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The Effect of Rice Straw Mulching and No-Tillage Practice in Upland Crop Areas on Nonpoint-Source Pollution Loads Based on HSPF

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Abstract: This study evaluates the watershed-scale effects of non-point-source (NPS) pollution loads caused by rice straw mulching and no-tillage applications in upland crop areas using the Hydrological Simulation Program–Fortran (HSPF) model. The study area is the Byulmi-cheon watershed (1.21 km^2) of South Korea. Hourly rainfall, discharge and stream water quality data were collected for three years (2011–2013) at the watershed outlet. The HSPF model under conventional (no rice straw mulching or tillage) conditions was calibrated and validated using 20 rainfall events for runoff and 14 rainfall events for stream water quality (sediment, T-N and T-P). The average Nash–Sutcliffe model efficiency value for runoff was 0.61, and determination coefficients for runoff, sediment, total nitrogen (T-N) and total phosphorus (T-P) were 0.70, 0.56, 0.58 and 0.61, respectively. The results of field experiments with slopes of 3% and 8% for radish and sesame cultivation showed decreases in the runoff ratio, sediment, T-N and T-P of 9.0%, 95.9%, 32.6% and 43.5% for rice straw mulching plots and 22.5%, 82.5%, 67.8 and 70.6% for no-tillage plots. The HSPF model parameters soil infiltration capacity (INFILT), soil bulk density (BD), wilting point (WP) and field capacity (FC) were controlled for the upland crop areas during the evaluation of the rice straw mulching and no-tillage effects. The HSPF evaluation using the application of Best Management Practices (BMPs) showed that the watershed runoff ratio, sediment, T-N and T-P values were reduced by 10.4%, 68.7%, 31.6% and 41.3% using rice straw mulching and 21.5%, 83.4%, 51.9% and 60.2% under no-tillage conditions compared with conventional conditions. The land use change scenarios for the baseline (upland crop areas 5%), Scenario 1 (upland crop areas 10%) and Scenario 2 (upland crop areas 30%) were applied in the model. The results of the evaluation show that the proportion of NPS pollution loads increased by a ratio approximately equal to that of the increasing upland crop area.

Keywords: HSPF watershed modeling; nonpoint source pollution; rice straw mulching; no-tillage; upland crop areas

1. Introduction

In South Korea, agricultural nonpoint-source (NPS) pollution has become a major issue because it contributes to the deterioration of stream water quality [1]. In general, NPS pollution is a rainfall runoff process that is complex, non-linear, temporally variably and spatially distributed in agricultural watersheds. Rainfall runoff is the driving mechanism; however, there are further complications and spatially varying factors, such as land use, topography and soil type, that affect pathways and source areas. The origin, quantity and routes of NPS pollution from agricultural areas are difficult to trace because of the influence of random and irregular characteristics [2]. Currently, approximately 60% of the total water pollution in South Korea entering aquatic environments through streams and reservoirs is caused by NPS pollution related to agricultural activities [3]. In recent decades, government agencies have concentrated their wastewater treatment efforts at downstream locations instead of following pretreatment practices at upstream sources.

Best Management Practices (BMPs) are nonstructural techniques that have been applied to the control and treatment of agricultural NPS pollution. A watershed-scale identification of NPS pollution loads via watershed modeling is helpful in supporting the economic planning of BMPs at the proper time and place. Environmental hydrologic models such as the Hydrological Simulation Program–Fortran (HSPF) model and the Soil and Water Assessment Tool (SWAT), among others, can be used to effectively evaluate the impact of BMPs.

A number of studies have recently assessed the effectiveness of agricultural BMPs in reducing NPS pollution loads through watershed modeling. Rao *et al.* [4] evaluated the effectiveness of a range of BMPs, including a nutrient management plan, riparian buffers, filter strips and fencing, in reducing phosphorus loading using a watered model for New York City source watersheds. Giri *et al.* [5] evaluated the performance of different targeting methods for native grass and terraces in reducing sediment, total nitrogen and total phosphorus using the SWAT model in the Saginaw River watershed. Liu *et al.* [6] investigated the effectiveness of BMPs in terms of changes in land use, fertilizer management and tillage management measures to reduce total nitrogen and total phosphorus through analysis of several scenarios by the SWAT model in the same watershed. Dechmi and Skhiri [7] evaluated the effects of several BMPs, considering tillage (conservation and no-tillage), fertilizer application (incorporated, recommended and reduced) and irrigation (adjusted to crop needs) on irrigation return flows, total suspended sediment, organic P, soluble P and total P, using the SWAT-IRRIG model for the Del Reguero stream watershed. Strauch *et al.* [8] assessed the impact of BMPs such as parallel terraces and small sediment basins on streamflow and sediment loads in the intensively cropped catchment of the Pipiripau River. The BMP scenarios (tillage management measures) in the above two studies [6,7] were applied to this study. The results indicate that the BMP scenarios showed a clear downward trend in terms of NPS pollution loads.

However, most of these previous studies focused on BMP scenario-based approaches using a watershed model; few studies have performed evaluations with watershed modeling using data obtained from an analysis of the discharge characteristics of pollutants from field-scale surveys and tests through actual application of BMPs. For example, Jung *et al.* [9], Jang *et al.* [10] and Ahn *et al.* [2] evaluated the effectiveness of BMP for rice straw mulching and no-tillage in reducing runoff, sediment, total nitrogen and total phosphorus using the SWAT and HSPF models.

In this study, the HSPF model was used to evaluate the impact of a rice straw mulching and no-tillage BMP on watershed runoff and NPS pollution loads for a 1.21 km^2 agricultural watershed in South Korea. Field-scale experiments under conventional, rice straw mulching and no-tillage conditions were conducted to identify the NPS pollution load reduction effects and the results were used as HSPF model parameters in upland crop areas of the watersheds. The parameters related to the physical properties of soil were adjusted in the model to evaluate the effects of the rice straw mulching and no-tillage BMP application on the stream water quality. The change scenarios of upland crop areas were applied in the model to evaluate the influence of upland crop areas on runoff and NPS pollution loads.

2. HSPF Model Description

The HSPF model is based on the original Stanford Watershed Model IV [11] and is a consolidation of three previously developed models: (1) the Agricultural Runoff Management Model (ARM) [12], (2) the NPS Runoff Model [13] and (3) the Hydrological Simulation Program (HSP), which includes HSP Quality [14–16]. Additionally, the HSPF model is embedded in the water quality assessment tool Better Assessment Science Integrating Point and Nonpoint Sources (BASINS, Lahlou *et al.* [17]), developed by the US Environmental Protection Agency. An extensive description of the HSPF model is provided in Bicknell *et al.* [18].

The HSPF model is a lumped parameter model with an organized modular structure. Pervious land segments over which an appreciable amount of water infiltrates into the ground are modeled with the PERLND module. Impervious land segments, such as paved urban surfaces, over which water infiltration is negligible, are simulated with the IMPLND module. Processes occurring in water bodies, such as streams and lakes, are treated by the RCHRES module. These modules have several components that simulate hydrological processes and processes related to water quality [19]. HSPF applies the Chezy-Manning equation for routing overland flow, the Philip equation for infiltration and the kinematic wave method for channel routing. Erosion and sediment transport along the land surface are simulated as the wash-off of detached sediment in storage and scour of the soil matrix [20]. Nutrients are modeled using a system of coupled mass balance equations describing each nutrient compartment and each of the following constituents: dissolved inorganic and organic nutrients, particulate organic nutrients and sediment nutrients [21]. Detailed information on the structure of and theories behind HSPF can be found in the HSPF version 12 user's manual [18] and in the literature [13,22–25].

Figure 1 presents a flowchart of the modeling procedures with data for HSPF modeling. The study procedures will be discussed in greater detail in the next chapter.

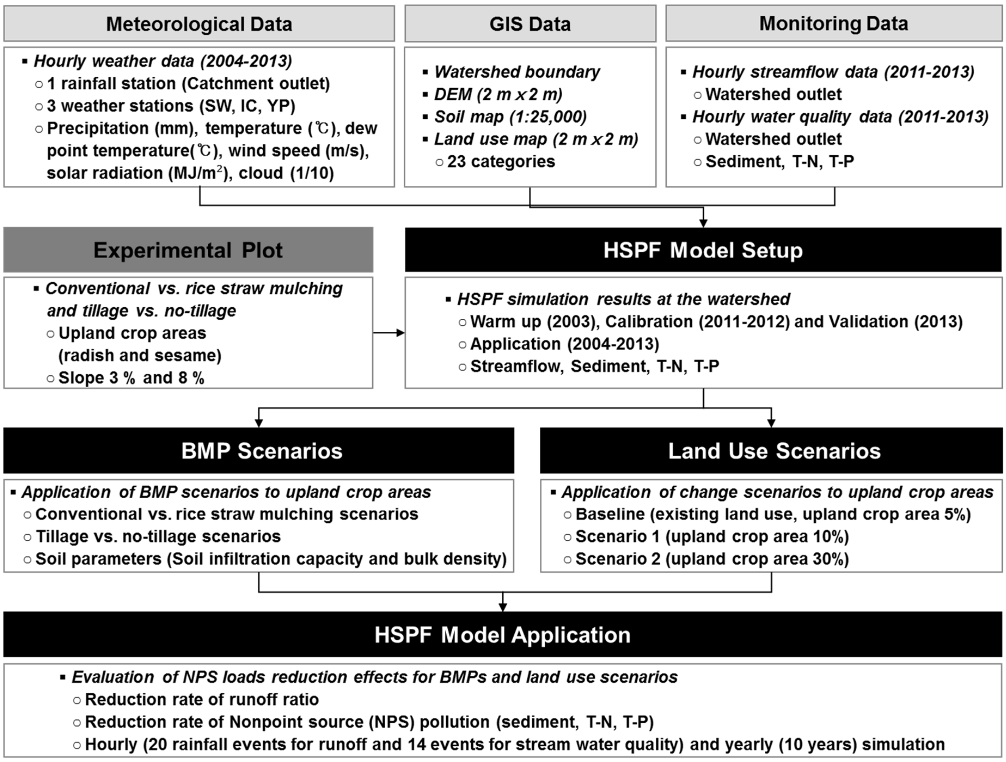

Figure 1. Flowchart of the study procedure.

3. Study Area and Data for HSPF Modeling

3.1. Study Area Description

The study area was the Byulmi-cheon watershed (1.21 km²), which is located along the upstream area of the Gyeongan-cheon watershed (255.4 km²) in the northwest region of South Korea. The Gyeongan-cheon watershed stream is one of the main tributaries of the Han River basin (the largest river in South Korea), which is directly linked to the Paldang multipurpose dam. Because the pollution source of the Gyeongan-cheon watershed accounts for 16 percent of Paldang dam, whereas the quantity of water in the Gyeongan-cheon watershed only represents 1.6 percent of Paldang dam, the water quality of the Gyeongan-cheon watershed must be sustainably managed. Therefore, the

Byulmi-cheon watershed, which has been used to obtain substantial observation data of water quantity and quality, was selected.

The study site lies within the latitude and longitude range of 127.16° E–127.17° E and 37.11° N–37.12° N (Figure 2). The watershed is 75% (0.83 km²) forest area and 11% (0.12 km²) cropland in the lowland fertile areas. Rice paddies and upland crops cover 6% and 5%, respectively, of the watershed. The remaining residential areas, including roads, grasslands and bare fields, constitute 4%, 3% and 7%, respectively, of the watershed. The average annual precipitation and mean air temperature over the past 30 years (1984–2013) were 1200.5 mm and 10.5 °C, respectively. Figure 2 shows the study area location and the distribution of agricultural areas within the watershed. The watershed was divided into three sub-watersheds for the HSPF modeling [2].

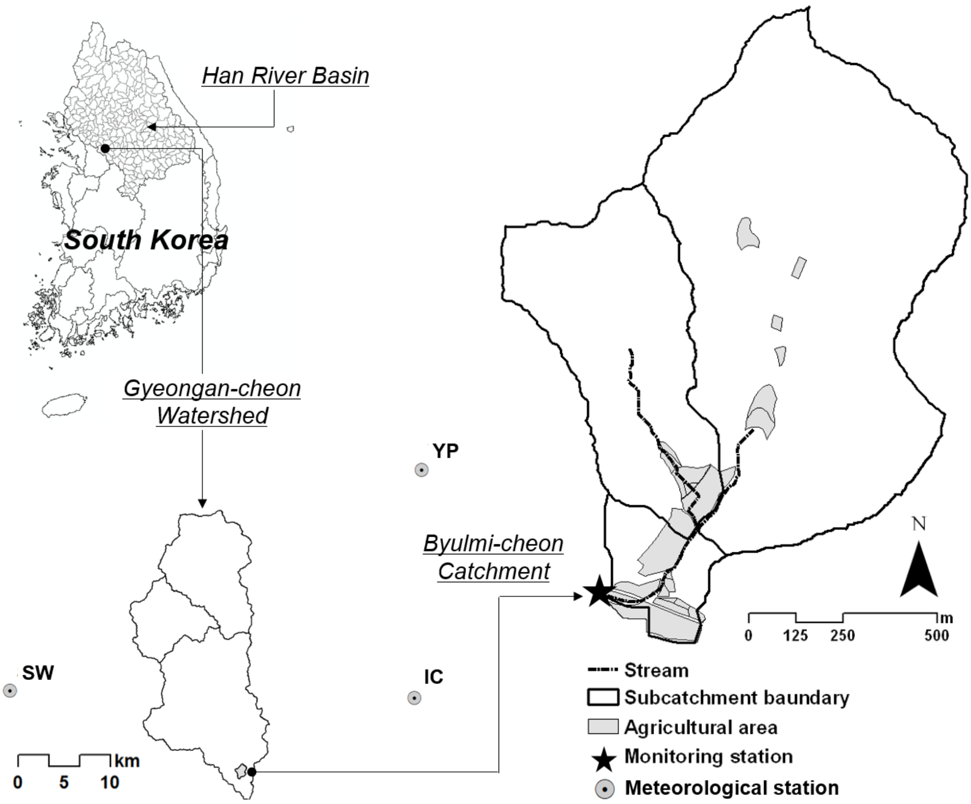

Figure 2. Location of the studied watershed, agricultural area distribution, and sub-watershed boundary for HSPF (Hydrological Simulation Program–Fortran) watershed modeling [2].

3.2. Spatial, Meteorological and Field Data

The Digital Elevation Model (DEM) was rasterized to 2-m grid cells from a 1:5000 scale vector map supplied by the Korea National Geography Institute (Figure 3a). The layer-related contour lines and elevation points were extracted from 1:5000-scale vector digital topographic maps and converted into grid Triangulated Irregular Network (TIN) coverage using Arc GIS. The soil properties with respect to texture, depth and drainage attributes were rasterized from a 1:25,000 scale vector map supplied by the Korea Rural Development Administration (Figure 3b). Twenty-three detailed classes of land-use data were prepared from a QuickBird satellite image captured on 1 May 2006, using on-screen digitizing with a Global Positioning System (GPS) field investigation (Figure 3c).

To simulate the hydrological cycle, the HSPF model required the following meteorological data: cloud cover, hourly rainfall, temperature, wind speed, solar radiation and dew-point temperature. Meteorological data for the 11-year period (2003–2013) were obtained from three weather stations located within the watershed (SW, IC and YP). Data from 2003 were used for the model's warm-up period. Data from a 10-year period (2004–2013) were used for the model application of change scenarios of upland crop areas. The hourly rainfall and stream discharge were monitored by automatic rainfall and water-level gauging stations with a Code Division Multiple Access (CDMA) wireless network system at the watershed outlet for three years (2011–2013). To facilitate the stream water quality measurements of sediment, total nitrogen (T-N) and total phosphorus (T-P), samples were collected using water quality auto samplers at the watershed outlet during rain events for three years (2011–2013).

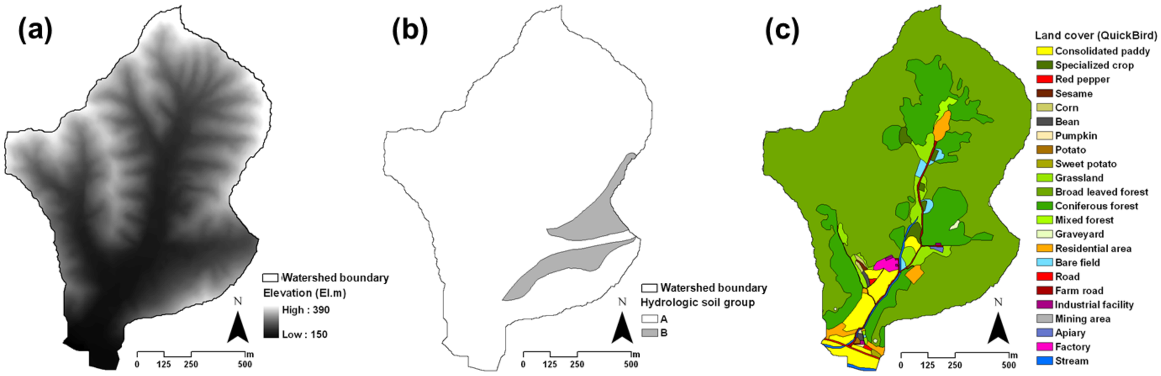

Figure 3. GIS data: (**a**) elevation; (**b**) hydrologic soil group and (**c**) land use [2].

3.3. Field Experiments for the Evaluation of Rice Straw Mulching and No-Tillage Crop Cultivation Effects

Field-scale experiments were conducted (2009–2012) to measure the runoff and water-quality reduction efficiency for radish and sesame under conventional farming, rice straw mulching and no-tillage conditions. Eight field plots 5 m in width by 30 m in length were built and operated on sandy loam soil. Four of these plots have slopes of 3% (representative of flatland), and the other four plots have slopes of 8% (representative of gentle slope land). The farming conditions were equally applied to plots under the two slope conditions for a comparison group of two conventional farming and two rice straw mulching practices for two years (2009–2010) and two conventional farming and two no-tillage practices for two years (2011–2012). Each plot was equipped with a sediment trap and flume at the end of the plots to measure runoff, sediment, T-N and T-P during rainfall events. Runoff was measured in five-minute intervals, and water sampling for sediment, T-N and T-P was conducted at one-hour intervals. The EMCs (Event Mean Concentrations) and NPS pollution loads were calculated via the official testing method with respect to water pollution processes in a laboratory. Conventional farming, rice straw mulching and no-tillage practices were repeatedly applied to plots 10 times every year.

3.4. Change Scenarios of Upland Crop Areas

The watershed is 75% forest area and 11% (6% rice paddies and 5% upland crops) cropland in the lowland fertile areas. For the model application of changes in upland crop (potato, sweet potato, pepper, radish, sesame, corn, bean, pumpkin, *etc.*) areas, land use maps of each land use type were prepared as one baseline and two scenarios: upland crop areas (1) 5% (baseline 2006, existing land use), (2) 10% (Scenario 1, all land use transforming into upland crop areas, except for forests and streams) and (3) 30% (Scenario 2, same conditions as (2) but with 20% of the forest transforming into upland crop areas). Figure 4 shows the land use scenarios and the distribution of upland crop areas within the watershed. The change scenarios of the upland crop areas were designed to obtain as realistic as possible an application range in this watershed and changed upland crop areas close to the stream.

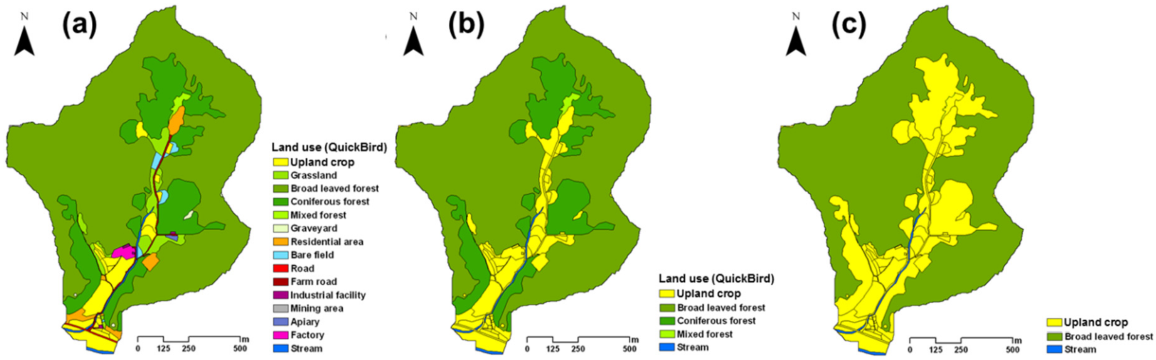

Figure 4. Comparison of the land use change areas in (**a**) baseline; (**b**) Scenario 1; and (**c**) Scenario 2.

3.5. HSPF Model Implementation

The HSPF model under conventional conditions was calibrated and validated hourly using 20 rainfall events for runoff and 14 rainfall events for stream water quality (sediment, T-N and T-P) using three years of data (2011–2013). Rainfall events were selected based on a minimum of two-hour durations and greater than 20 mm rainfall amount. The calibration was performed in four steps: (Step 1) the physical rate of the total runoff was controlled by parameters related to streamflow, (Step 2) the parameters related to evapotranspiration and soil moisture were calibrated, (Step 3) the baseflow was calibrated using parameters related to interflow and groundwater and (Step 4) the recession curve and peak runoff were calibrated.

Based on the field experiment results, the rice straw mulching and no-tillage effects were applied to the reduction of surface runoff from agricultural areas in the study watershed. These rice straw mulching and no-tillage effects were controlled by the following parameters: the infiltration capacity (INFILT), soil bulk density (BD), wilting point (WP) and field capacity (FC).

For the influence evaluation of changes in upland crop areas on runoff and NPS pollution loads, the HSPF model was run for three years (2011–2013, hourly simulations of rainfall event average) and 10 years (2004–2013, hourly simulations of annual average).

4. Results and Discussion

4.1. HSPF Model Calibration and Validation

A total of 21 of the most influential parameters were selected for calibration. The model parameters related to streamflow (NSUR, LSUR, LZSN and UZSN), evapotranspiration and soil moisture (INFILT, LZETP and AGWETP), interflow (INTFW and IRC), groundwater (AGWRC, KVARY and DEEPER), sediment (JSER, KSER and KRER), T-N (KDSAM, KADAM and KIMNI) and T-P (KDSP, KADP and KIMP) were calibrated (Table 1).

The results of the model calibration (2011–2012) and validation (2013) are summarized in Table 2. Nash and Sutcliffe [26] model efficiency (NSE) values and coefficients of determination (R^2) were used to assess the model performance. R^2 values are defined as the square of the coefficient of correlation [27]. The NSE ranges from $-\infty$ to 1. A value of 1 (E = 1) corresponds to a perfect match of the modeled discharge to the observed data. A value of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency of less than zero (E < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression above) is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1, the more accurate the model is [26]. The average NSE value for runoff was 0.64, and the average R^2 values for runoff, sediment, T-N, and T-P were 0.70, 0.56, 0.58 and 0.61, respectively. The average NSE values of streamflow were greater than 0.50, thereby indicating a satisfactory simulation [28]. According to Donigan and Love [29], the model calibration and validation could be classified as fair. The poorer model performance obtained for two events (18 June and 13 July in 2013) according to the runoff volume errors may be caused by the continuous hourly simulation during three years (2011–2013), whereas the model performance was evaluated based on rainfall events. The runoff volume errors affect the water quality errors. Hourly continuous HSPF modeling and evaluation are necessary to better understand contaminant transport during the rain events in the watershed.

Table 1. Calibrated parameters of the HSPF model.

Parameter		Definition	Range		Adjusted Value
			Min	Max	
Streamflow	NSUR	Manning's roughness coefficient	0.001	1	0.03–0.8
	LSUR	Length of the assumed overland flow plane (m)	0.3048	none	45.7
	LZSN*	Lower zone nominal storage (mm)	0.254	2540	304.8
	UZSN*	Upper zone nominal storage (mm)	0.254	254	2.5
Evapotranspiration and soil moisture	INFILT*	Soil infiltration capacity index (mm/h)	0.00254	2540	2.5–5.1
	LZETP	Lower zone ET parameter	0	2	0.1
	AGWETP*	Fraction of PET that can be satisfied from groundwater	0	1	0
Interflow	INTFW*	Interflow inflow parameter	0	none	8
	IRC*	Interflow recession parameter (/day)	0	0.999	0.1
Ground water	AGWRC	Groundwater recession coefficient	0.001	0.999	0.98
	KVARY	Groundwater recession parameter (mm)	0	none	0.8
	DEEPER	Fraction of groundwater inflow lost to deep groundwater	0	1	0.01
Sediment	JSER	exponent for transport of detached sediment	none	none	1.3
	KSER	coefficient for transport of detached sediment	0	none	0.4
	KRER	coefficient in the soil detachment equation	0	none	0.2
T-N	KDSAM	Ammonium desorption (/day)	0	none	0.1
	KADAM	Ammonium adsorption (/day)	0	none	0.1
	KIMNI	Nitrate immobilization (/day)	0	none	0.1
T-P	KDSP	Phosphate desorption (/day)	0	none	2
	KADP	Phosphate adsorption (/day)	0	none	0.1
	KIMP	Phosphate immobilization (/day)	0	none	0.1

* High-sensitivity parameters.

Table 2. Statistical summary of the HSPF calibration (2011–2012) and validation (2013) results.

Year	Date of Event	Rainfall			Runoff						Water Quality		
		Duration (h)	Amount (mm)	Intensity (mm/h)	Volume (mm)		QR[a] (%)		NSE[a]	$R^{2[a]}$	$R^{2[a]}$		
				Avg.	Obs.	Sim.	Obs.	Sim.			Sed. [a]	T-N	T-P
2011	22 June	65	202.3	3.1	89.6	71.2	44.4	35.3	0.56	0.65	-	-	-
	29 June	19	140.5	7.4	112.8	98.8	80.6	70.6	0.62	0.68	0.61	0.52	0.48
	3 July	19	121.0	6.4	108.2	88.7	89.4	73.3	0.79	0.81	0.42	0.71	0.52
	26 July	27	259.1	9.6	230.4	215.7	88.9	83.3	0.82	0.85	0.45	0.59	0.68
2012	2 April	22	74.2	3.4	28.6	30.2	38.6	40.8	0.64	0.68	0.94	0.61	0.82
	21 April	23	56.0	2.4	-	-	-	-	-	-	0.55	0.67	0.48
	5 July	30	220.1	7.3	121.6	103.2	55.3	46.9	0.79	0.73	0.79	0.91	0.76
	15 July	26	92.5	3.5	80.7	56.3	87.7	61.2	0.72	0.77	-	-	-
	19 July	9	67.0	7.4	42.7	44.8	63.8	66.8	0.45	0.50	-	-	-
	15 August	9	75.1	8.1	37.4	49.2	49.8	65.6	0.57	0.62	-	-	-
	20 August	58	138.2	2.4	109.2	61.1	79.1	44.3	0.58	0.54	0.48	0.54	0.49
	30 August	17	89.7	5.3	78.3	55.9	88.0	62.8	0.66	0.77	-	-	-
	4 September	21	79.0	3.8	43.7	44.6	55.4	56.5	0.59	0.61	-	-	-
	16 September	26	94.0	3.1	61.2	52.9	65.1	56.3	0.63	0.78	-	-	-
2013	27 May	28	74.5	2.6	50.6	24.9	68.3	33.6	0.73	0.83	0.61	0.89	0.72
	18 June	23	87.8	3.8	24.9	26.1	28.7	30.0	0.47	0.51	0.38	0.45	0.43
	8 Jule	8	44.2	5.5	28.9	17.0	65.4	38.4	0.51	0.62	0.42	0.43	0.55
	13 July	69	136.2	2	100.8	60.6	74.0	44.5	0.43	0.58	0.48	0.42	0.57
	22 July	50	260.0	5.2	194.0	210.7	74.6	81.0	0.69	0.71	-	-	-
	29 July	7	22.0	3.1	-	-	-	-	-	-	0.51	0.39	0.61
	31 July	4	36.8	9.2	-	-	-	-	-	-	0.63	0.55	0.72
	4 August	7	47.9	6.8	-	-	-	-	-	-	0.52	0.48	0.68
	10 August	2	75.3	37.5	44.7	38.7	59.6	51.6	0.71	0.84	-	-	-
	14 September	11	72.6	6.5	47.9	56.7	66.5	78.7	0.78	0.86	-	-	-
Average		24	106.9	6.5	81.8	70.4	66.2	56.1	0.64	0.70	0.56	0.58	0.61

[a] QR = runoff ratio, NSE = Nash and Sutcliffe model efficiency, R^2 = coefficient of determination, Sed. = sediment

4.2. HSPF Watershed-Scale Evaluation of Rice Straw Mulching and No-Tillage BMPs Based on Field-Scale Results

Figure 5 presents an example of field experiment results for runoff caused by a 42.5-mm rainfall for radish and sesame under rice straw mulching and no-tillage conditions compared to conventional farming (no-rice-straw mulching and tillage) with sloped plots at 3% and 8%, respectively. Compared with the conventional no-rice-straw mulching conditions, the rice straw mulching conditions reduced the runoff ratio, sediment, T-N and T-P by 9.0%, 95.9%, 32.6% and 43.5%, respectively. Compared with the conventional tillage conditions, the no-tillage conditions reduced the runoff ratio, sediment, T-N and T-P by 22.5%, 82.5%, 67.8% and 70.6%, respectively. Table 3 shows the average reduction rates of the runoff and NPS pollution loads based on the results of the field experiment of 3% and 8%, respectively. The rice straw mulching method applied to cover the soil surface of penetration straw has been found to be effective for facilitating the soil infiltration of rainwater and for preventing soil loss by reducing surface runoff. Generally, the tillage practice disturbs the soil surface layer (to a depth of 20–30 cm), therein providing high soil porosity and infiltration capacity but compacts the underlying soil layers, thus impeding the soil water flow. The soil properties after tillage are stabilized by the rainfall energy impact and irrigation practices [2]. The no-tillage practice maintains the natural physical soil properties of the entire soil layer, which allows microbial and biotic activities to increase the INFILT, BD, WP and FC of the soil environment. Therefore, for the conventional, rice straw mulching and no-tillage conditions of HSPF watershed modeling, the parameter values for INFILT, BD, WP and FC in the upland crop areas were selected to reproduce the runoff and nutrient discharge characteristics observed in the field results.

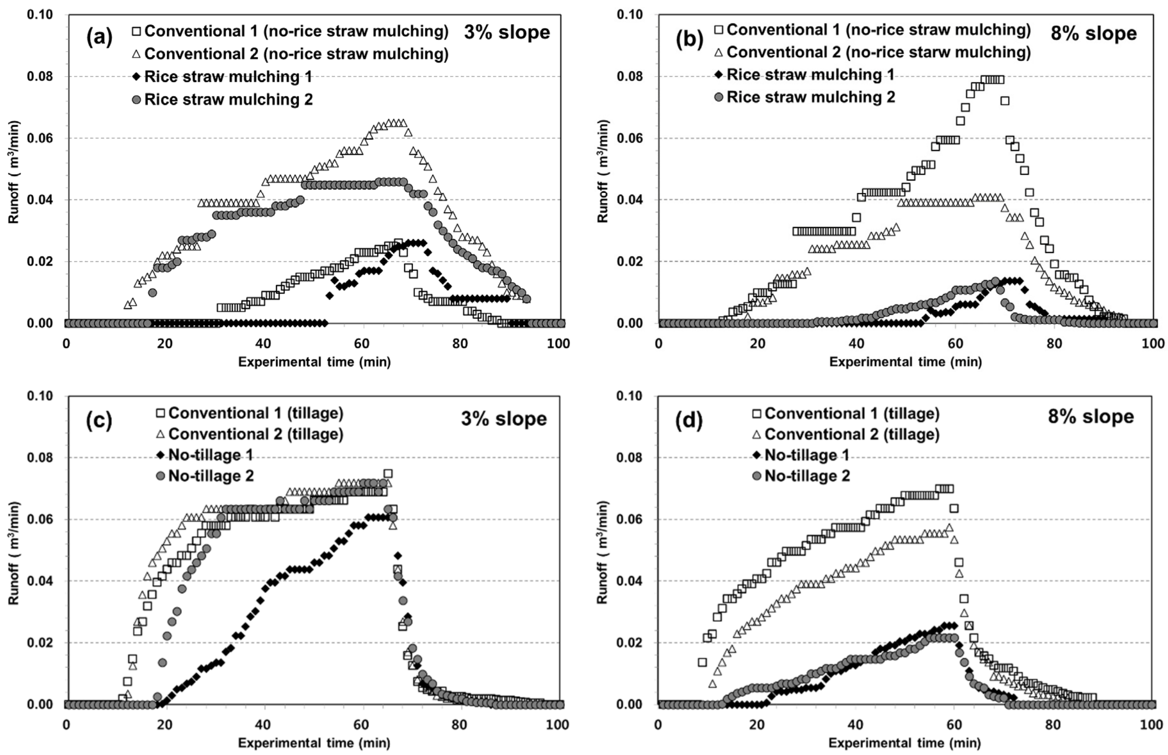

Figure 5. Field experiment results for runoff under the (**a**) rice straw mulching at 3% slope plot; (**b**) rice straw mulching at 8% slope plot; (**c**) no-tillage conditions at 3% slope plot; and (**d**) no-tillage conditions at 8% slope plot.

Table 3. Summary of the field experiment results under rice straw mulching and no-tillage conditions.

Item	2009–2010			2011–2012		
	Conventional (No-Rice Straw Mulching)	Rice Straw Mulching	Variation (%)	Conventional (Tillage)	No-Tillage	Variation (%)
Runoff ratio (%)	12.4	3.5	−9.0	41.8	19.4	−22.5
Sediment (kg/ha)	1219.4	49.9	−95.9	137.1	24.0	−82.5
T-N (kg/ha)	3.6	2.4	−32.6	7.0	2.3	−67.8
T-P (kg/ha)	3.2	1.8	−43.5	0.4	0.1	−70.6

Based on the reductions in the runoff ratio of 9.0% and 22.5% under the rice straw mulching and no-tillage conditions observed in the average results for each field slope, the 1 parameter value (INFILT) for the rice straw mulching conditions and the 4 parameter values (INFILT, BD, WP and FC) for the no-tillage conditions were estimated by trial and error method until they achieved similar reductions in the runoff ratio (Table 4). The HSPF simulation was conducted with the INFILT, BD, WP and FC values, and the percent changes in runoff, sediment, T-N and T-P for the applications of rice straw mulching and no-tillage BMPs are shown in Table 5. The watershed runoff ratio, sediment, T-N and T-P values under the rice straw mulching conditions were reduced by 10.4%, 68.7%, 31.6% and 41.3%, respectively, compared with the parameters of the conventional conditions. The results for the no-tillage conditions show that the watershed runoff ratio, sediment, T-N and T-P values were reduced by 21.5%, 83.4%, 51.9% and 60.2%, respectively, compared with the parameters under the tillage conditions. The reduction in sediment was the greatest, followed by the reduction in T-P, which is closely correlated with sediment. Under runoff conditions, sediment with a high phosphate adsorption capacity can remove phosphate from the solution phase [30]. T-N reduction within a watershed is affected by slow discharge to the baseflow and by the uncertainty of nitrogen characteristics such as volatilization into air and interactions with the soil [2].

To further illustrate the reduction effect, comparisons of the quantile plots for the hourly runoff discharge, sediment T-N and T-P discharge loads under conventional, rice straw mulching and no-tillage conditions are shown for each year in Figure 6. The reduced runoff discharge, sediment T-N and T-P discharge loads increase the no-tillage, rice straw mulching and conventional conditions in that order. The rice straw mulching and no-tillage conditions significantly reduced the discharge within the top 10% of the distribution (Figure 6a). Significant reductions in the sediment, T-N and T-P also occurred within the top 2%, 10% and 10%, respectively, of the distribution (Figure 6b–d).

Table 4. Parameter values for the soil bulk density (BD) and infiltration capacity (INFILT) for the rice straw mulching and no-tillage modeling.

Parameter		Conventional (No Rice Straw Mulching or Tillage)	Rice Straw Mulching	No-Tillage
Soil infiltration capacity (mm/h)	Upland crop	2.5	5.1	12.7
	Forest	5.1	10.2	25.4
	Etc.	5.1	10.2	20.3
Bulk density (Mg/m^3)		1.3	1.3	1.9
Wilting point		0.146	0.146	0.240
Field capacity		0.263	0.263	0.381

Table 5. Variation of runoff and NPS pollution for each rainfall event for the rice straw mulching and no-tillage applications.

Year	Date of Event	Rainfall (mm)	QR[a] (%)			Variation (%)							
			Conventional	Rice Straw Mulching	No-Tillage	Rice Straw Mulching				No-Tillage			
						QR[a]	Sed.[a]	T-N	T-P	QR[a]	Sed.[a]	T-N	T-P
2011	22 June	202.3	35.3	23.4	16.5	−11.9	-	-	-	−18.7	-	-	-
	29 June	140.5	70.6	58.3	39.3	−12.3	−75.0	−16.5	−30.1	−31.2	−92.5	−41.8	−57.8
	3 July	121.0	73.3	61.2	45.5	−12.2	−70.7	−15.8	−26.4	−27.8	−90.3	−39.0	−51.8
	26 July	259.1	83.3	57.3	55.6	−26.0	−70.2	−9.3	−21.4	−27.6	−90.9	−28.4	−40.4
2012	2 April	74.2	40.8	24.1	12.8	−16.7	−73.8	−46.4	−54.4	−28.0	−90.0	−75.8	−82.7
	21 April	56.0	-	-		-	−59.1	−55.5	−59.2	-	−70.1	−73.9	−75.1
	5 July	220.1	46.9	33.7	18.6	−13.2	−59.0	−25.6	−32.0	−28.3	−86.6	−58.4	−66.5
	15 July	92.5	61.2	52.0	29.4	−9.1	-	-	-	−31.8	-	-	-
	19 July	67.0	66.8	60.4	42.2	−6.4	-	-	-	−24.6	-	-	-
	15 August	75.1	65.6	62.7	27.8	−2.9	-	-	-	−37.8	-	-	-
	20 August	138.2	44.3	36.4	37.3	−7.9	−69.2	−28.8	−34.9	−7.0	−85.1	−43.0	−46.5
	30 August	89.7	62.8	49.2	32.9	−13.6	-	-	-	−29.9	-	-	-
	4 September	79.0	56.5	48.6	38.5	−7.8	–	–	–	−18.0	–	–	–
	16 September	94.0	56.3	47.9	46.0	−8.3	–	–	–	−10.3	–	–	–
2013	27 May	74.5	33.6	21.1	15.9	−12.5	−73.0	−46.4	−55.0	−17.7	−85.5	−72.0	−79.1
	18 June	87.8	30.0	13.4	12.0	−16.6	−82.7	−62.8	−74.2	−18.0	−88.2	−80.1	−86.3
	8 July	44.2	38.4	27.8	23.5	−10.6	−77.8	−36.2	−53.0	−14.9	−88.1	−60.1	−71.9
	13 July	136.2	44.5	35.3	27.5	−9.2	−68.0	−30.6	−38.3	−17.0	−84.2	−54.7	−62.5
	22 July	260.0	81.0	75.4	49.5	−5.7	-	-	-	−31.5	-	-	–
	29 July	22.0			-	-	−25.5	−6.6	−7.3	–	−30.9	+8.6	+10.7
	31 July	36.8	-	-	-	-	−69.0	−19.4	−31.2	–	−87.6	−38.0	−51.7
	4 August	47.9	-	-	-	-	−89.4	−42.2	−60.6	–	−97.3	−69.9	−81.6
	10 August	75.3	51.6	58.5	63.8	6.9	-	-	-	+12.2	–	–	–
	14 September	72.6	78.7	67.3	56.1	−11.4	-	-	-	−22.6	–	–	–
Average		106.9	56.1	45.7	34.5	**−10.4**	**−68.7**	**−31.6**	**−41.3**	**−21.5**	**−83.4**	**−51.9**	**−60.2**

[a] QR = runoff ratio, Sed. = sediment

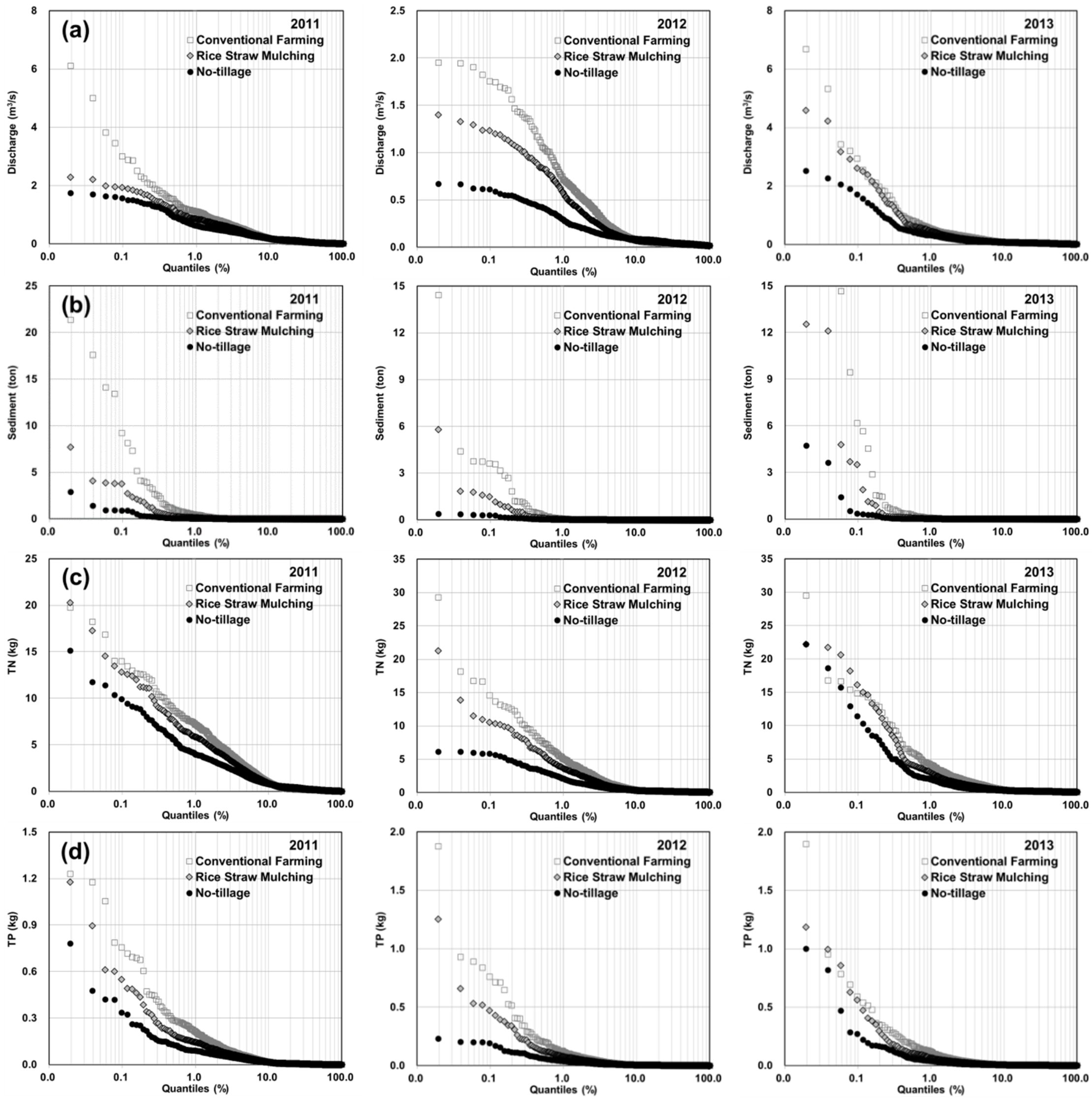

Figure 6. Quantile plots of the hourly simulated (**a**) discharge; (**b**) sediment; (**c**) T-N; and (**d**) T-P for the conventional, rice straw mulching and no-tillage BMP scenarios.

4.3. HSPF Evaluation of Rice Straw Mulching and No-Tillage BMPs Based on Change Scenarios of Upland Crop Areas

To evaluate the influence of changes in upland crop areas on runoff and NPS pollution loads, the HSPF model was run for three years (2011–2013, hourly simulation of rainfall event average) and 10 years (2004–2013, hourly simulation of annual average) with land use data for the baseline scenario (upland crop area of 5%), Scenario 1 (upland crop area of 10%) and Scenario 2 (upland crop area of 30%). Then, the runoff and NPS pollution loads were compared to those with rice straw mulching and no-tillage BMPs. Table 6 shows the variations of runoff and NPS pollution loads for rainfall events and annual averages using the model and land use scenarios. The hourly results for rainfall event averages show that the runoff ratio, sediment, T-N and T-P values increased by 3.2%, 15.7%, 44.5% and 22.7% in Scenario 1 and by 5.1%, 65.7%, 252.2% and 133.3% in Scenario 2 under the conventional condition. In addition, they increased by 2.7%, 16.6%, 51.1% and 28.4% in Scenario 1 and 5.0%, 87.4%, 276.8% and 161.3% Scenario 2 under the rice straw mulching condition, by 1.9%, 0.4%, 48% and 26.8% in Scenario 1, and by 4.0%, 45.1%, 262.8% and 155% in Scenario 2 under the no-tillage condition. Because the upland crop areas within the watershed increased the runoff ratio, sediment, T-N and T-P values increased. The sediment, T-N and T-P values were greatly increased compared to the runoff discharge.

Table 6. Variation of runoff and NPS pollution for rainfall events and annual averages of the hourly simulated results for conventional, rice straw mulching and no-tillage applications when applying change scenarios of upland crop areas in the model

Scenario		Variation (%)							
		Scenario 1 (UCA[a] 10%)				Scenario 2 (UCA[a] 30%)			
		QR[a]	Sed.[a]	T-N	T-P	QR[a]	Sed.[a]	T-N	T-P
Conventional	Rainfall event average (2011–2013)	+3.2	+15.7	+44.5	+22.7	+5.1	+65.7	+252.2	+133.3
	Annual average (2004–2013)	+1.7	+15.1	+36.8	+22.0	+1.8	+59.4	+208.2	+127.6
Rice straw mulching	Rainfall event average (2011–2013)	+2.7	+16.6	+51.1	+28.4	+5.0	+87.4	+276.8	+161.3
	Annual average (2004–2013)	+1.6	+13.8	+35.5	+22.2	+1.6	+66.4	+200.7	+130.1
No−tillage	Rainfall event average (2011–2013)	+1.9	+0.4	+48.0	+26.8	+4.0	+45.1	+262.8	+155.0
	Annual average (2004–2013)	+1.6	+3.4	+33.2	+21.0	+1.5	+56.4	+188.6	+125.8

[a] QR = runoff ratio, Sed. = sediment, UCA = Upland crop area.

Figure 7 shows the hourly simulated peak runoff and runoff volume for rainfall events in relation to rainfall for three years (2011–2013) for the above land use scenarios. The straight line method was used for baseflow separation of the hydrograph. The results show that substantial reductions in peak runoff and runoff volume in all scenarios were found for large rainfall events. The average peak runoff and runoff volume for all scenarios father decreased by 9.2% and 6.0% under the rice straw mulching condition and by 7.3% and 11.5% under the no-tillage condition when the rainfall amount was over 200 mm when compared with rainfall events over 100 mm. Although peak runoff and runoff volume increased with increasing upland crop area, peak runoff and runoff volume can be reduced compared to conventional farming by applying rice straw mulching and no-tillage BMPs. Figure 8 presents the annual change in discharge, sediment, T-N and T-P for 10 years (2004–2013) for the above land use scenarios. The discharge, sediment, T-N and T-P were more strongly affected by upland crop area within the watershed compared with BMPs. In particular, the no-tillage practice was certainly helpful for reducing NPS pollution loads (sediment, T-N and T-P) compared to using rice straw mulching. The proportion of NPS pollution loads was increased at the same ratio of increasing upland crop area (a tripling of the upland crop area corresponded to a six-fold increase in NPS pollution loads). In particular, Table 6 and Figure 8b show the obvious change in sediment loads by land use scenarios at the watershed outlet main channel. Based on the result of the study, rainfall−runoff can be effectively controlled by farming methods in upland areas such as rice straw mulching and no-tillage practices. In addition, as a result, sediment loads flowing into the stream are decreased.

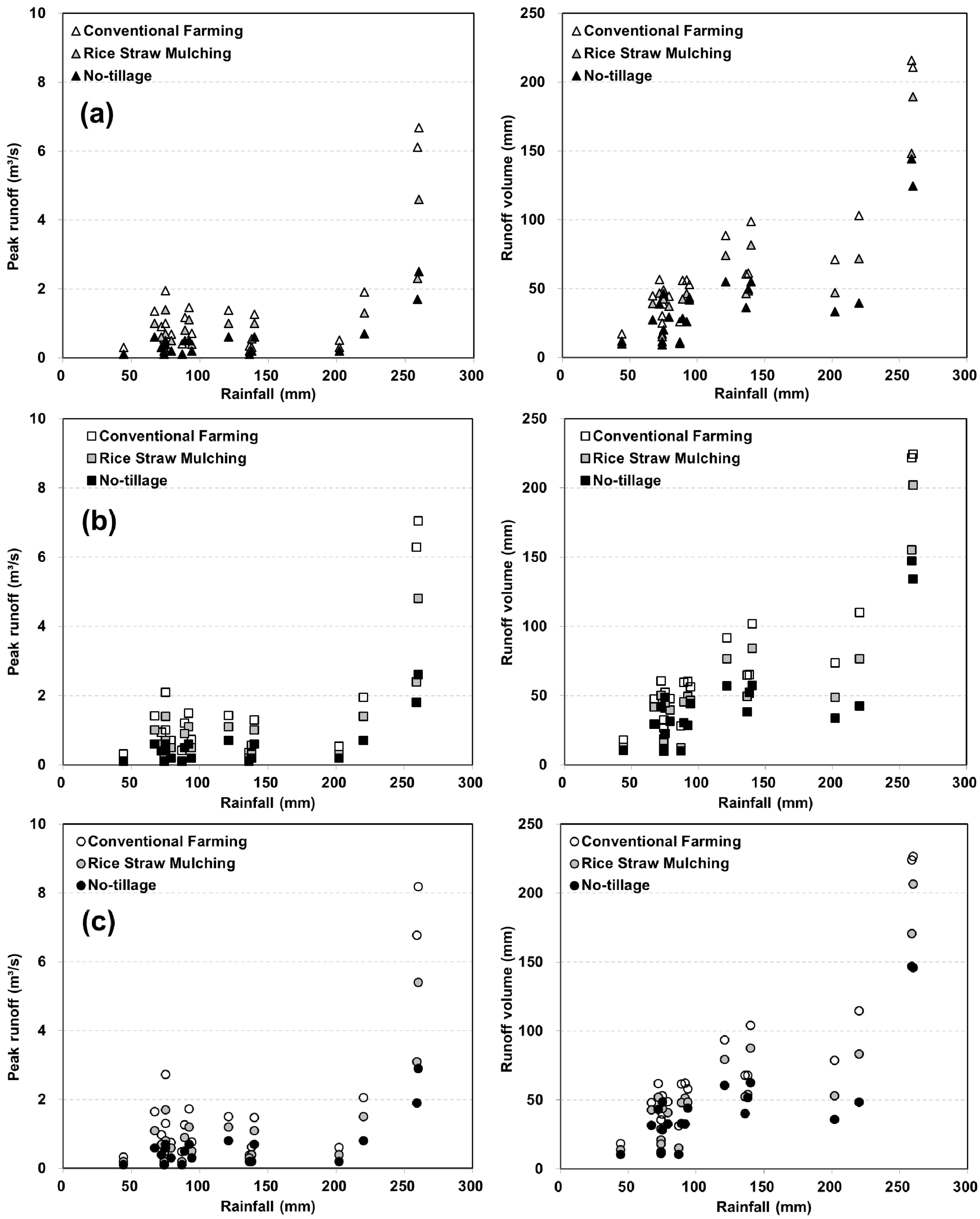

Figure 7. The peak runoff (left figure) and runoff volume (right figure) for rainfall events of the hourly simulated of the conventional, rice straw mulching and no-tillage operations for (**a**) baseline; (**b**) Scenario 1; and (**c**) Scenario 2 when applying change scenarios of upland crop areas

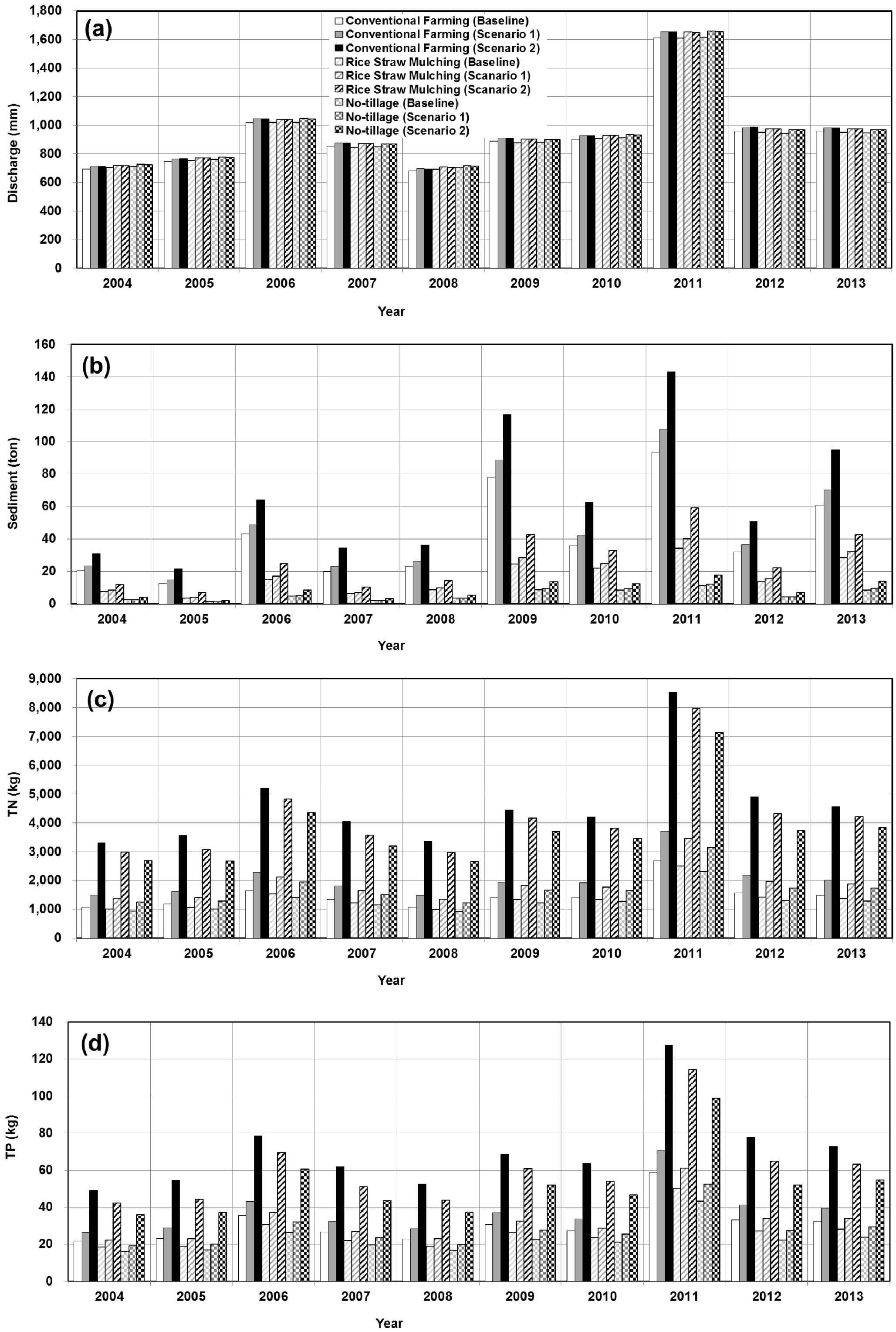

Figure 8. Annual change in the hourly simulated (**a**) discharge; (**b**) sediment; (**c**) T-N; and (**d**) T-P for conventional, rice straw mulching and no-tillage operations when applying change scenarios of upland crop areas

5. Conclusions

In this study, the HSPF model was applied at a watershed scale to evaluate whether NPS pollution loads to streams are reduced by applying rice straw mulching and no-tillage BMPs in upland crop areas.

Before the evaluation, the model was calibrated and validated using 20 rainfall events for runoff and 14 rainfall events for stream water quality (sediment, T-N and T-P) for a 1.21 km^2 watershed with 5% upland crop areas (baseline). For the application of rice straw mulching and no-tillage BMP evaluation using the HSPF model, field-scale experiments under conventional (no-rice straw mulching or tillage), rice straw mulching and no-tillage conditions were conducted to determine the model parameters and degree to which they should be controlled. Based on results from field experiment from plots with 3% and 8% slopes under radish and sesame cultivation, the INFILT parameter under the rice straw mulching condition and the INFILT, BD, WP and FC parameters under the no-tillage condition of the HSPF model were selected to reproduce the field runoff and nutrient discharge characteristics. The HSPF evaluation based on the application of BMPs for the 1.21 km^2 watershed showed that the watershed runoff ratio, sediment, T-N and T-P values were reduced by 10.4%, 68.7%, 31.6% and 41.3% under the rice straw mulching condition and 21.5%, 83.4%, 51.9% and 60.2% under the no-tillage condition compared with conventional conditions. The greatest reduction in NPS pollution loads was observed for the sediment value, followed by T-P and T-N. In addition, the land use change scenarios for the baseline (5% upland crop area), Scenario 1 (10% upland crop area) and Scenario 2 (30% upland crop area) were applied with the model for three years (2011–2013, hourly simulation for rainfall event average) and 10 years (2004–2013, hourly simulation for annual average). The hourly results for the rainfall event averages of the evaluation show that the runoff ratio, sediment, T-N and T-P values increased by 1.9%, 0.4%, 48.0% and 26.8% in Scenario 1 and by 4.0%, 45.1%, 262.8% and 155.0% in Scenario 2 under the no-tillage condition. The no-tillage practice was more effective at reducing NPS pollution loads (sediment, T-N and T-P) compared to using rice straw mulching.

The rice straw mulching and no-tillage conditions for BMPs cannot be perfectly simulated due to limited results from model parameters. However, this study attempted to combine field experiments and watershed modeling to facilitate parameter adjustment and reduce uncertainty in the model. The results of this study are useful in terms of non-structural mitigation measures in regard to how agricultural NPS pollution loads can be reduced in watersheds. The rice straw mulching and no-tillage operations can provide large reductions in NPS pollution loads and the enhancement of the ecological health of the Byulmi−cheon watershed. The BMPs recommended in this study entirely depend on farmers maintaining efforts towards rice straw mulching and no-tillage practices. However, farmers have difficulties in securing and/or managing rice straw mulching and no-tillage practices as a result of machinery work destruction and the succession of conditions to the next year. Therefore, the participation of farmers as well as institutional support are necessary for the successful enactment of non-structural mitigation measures. The lessons learned from this study will be incorporated into the TMDL (Total Maximum Daily Loads) planning and management of the local governments of the watershed to achieve the target water quality.

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