	13.7	567	0	43,174,000	12,952,000	56,126,000	98,988
4	3.8	157	9,909,900	0	0	9,909,900	63,120
5	3.6	149	990,900	8,634,000	4,318,000	13,942,900	93,577
6	17.3	715	9,909,900	43,174,000	12,952,000	66,035,900	92,358

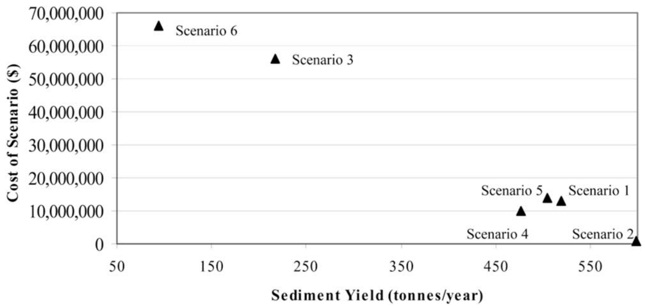

Fig. 6. Costs and benefits of the six scenarios (based on 1999 dollars)

basins was required, costs were increased. The estimated cost of new detention basins was $2,000. These detention basins would also likely require permits from the New Mexico Office of the State Engineer. Sediment basins in construction areas were also estimated at $2,000 each.

The calculated costs are estimates and are based on limited cost data (Novotny and Olem 1994); however, they can provide an estimate of the relative expense of each option. The total estimated costs of the various options ranged from under $1 million to over $66 million. To put these cost estimates in perspective, over $35 million in funded projects (not including matching funds) are listed in the Santa Fe Watershed Restoration Action Strategy (Grant 2002). Costs and load reductions associated with each of the six scenarios are shown in Table 7. Fig. 6 displays the costs and benefits of the six scenarios. Scenarios one, two, four and five are the least expensive but are also the least effective at reducing sediment yield. Scenarios three and six conserve significantly more sediment but are also considerably more expensive.

These options can be prioritized in terms of sediment reduction, cost minimization, or in consideration of both; however, these decisions need to be made through a stakeholder participation process. Stakeholder involvement is required because of the increasing complexity of environmental policy issues, the complexity of stakeholder roles in environmental problems, and the competing interests of stakeholders (Slob et al. 2008). Selection of the most appropriate management scenario will require a careful balance of costs and benefits by stakeholders.

Sources of Modeling Uncertainty

Models are mathematical representations of complex systems. Because modeling results can be used for public decision making, the uncertainty involved in any particular modeling exercise should be assessed (Harmel and Smith 2007). Uncertainty associated with modeling results are produced by many factors including mathematical errors, errors in empirical data, and misunderstandings of the modeled system to name a few (Rode and Suhr 2006). These areas are also sources of uncertainty within the Santa Fe Watershed model.

To date, several data sets in particular are problematic for modeling the Santa Fe River. Troublesome data sets include spring flow and quality and ground-water loss data. Although several USGS gauges have gathered infrequent spring flow and water quality samples over the years, inadequate data exist to accurately represent this contribution to surface flow. Spring flow was therefore not represented in the Santa Fe Watershed model. As previously described, surface water losses to ground water in the region were measured in a 2000 USGS report (Thomas et al. 2000) and used to estimate ground-water losses in the Santa Fe Watershed model. Thomas et al. (2000) suggested that the calculated infiltration rates were underestimated at a percent not calculated equal in magnitude to unmeasured irrigation return flow. USGS flow data can also introduce simulation uncertainty. Observed values for Santa Fe Watershed model calibration were obtained from USGS gauge station 08317200. The estimated error for records at gaging stations rated good to fair is 10–15% (Ortiz et al. 1998).

Brun and Band (2000) showed that simulation of the future conditions can increase model error if future activities differ from those modeled (Semmens et al. 2006). In this study, model uncertainty would be increased if urbanization does not take place according to the City of Santa Fe's approved future land use layer. Additionally, all current and future scenarios are considered under constant climactic conditions. Future changes in climate might significantly impact hydrologic response (Minville et al. 2008) but are not represented in this study.

Conclusion

Sustainable management of the Santa Fe Watershed will require integrated socioeconomic, biophysical, and political factors as detailed in Macleod et al. (2007). This study describes one aspect of sustainable management, the use of hydrologic models for detailed assessment of the pollution problem and evaluation of management options at the watershed scale. Hydrologic modeling capabilities provide detailed, locale-specific information necessary for sound decision making. The cumulative impacts of effectively managing pollutants of concern may improve water quality at the local and basin-wide scale.

The Santa Fe Watershed model was used to understand the current status of sediment generation and transport, assess impacts of management on suspended sediment loadings, and calculate the costs of management techniques to facilitate local decision making. The management techniques that provided the greatest load reduction were identified for each land use. Grassed waterways were shown to be most effective on croplands. Revegetation was shown to be most effective on barren or mining areas. Pasture sediment loads were smallest in areas where livestock were excluded. In urban areas, sediment basins were most effective at reducing sediment yield. Six scenarios were created and the costs and benefits of each were weighed. The total estimated costs ranged from under $1 million to over $66 million. Total average annual sediment yields at the watershed outlet ranged from 3,441 to 4,111 tonnes/year. These observations confirm previous observations of sediment management technique effectiveness in general. Additionally, they provide an indication of the magnitude of expected sediment reductions in the Santa Fe Watershed and the estimated cost of each management practice.

Acknowledgments

The writers would like to gratefully acknowledge Mr. Darwin Ockerman from the USGS Texas Water Science Center, Dr. Chad Smith and Dr. Paula Williamson from Texas State University-San Marcos, and Dr. Vladimir Novotny from Northeastern University for their contributions to this study.

References

Bao, Y., Clapp, R. B., Brenkert, A. L., Moore, T. D., and Fontaine, T. A. (1996). "Simulation of contaminated sediment transport in White Oak Creek Basin." *Proc., 6th Federal Interagency Sedimentation Conf.*, Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data, Las Vegas, VIII-1–VIII-6.

Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Donigian, A. S., and Johanson, R. C. (1993). "Hydrological simulation program-FORTRAN user's manual for release 10." *Rep. No. EPA/600/R-93/174*, Environmental Research Laboratory Office of Research and Development, U.S. Environmental Protection Agency, Athens, Ga.

Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Jobes, T. H., and Donigian, A. S. (2001). *Hydrological simulation program-Fortran (HSPF) version 12 user's manual*, Aqua Terra Consultants, Mountain View, Calif., 873, ⟨http://www.epa.gov/waterscience/basins/bsnsdocs.html⟩.

Brun, S. E., and Band, L. E. (2000). "Simulating runoff behavior in an urbanizing watershed." *Comput. Environ. Urban Syst.*, 24, 5–22.

Chesapeake Bay Program Modeling Subcommittee. (1998). *Chesapeake Bay watershed model application and calculation of nutrient and sediment loadings*, U.S. EPA Chesapeake Bay Program, Annapolis, Md.

Collins, A. L., and Anthony, S. G. (2008). "Predicting sediment inputs to aquatic ecosystems across England and Wales under current environmental conditions." *Appl. Geogr.*, 28(4), 281–294.

DeVries, B. (2007). "American Rivers announces ten rivers at risk." *American rivers*, Washington, D.C., ⟨http://www.americanrivers.org/site/News2?page=NewsArticle&id=10199⟩.

Donigian, A. S., Jr. (1995). "Hydrological simulation program-Fortran (HSPF)." *Computer models of watershed hydrology*, V. P. Singh, ed., Water Resources Publications, Highlands Ranch, Colo., 442.

Donigian, A. S., Jr. (2002). "Watershed model calibration and validation—the HSPF experience." *Specialty Conf. Proc.: Water Environment Foundation*, National TMDL Science and Policy 2002, Phoenix, 30.

Environmental Protection Agency (USEPA). (1999). "Preliminary data summary of urban storm water Best Management Practices." *Rep. No. EPA-821-R-99-021*, EPA Office of Water, Washington, D.C.

Environmental Protection Agency (USEPA). (2000). "Estimating hydrology and hydraulic parameters for HSPF." *BASINS Technical Note 6*, Office of Water, Washington, D.C., 32.

Environmental Protection Agency (USEPA). (2006). "Sediment parameter and calibration guidance for HSPF." *BASINS Technical Note 8*, Office of Water, Washington, D.C., 46.

Fontaine, T. A., and Jacomino, V. M. F. (1997). "Sensitivity analysis of simulated contaminated sediment transport." *J. Am. Water Resour. Assoc.*, 33(2), 313–326.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G. (2007). *The soil and water assessment tool: Historical development, applications, and future research directions*, Center for Agricultural and Rural Development, Iowa State Univ., Ames, Iowa, 102.

GIS Department. (2008). "Future land use map." *Adopted by city council resolution No. 1999-45*, Santa Fe, N.M.

Grant, P. (2002). "Santa Fe Restoration Action Strategy (WRAS)." *Prepared pursuant to the Clean Water Action Plan and Unified Assessment of New Mexico watersheds*, New Mexico Environment Department Surface Water Quality Bureau, Santa Fe, N.M., 57.

Harmel, R. D., and Smith, P. K. (2007). "Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling." *J. Hydrol.*, 337(3–4), 326–336.

Hayashi, S., Murakami, S., Watanabe, M., and Bao-Hua, X. (2004). "HSPF simulation of runoff and sediment loads in the Upper Changjiang River Basin, China." *J. Environ. Eng.*, 130(7), 801–815.

Hummel, P. R., Imhoff, J. C., Dusenbury, R., and Gray, M. (2000). *TMDL USLE: A practical tool for estimating diffuse sediment source loads within a watershed context*, U.S. EPA National Exposure Research Laboratory, Athens, Ga.

Lumb, A. M., McCammon, R. B., and Kittle, J. L. (1994). "Users manual for an Expert System (HSPEXP) for calibration of the Hydrological Simulation Program: Fortran." *Rep. No. 94-4168*, United States Geological Survey Water Resources Investigations, Reston, Va., 102.

Macleod, C. J. A., Scholefield, D., and Haygarth, P. M. (2007). "Integration for sustainable catchment management." *Sci. Total Environ.*, 373(2–3), 591–602.

Minville, M., Brissette, F., and Leconte, R. (2008). "Uncertainty of the impact of climate change on the hydrology of a Nordic watershed." *J. Hydrol.*, 358(1–2), 70–83.

Morgan, R. P. C. (1995). *Soil erosion and conservation*, Longman Limited, Essex, U.K.

Nash, J. E., and Sutcliffe, J. V. (1970). "River flow forecasting through conceptual models, Part I: A discussion of principles." *J. Hydrol.*, 10, 282–290.

Novotny, V., and Olem, H. (1994). *Water quality: Prevention, identification, and management of diffuse pollution*, Van Nostrand Reinhold, New York.

Ockerman, D. J. (2007). "Simulation of streamflow and estimation of ground-water recharge in the Upper Cibolo Creek Watershed, South-Central Texas, 1992–2004." *Rep. No. 2007-5202*, U.S. Geological Survey Scientific Investigation, Reston, Va., 34.

Ortiz, D., Lang, K., and Beal, L. (1998). "Water resources data for New Mexico, water year 1997." *Rep. No. NM-97-1*, U.S. Geological Survey Water-Data, Reston, Va., 574.

Owens, P. N. (2008). "Sediment behaviour, functions, and management in river basins." *Sustainable management of sediment resources: Sediment management at the river basin scale*, P. N. Owens, ed., Vol. 4, Elsevier, Amsterdam, The Netherlands.

Pimentel, D. et al. (1995). "Environmental and economic costs of soil erosion and conservation benefits." *Science*, 267(5201), 1117–1123.

Rode, M., and Suhr, U. (2006). "Uncertainties in selected surface water quality data." *Hydrology Earth Syst. Sci.*, 3, 2991–3021.

Schoonover, J. E., Lockaby, B. G., and Shaw, J. N. (2007). "Channel morphology and sediment origin in streams draining the Georgia Piedmont." *J. Hydrol.*, 342(1–2), 110–123.

Semmens, D., Hernandez, M., Goodrich, D. C., and Kepner, W. G. (2006). "A retrospective analysis of model uncertainty for forecasting hydrologic change." *Proc., iEMSs 3rd Biennial Meeting: Summit on Environmental Modeling and Software*, International Environmental Modeling and Software Society, Burlington, Vt.

Slob, A. F. L., Ellen, G. J., and Gerrits, L. (2008). "Sediment management and stakeholder involvement." *Sustainable management of sediment resources: Sediment management at the river basin scale*, P. N. Owens, ed., Vol. 4, Elsevier, Amsterdam, The Netherlands.

Stephens and Associates, Inc. (2003). "Jemez y Sangre regional water plan, Volume 1." *Rep. Prepared for Jemez y Sangre Water Planning Council*, Albuquerque, N.M., 234.

Thomas, C. L., Stewart, A. E., and Constantz, J. E. (2000). "Determination of infiltration and percolation rates along a reach of the Santa Fe River near La Bajada, New Mexico." *Rep. No. 00-4141*, U.S. Geological Survey Water Resources Investigations, Reston, Va., 65.

U.S. Census Bureau. (2008). "Santa Fe County, New Mexico." *State and county quick facts*, U.S. Census Bureau, Washington, D.C.