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Risk assessment of watershed erosion at Naesung Stream, South Korea

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ABSTRACT

A three-tiered approach was used to assess erosion risks within the Nakdong River Basin in South Korea and included: (1) a screening based on topography and land use; (2) a lumped parameter analysis using RUSLE; and (3) a detailed analysis using TREX, a fully distributed watershed model. These tiers span a range of spatial and temporal scales, with each tier providing increasing detail and resolution. The first two tiers were applied to the entire Nakdong River Basin and the Naesung Stream watershed was identified as having the highest soil erosion risk and potential for sedimentation problems. For the third tier, the TREX watershed model simulated runoff, channel flow, soil erosion, and stream sediment transport in the Naesung Stream watershed at very high resolution. TREX was calibrated for surface flows and sediment transport, and was used to simulate conditions for a large design storm. Highly erosive areas were identified along ridgelines in several headwater areas, with the northeast area of Songriwon having a particularly high erosion potential. Design storm simulations also indicated that sediment deposition of up to 55 cm could occur.

1. Introduction

Upland erosion and sediment yield from large watersheds is a significant river management issue and critical environmental problem (Kane and Julien, 2007). Typically, land use changes disturbing natural vegetative cover increase soil erosion and watershed-scale sediment yield (Ramos-Scharrón and MacDonald, 2007). Watershed-scale erosion risk assessments can serve as a reference point to identify areas where countermeasures to reduce soil erosion and sediment yield would be most effective.

Numerous studies have tried to simulate soil erosion processes, evaluate soil erosion hazards or model hydrological processes at the landscape level (Nekhay et al., 2009). Assessment of land degradation is difficult if there is not sufficient data and financing (Hammad, 2011). Although several models for erosion risk assessment have been developed and used for the last two decades, the Revised Universal Soil Loss Equation (RUSLE) has been widely applied to predict soil losses due its simplicity (Morgan, 1986; Soil and Water Conservation Society, 1994). RUSLE enables users to estimate erosion potentials on a cell-by-cell basis and is an effective tool to identify spatial patterns of soil loss (Kim and Julien, 2006; Hammad, 2011). Spatially-distributed, physically-based models are even more powerful tools for analysis of precipitation, overland runoff, channel flow, soil erosion, and stream sediment transport. While simpler tools like impairment indexes and RUSLE can be applied at broad scales to screen watersheds and identify areas likely to contribute most to soil erosion losses, detailed physically-based models can be applied at finer scales to assess soil erosion potentials in high risk areas with high resolution.

This study was performed as an outgrowth of the Four Major Rivers Restoration Project (FMRRP) in Korea. The FMRRP was conducted in the Han, Nakdong, Geum, and Yeongsan River Basins with the objectives to: (1) secure abundant water resources; (2) implement flood control measures; (3) improve water quality and restore the ecosystem; and (4) create multipurpose spaces such as waterfront for local residents (Ji et al., 2012). Most of the annual precipitation in Korea is concentrated from June to September as part of the Pacific typhoon season. During intense storms, the Nakdong River Basin is impacted by soil erosion, land slides, and major flashfloods (Kim and Julien, 2006; Ji et al., 2011). As part of FMRRP implementation, eight large-scale weirs were constructed on the Nakdong River, along with dredging to increase flood control capacity of the weirs and to maintain lower water levels during floods. However, construction may have altered the watershed's sediment transport regime, increasing the need for soil

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conservation and management practices to reduce sediment loads from upstream watersheds and tributaries to protect flood control infrastructure. A watershed-scale erosion risk assessment was therefore indicated to identify erosion-prone areas so control practices could be targeted for better management practices of the Nakdong River Basin.

The objectives of this study were to develop a new approach for watershed soil erosion risk assessment. A three tiered approach that includes a landscape-based impairment ranking, a lumped parameter assessment driven by annual rainfall, and a detailed physically-based model was developed to target areas prone to the highest erosion. The applicability of this three-tiered approach is demonstrated for the Nakdong River Basin in South Korea. These first two tiers identified sub-watershed areas prone to the highest erosion. The third tier was utilized a high-resolution physically-based watershed model to provide spatial detail about erosion potentials needed to inform management decisions regarding erosion control practices. For this third tier analysis, a watershed model was calibrated and used to simulate a large design rainstorm. The high-resolution watershed model was also used to estimate the maximum potential sediment deposition in the stream network.

2. Study area and database

2.1. Site description

The Nakdong River Basin is in the southeastern region of South Korea and covers a drainage area of about 23,384 km^2 as shown in Fig. 1. The Nakdong River flows 510 km from the Taebaek Mountains to the East Sea. Every year from June to September, the River is impacted by several typhoons resulting in major floods (Ji et al., 2011). Mean annual precipitation over the Basin is 1186 mm and mean annual temperatures range from 12 to 16 °C (Park et al., 2008). During the FMRRP, eight new weirs were constructed along the main channel of the Nakdong River since 2008 (Fig. 1). The Naesung Stream watershed is located within the upper region of the Nakdong River Basin (North Gyeongsang Province, Gyeongsangbuk-do) and drains an area of approximately 1815 km^2. Naesung Stream joins the main river upstream of the Sangju Weir, which is the upper-most of the new weirs constructed on the Nakdong River. Surface topography of the Naesung Stream watershed ranges from 54 m to 1420 m above mean sea level.

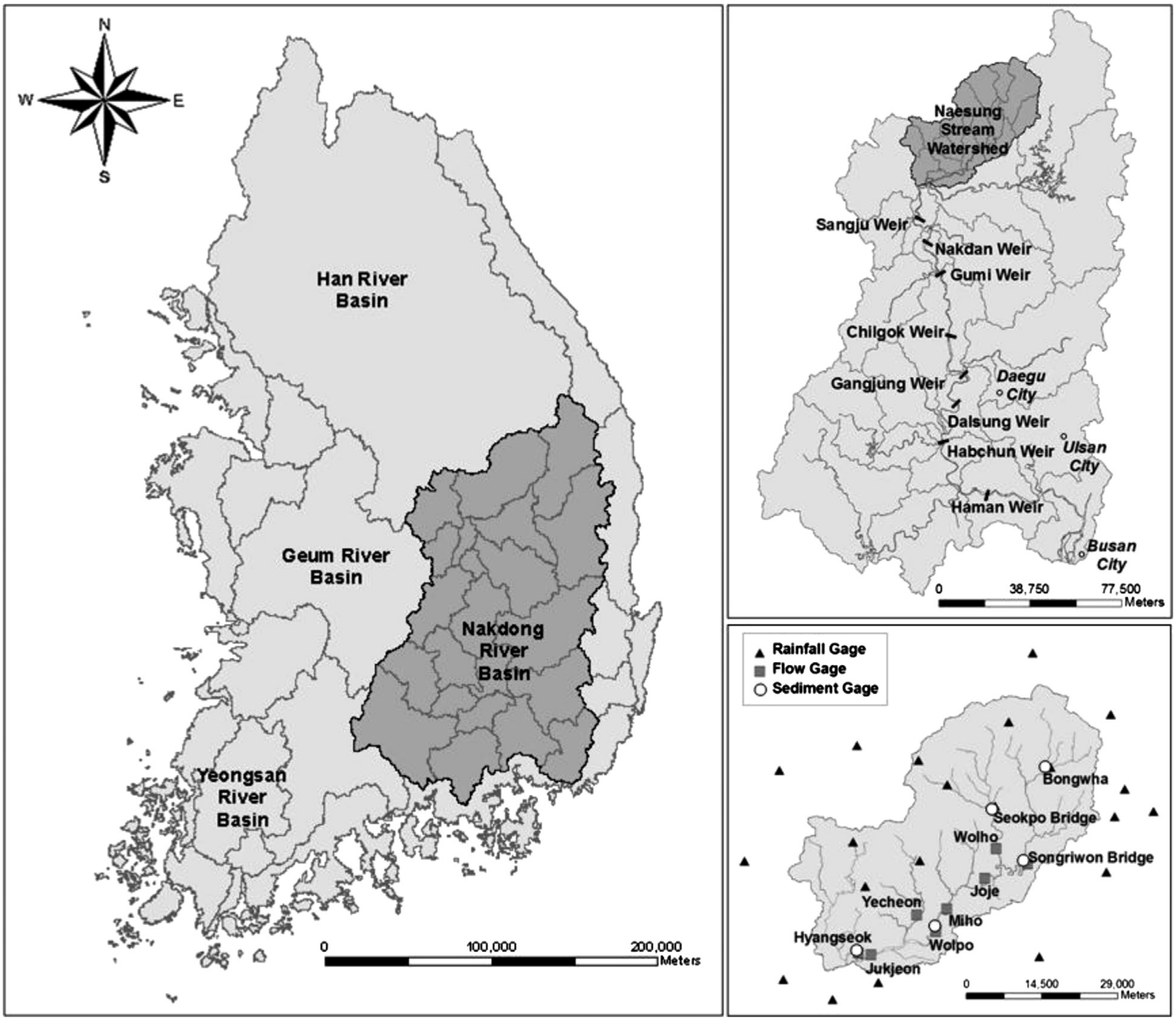


Fig. 1. Nakdong River and Naesung Stream watersheds in South Korea.

2.2. *Database establishment*

The database for the Naesung Stream watershed includes rainfall measurements reported at 22 stations, stream flows reported at nine stations, and sediment discharges and yields estimated at seven stations. Rainfall and flow data were reported on an hourly basis and were available for 2008 and 2009 as well as other periods. Maps displaying locations of the Naesung Stream watershed, stream network, and monitoring stations are presented in Fig. 1. Stations at Hyangseok, Miho, Wolho, and Yecheon provide stream flow measurements for sub-basins within the watershed as well as near the watershed outlet. Stations at Hyangseok and Songriwon provide sediment discharge and yield estimates. The database also included geographic information system (GIS) files for ArcGIS 9.3 (ESRI, 2008), HEC-RAS hydraulic model files (USACE, 2008), as well as additional data such as stage-discharge relationships and sediment discharge information. Watershed land surface elevations were defined using digital elevation model (DEM) data. The database for soil types, land uses, and their spatial distributions were also established for the upland erosion modeling.

3. Tier 1 and 2 analyses of upland erosion risk

The first two tiers of analysis were applied to the entire Nakdong River Basin to identify sediment source areas and sub-basins that present the highest soil erosion risks. The first tier provided a rapid screening of the entire basin using a sediment impairment ranking based on topography and land use. The second tier provided a more detailed evaluation based on a lumped-parameter assessment of soil erosion losses using RUSLE and annual rainfall. In addition to topography and land use, the second tier assessment included the impact of rainfall and soil property variation.

3.1. *Tier 1: sediment impairment ranking*

Land use distributions and topography of watersheds are major impact factors on soil erosion losses. Although land covered by forest, lakes, and wetlands would deliver little sediment to streams, agricultural use and developing areas are expected to be larger sediment contributors. The 226 sub-basins of the Nakdong River basin were assessed using their land use percentages (Fig. 2)

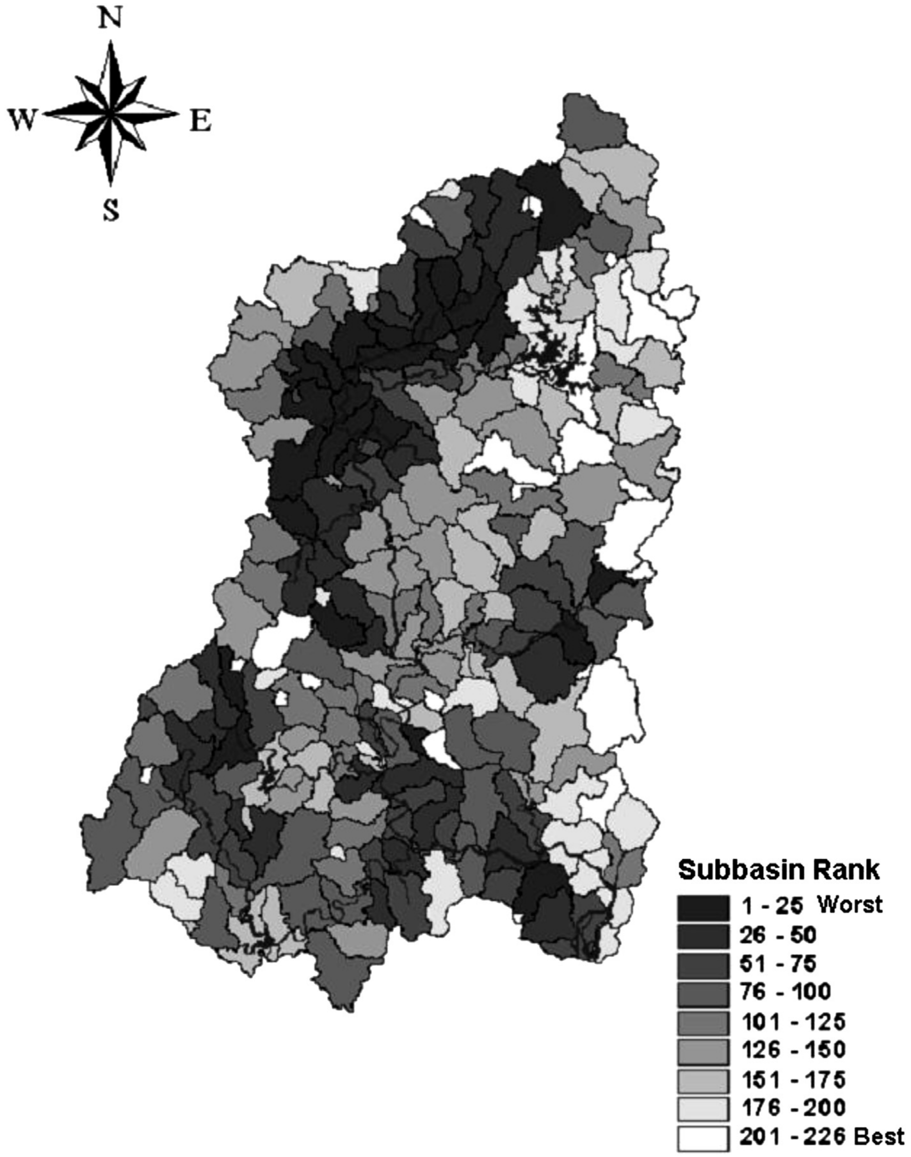
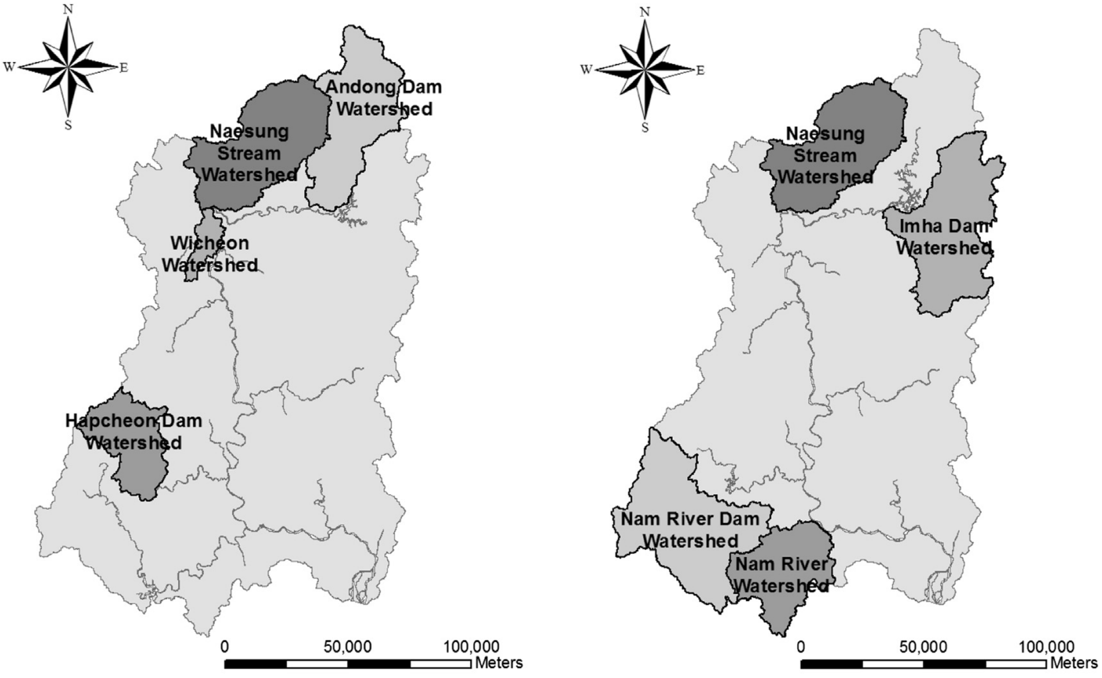


Fig. 2. Nakdong River basin ranking for sediment assessment.



(a) Sediment impairment ranking (b) RUSLE

Fig. 3. Sub-basins with high risk of soil loss.

to rank sub-basins by their potential for soil loss. Sub-basins with higher percentages of developed and agricultural areas were given higher rankings. Sub-basins with the lowest percentages of forested areas, lakes, and wetlands were also given higher rankings. Rankings for all land use percentages were added giving an overall ranking as shown in Fig. 2. Using this screening method, over 50% of Nakdong River watershed sub-basins were considered highly erodible. Sub-basins for Naesung Stream, Wi Stream, and the Hapcheon Dam watersheds had the highest erosion risk (Fig. 3a).

3.2. Tier 2: estimating soil loss using RUSLE

As a refinement to the initial screening by land use, watershed erosion potentials were evaluated using annual rainfall and a soil erosion relationship. Common soil erosion relationships include the Universal Soil Loss Equation (USLE) and its variants. The USLE (Wischmeier and Smith, 1978) is an empirical approach based on a large database of field plot measurements. It was developed to predict soil losses from agriculture and is designed to estimate long-term average annual soil loss associated with sheet and rill

Table 1
Particle classes and properties.

Particle class name	Representative size range (mm)	Effective diameter d_p (mm)	Specific gravity G_s (dimensionless)	Fall velocity w_s (m/s)	Critical shear stress for deposition $\tau_{cd,ov}$, $\tau_{cd,ch}$(Pa)	Critical erosion velocity $v_{c,ch}$ (m/s)
Gravel-Cobble	>16	32	2.65	0.678	26	1.39
Gravel	4–16	8	2.65	0.338	5.7	0.693
Sand	0.125–4	0.5	2.65	0.066	0.27	0.268
Silt/Clay	>0.125	0.016	2.65	0.000167	0.065	0.022

Table 2
Soil classes and properties.

Soil type	Critical erosion velocity $v_{c,ov}$ (m/s)	Effective porosity ϕ	K_h (m/s)	Initial soil moisture deficit θ	H_c (m)	K_{USLE} (tons/acre/year)	Soil grain size distribution			
							Gravel-cobble	Gravel	Sand	Silt/Clay
Rocky	0.0071	0.44	8.35E-07	0.051–0.409	0.05	0.1	0.50	0.20	0.15	0.15
Loamy Fine Sand	0.0278	0.40	1.66E-07	0.047–0.387	0.061	0.44	0.00	0.05	0.75	0.20
Rocky Loam	0.0118	0.43	4.18E-07	0.035–0.400	0.069	0.1	0.05	0.15	0.30	0.50
Rocky Silty Loam	0.0120	0.49	6.05E-08	0.037–0.371	0.137	0.16	0.10	0.15	0.15	0.60
Sandy Loam	0.0238	0.41	3.33E-09	0.033–0.363	0.11	0.27	0.00	0.00	0.55	0.45
Silt Loam	0.0339	0.49	1.89E-08	0.031–0.351	0.167	0.48	0.00	0.00	0.25	0.75
Silty Clay Loam	0.0244	0.43	5.55E-09	0.001–0.231	0.273	0.37	0.00	0.00	0.15	0.85
Paddy Field	0.0244	0.43	4.68E-09	0.000	0.000	0.37	0.00	0.00	0.15	0.85

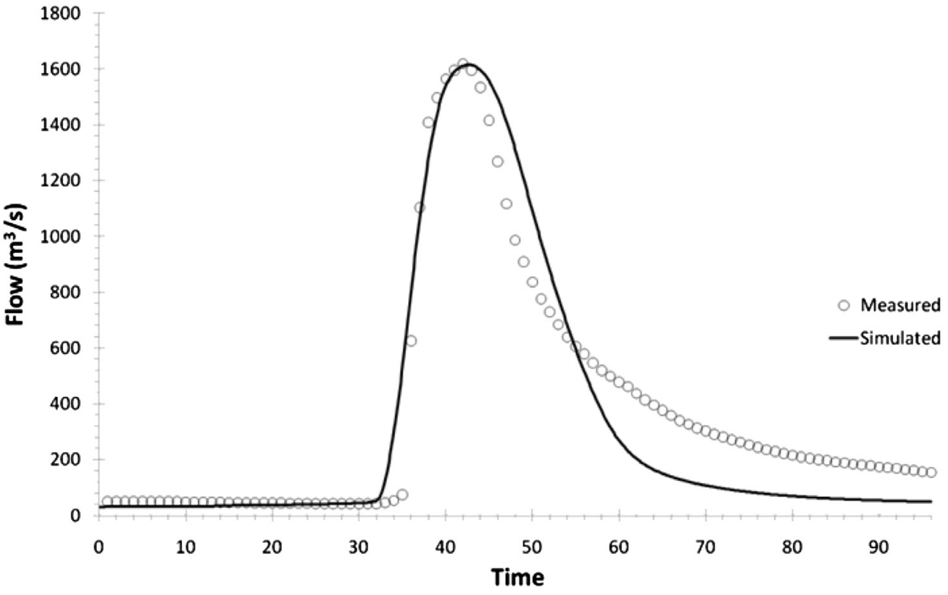
Notes: Lower soil moisture deficit values represent wet initial conditions for July 2008 and larger values represent drier conditions for July 2009.

Table 3
Land use classes and properties.

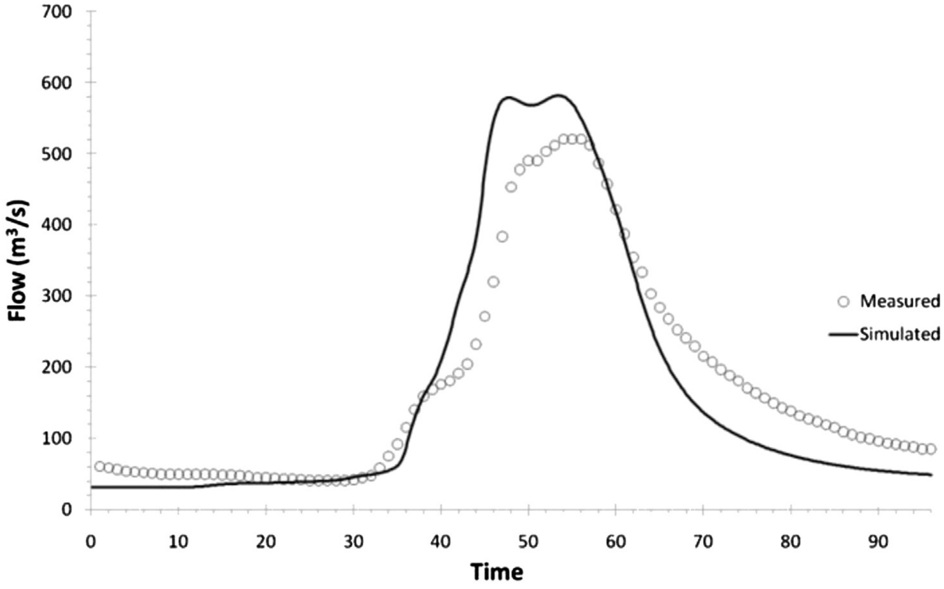
Land use	Manning *n*	Interception depth (mm)	C_{USLE}	P_{USLE}
Wetland	0.100	0.00	0.000	1.00
Water	0.050	0.00	0.000	1.00
Developed	0.010	0.10	0.008	1.00
Barren	0.200	0.00	0.050	1.00
Grassland	0.300	1.00	0.013	1.00
Forest	0.400	2.00	0.002	1.00
Paddy	0.500	1.00	0.050	1.00
Crop	0.300	1.00	0.013	1.00

erosion using six factors associated with climate, soil, topography (runoff length and slope), vegetation and land use management. RUSLE and later versions of the RUSLE framework (Renard et al., 1991, 1994, 1997) have the same basic form as the original USLE but use modified algorithms to calculate soil erosion losses. In particular, a subfactor approach to determine crop management factors enables RUSLE to be applied to crops and management systems there were not examined in the original experiments used to develop the USLE.

Based on application of RUSLE with annual average rainfall from 2000 to 2009, the average annual soil loss rate for the Nakdong River Basin was 42.65 tons/ha/yr and the maximum soil erosion was estimated to occur in the Naesung Stream watershed. Soil loss rates were categorized into four classes using the approach suggested by Gupta (2001): slight (1–50 ton/ha/yr),



(a) July 24-26, 2008

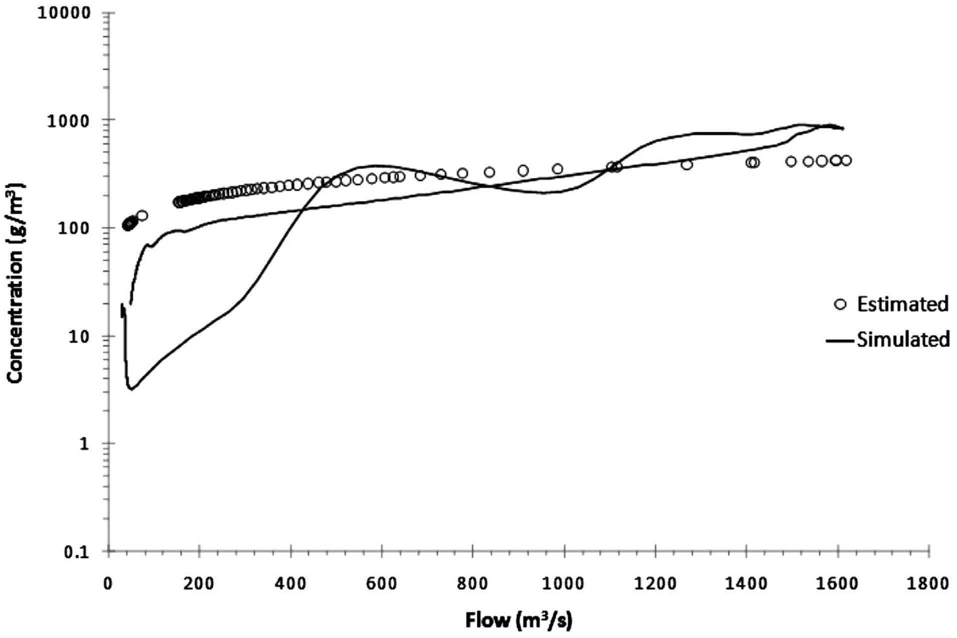


(b) July 8-10, 2009

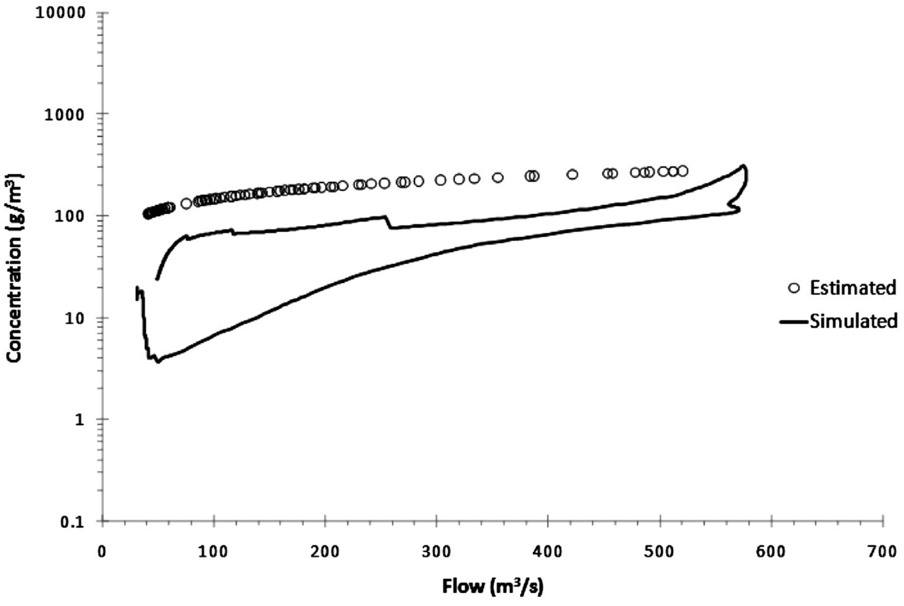
Fig. 4. Flow calibration and validation at the Hyangseok station.

Table 4
Summary statistics for hydrologic model performance.

Event	Station	Total flow volume (m^3)			Peak flow (m^3/s)			Time to peak flow (hrs)		Flow time series		
		Measured	Simulated	RPD (%)	Measured	Simulated	RPD (%)	Measured	Simulated	RPD (%)	NSEC	RMSE (%)
July 24–26, 2008	Hyangseok	8.21E+07	9.09E+07	10.72	1619	1615	−0.25	42.0	42.8	1.79	0.94	25.0
	Miho	8.45E+07	8.36E+07	−1.07	1569	1457	−7.14	34.0	41.9	23.09	0.62	61.6
	Wolho	3.27E+07	3.11E+07	−4.89	638	617	−3.30	30.0	34.8	16.00	0.84	38.0
	Yecheon	4.69E+06	9.29E+06	98.08	92	270	193.85	36.0	36.5	1.25	−4.47	199.2
July 8–10, 2009	Hyangseok	3.56E+07	4.07E+07	14.33	520	582	11.79	54.0	53.4	−1.11	0.80	42.5
	Miho	2.93E+07	3.58E+07	22.18	452	519	14.76	50.0	51.5	2.90	0.93	26.4
	Wolho	9.23E+06	1.38E+07	49.51	196	250	27.59	45.0	46.1	2.33	0.43	71.9
	Yecheon	4.35E+06	7.25E+06	66.67	90	188	107.45	44.0	43.7	−0.79	−1.02	133.6



(a) July 24-26, 2008



(b) July 8-10, 2009

Fig. 5. Total suspended solids concentrations calibration and validation at the Hyangseok station.

Table 5
Summary of measured, estimated, and simulated suspended solids concentrations.

Station	Measured (g/m^3)		Estimated (g/m^3)		Simulated (g/m^3)		Storm
	Geometric mean	Range	Geometric mean	Range	Geometric mean	Range	
Hyangseok	30	7–210	187	106–423	48	3–901	July 2008
			159	105–275	31	4–308	July 2009
Gopyeong Bridge	15	6–30	–	–	63	5–1040	July 2008
					43	7–326	July 2009
Songriwon	6	0.4–52	797	290–21,700	40	0.7–1940	July 2008
			11	0.05–1720	17	0.5–250	July 2009
Seokpo	4	0.4–22	–	–	4	5–1950	July 2008
					4	3–260	July 2009

Notes: (1) Measured values were determined from samples collected at six stations within the watershed as part of monthly monitoring efforts during the month July in 2003, 2006, 2008, and 2009. (2) Estimated values were determined from flow and sediment discharge relationships for each station.

moderate (more than 200 ton/ha/yr), high (51–100 ton/ha/yr), and severe (101–200 ton/ha/yr). The severe class occurred on 6.1% (1424 km^2) of the total watershed area. Sub-basins with the greatest areas in the severe erosion class were watersheds for the Nam River Dam (143.4 km^2), Imha Dam (133.4 km^2), Naesung Stream (128.4 km^2), and Nam River (123.3 km^2) (Fig. 3b).

3.3. Sub-basin selection for high-resolution modeling

The first and second tier assessments each identified the Naesung Stream watershed as a site with high risk for severe erosion. In particular, erosion potentials for 14 of the 22 sub-basins in the Naesung Stream watershed were ranked in the top 50 of the 226 sub-basins in the overall Nakdong River basin. For these reasons, subsequent analysis focused on soil erosion and sediment transport in the Naesung Stream watershed.

4. Tier 3: upland erosion modeling for the Naesung Stream watershed

The third tier of analysis consisted of a detailed evaluation of watershed erosion using a physically-based model. A fully-distributed and physically-based modeling approach can then be applied to the areas identified in the preliminary analysis as

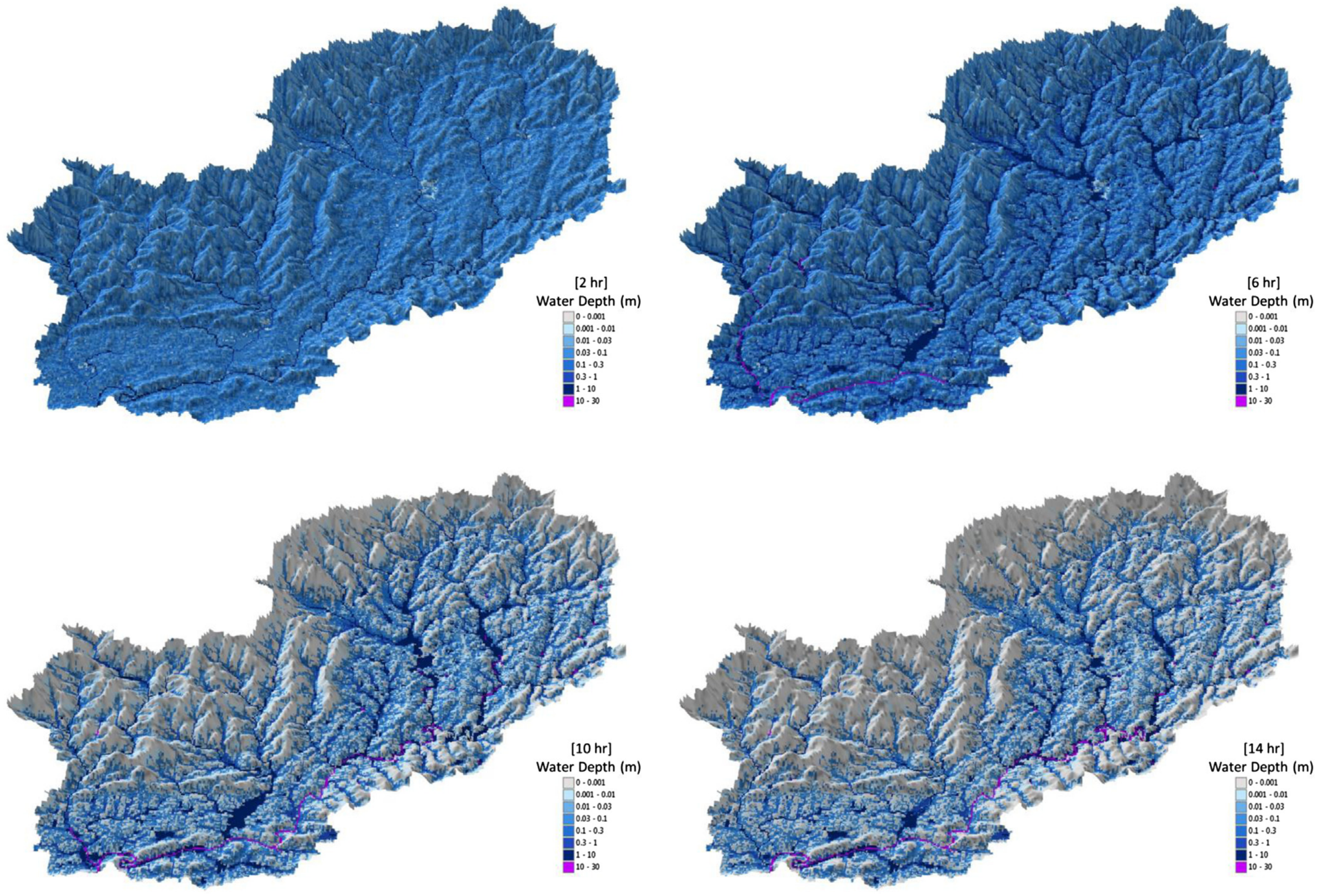


Fig. 6. Design storm simulation of flow depth on the Naesung Stream Watershed.

particularly prone to significant watershed erosion losses. Once the model was calibrated, simulations for large design rainstorms were performed to quantify sediment transport and assess the deposition potential for stream degradation and aggradation.

4.1. *TREX watershed model description and set-up*

TREX (Two-dimensional Runoff, Erosion, and Export) is a spatially-distributed, physically-based model that can be used to simulate precipitation, overland runoff, channel flow, soil erosion, and stream sediment transport at the watershed scale and can also simulate chemical transport and fate (Velleux et al., 2008; England et al., 2007; Velleux et al., 2006; Velleux, 2005). Based on source code availability and past performance, TREX was used to conduct high-resolution simulations for the Naesung Stream watershed.

Watershed land surface elevations were defined using digital elevation model (DEM) data. Soil types, land uses, and their spatial distributions were defined according to the associations and classes within the watershed. DEM, soil type, and land use data were established at a 30-m resolution (1 arc second) and subsequently processed for model use at a 150-m grid scale (i.e., where each model cell is 150 m by 150 m). At the 150-m scale, the Naesung Stream Watershed is comprised of 80,690 grid cells. Watershed boundaries and the stream channel network were delineated using TauDEM 4.0 (Tarboton, 1997). The stream network was defined as 53 links comprised of 2135 nodes, yielding a total stream length of approximately 34.8 km and a drainage density of 0.2 km of stream length per square kilometer of watershed (0.2 km/km^2). Physical dimensions of the channel network (e.g. width, bank height, sideslope) were determined from data in HEC-RAS geometry files for Naesung Stream.

Soil types and land uses were defined based on major associations and classifications and combined to simplify model set-up. Rice paddy fields were also included as a distinct soil type. Inclusion of paddy fields as a soil type was based on research indicating that paddy fields are often underlain by soil layers with very low hydraulic conductivities and higher clay contents (Jia et al., 2005). Interception depths and depression storage depths were assigned based on expected land use characteristics described in the literature (Linsley et al., 1982; Woolhiser et al., 1990; Bras, 1990). The paddy fields land use was specified to have 6 cm of storage to account for water retention in paddy fields (Jia et al., 2005). Initial values for overland and channel flow resistance (Manning n) values were determined by land use and substrate as defined by USACE (1998a and 1998b) and Chow (1959). Manning n values for stream channels were regularized by assigning values into two classes: (1) rocky substrate streams (higher flow resistance); and (2) wider sand bed streams (lower flow resistance). Final flow resistance values were determined by calibration.

Size distributions of particles comprising soils and sediments vary with the strata from which they originate. Particles ranged from coarse gravels and cobbles to silts and clays. Summaries of specified properties for particle classes, soil classes and land use classes are presented in Tables 1–3. Effective hydraulic conductivity

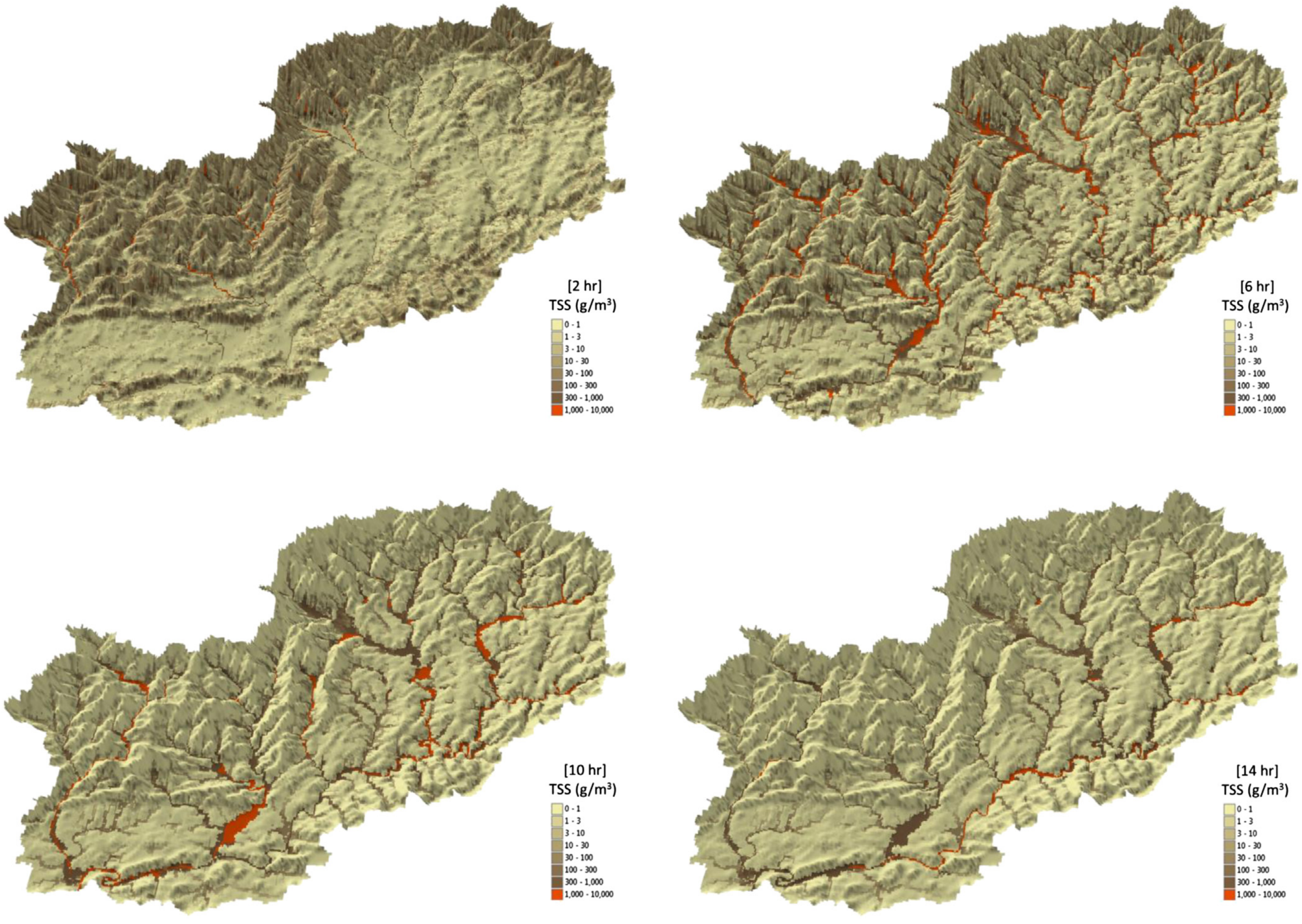


Fig. 7. Design storm simulation of total suspended solids (TSS) concentrations on the Naesung Stream Watershed.

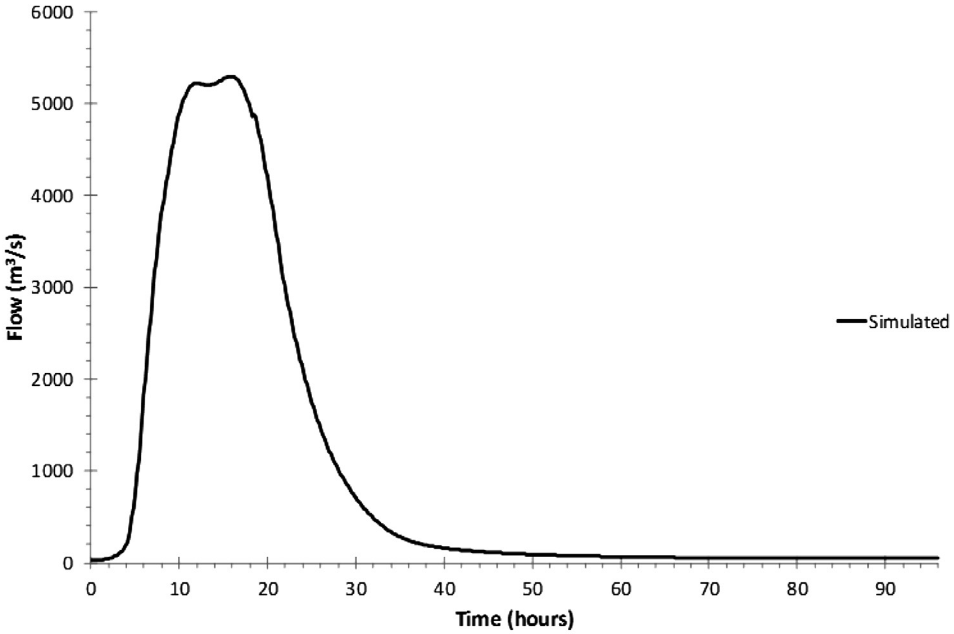
values were determined by calibration. Soil erodibility (K_{USLE}), cover factor (C_{USLE}), and practice factor (P_{USLE}) values were estimated based on literature values summarized by Wischmeier and Smith (1978) and Julien (1998). Effective particle diameters were estimated based on grain size distribution data for soils and sediments. Fall velocities were defined according to effective particle diameter as tabulated by Julien (1998).

4.2. TREX model calibration

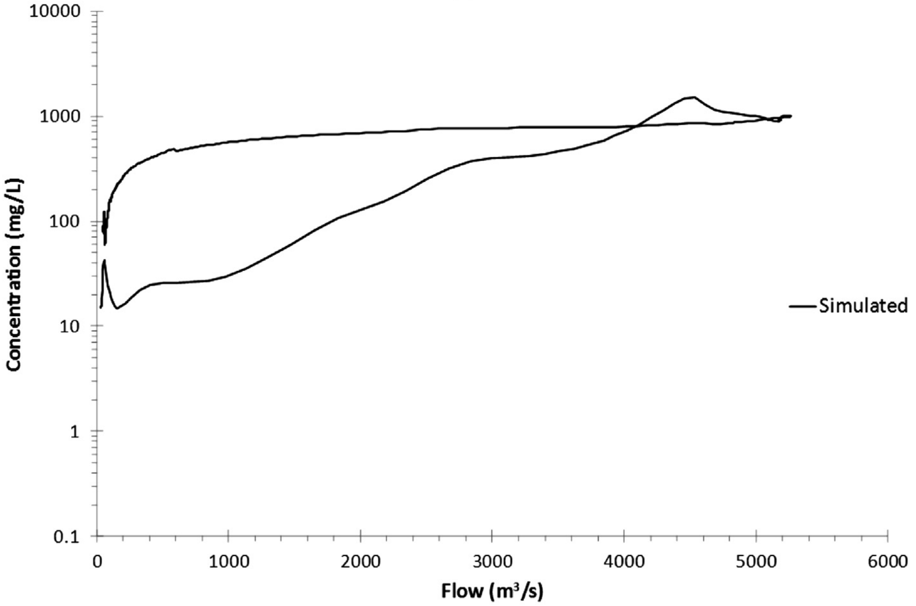
The watershed model was calibrated by simulating rainfall, runoff and sediment transport for two storms: (1) July 24–26, 2008; and (2) July 8–10, 2009. All simulations were 96-hours in duration and included each storm's rainfall period (up to 48 h) and an additional 48 h to simulate the recession limb of the hydrograph and return to baseflow conditions. Agreement between model results and measurements was assessed by graphical and statistical comparisons.

4.2.1. Hydrologic calibration

Hydrologic calibration was performed by varying effective hydraulic conductivity K_h, channel and overland flow resistance (Manning n), and soil moisture deficit θ. Calibrated and validated hydrologic simulation results and measurements for the July 2008 and July 2009 storms are presented in Fig. 4, respectively for the Hyangseok stations. Measured flows represent values calculated from reported river stage and stage-discharge relationships. Statistical comparisons of simulated and measured total flow



(a) Runoff simulation



(b) Sediment transport simulation

Fig. 8. Design storm simulation of runoff and total suspended solids concentrations at the Hyangseok station.

volumes, peak flows, and time to peak flow are presented in Table 4 for the Hyangseok, Yecheon, Miho, and Wolho stations. Statistical analyses include relative percent difference (RPD), Nash-Sutcliffe efficiency coefficient (NSEC) and root mean square error (RMSE).

Summary statistics suggest that model performance for hydrology is good. At the Hyangseok station, simulated total flow volumes for both storms were within 10–15% of measured values. Simulated peak flow and time to peak flow values for both storms were also typically within 10% of measurements. Reasonable performance was also achieved at the Miho and Wolho stations. Nash-Sutcliffe Efficiency Coefficient values at these three stations ranged from 0.43 to 0.94, indicating a relatively close correspondence between the time series of simulated and measured flows.

4.2.2. Sediment transport calibration

Sediment transport calibration was performed by varying effective particle diameter d_p and grain size distributions for soils and sediments. Calibrated sediment transport simulation results and measurements for the July 2008 and July 2009 storms are presented as functions of flow in Fig. 5 for the Hyangseok station. Estimated values represent data from the flow and sediment discharge relationship for the Hyangseok station. As shown in Fig. 5, simulated suspended solids concentrations are roughly within a factor of two-three of values estimated from flow and sediment discharge relationships at Hyangseok. Tabular summaries comparing simulated, measured, and estimated values for suspended solids concentration and sediment yield rates are presented in Table 5. Measured values in Table 5 represent concentrations measured as part of monthly monitoring efforts at several stations in the Naesung Stream Watershed. Those measurements were collected during the month of July in 2003, 2006, 2008, and 2009. In general, simulated suspended solids concentrations are within the range of measured values.

4.3. Design storm application

The calibrated and validated model was used to simulate runoff and sediment transport for a large design rainstorm. Design storm rainfall was defined as 300 mm of rain uniformly distributed over the entire watershed at a rate of 50 mm/h for 6 h. Initial moisture and water conditions for the design storm were assumed to be the same as those that occurred for the July 2009 rainfall event. Visual mapping of flow depth and total suspended solids in the Naesung Stream Watershed are presented in Figs. 6 and 7. Surface runoff in the main channel can be observed at 2 h after design storm start and is dominant at 6 h. The downstream reach is flooding at 6 h and water depths rise over 10 m. Upland erosion losses are clearly visible from the mountain area. High sediment concentrations reach the valleys after 6 h and sediment settling takes place at 10 h. Design storm hydrologic and sediment transport simulation results for the Hyangseok station are presented in Fig. 8. Driven by differences in total rainfall, the scale of simulated runoff and sediment transport for the design storm is larger than occurred for either calibration event. Simulated peak flows at the watershed outlet are a factor of 4–10 times larger than peak flows for calibration events. Simulated suspended solids concentrations are also approximately 3–5 times larger than occurred for calibration events.

Increased runoff and sediment transport for the design storm correspond to increased soil and sediment erosion across the watershed. A visualization of net elevation differences for the design storm is presented in Fig. 9. In the overland plane, the maximum erosion loss was 15 cm and maximum deposition was nearly 55 cm, while the average net elevation change was near zero. In stream channels, the maximum erosion loss was 15 cm and the

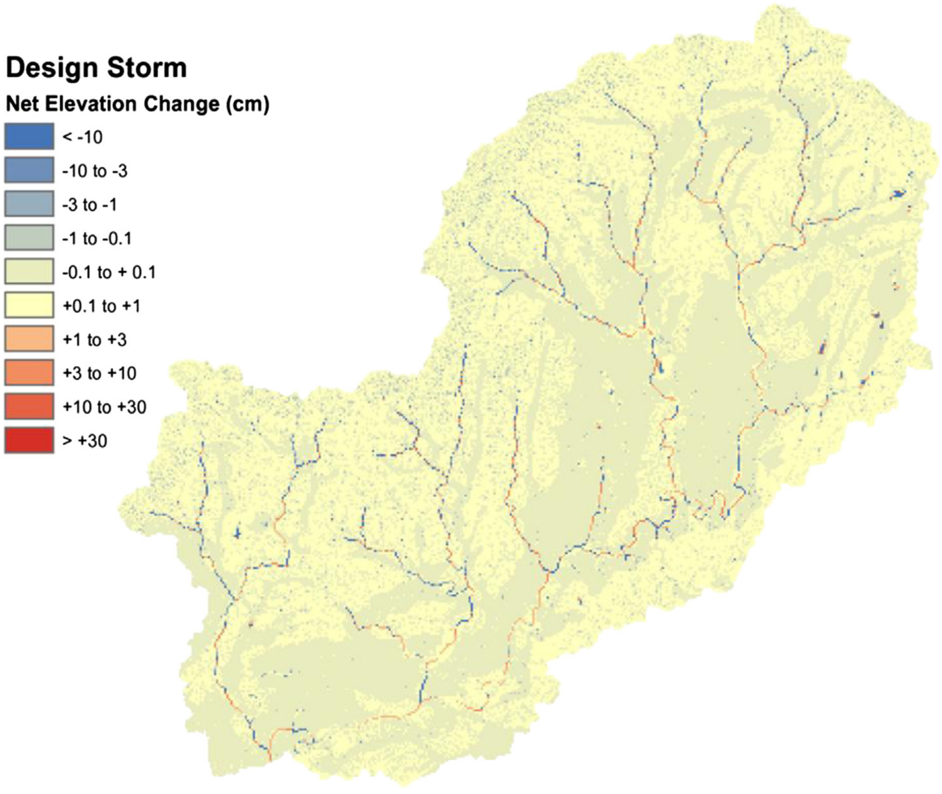


Fig. 9. Simulated net elevation changes in the Naesung Stream Watershed for the design storm rainfall.

maximum deposition was roughly 26 cm, while the average net elevation change was a loss of approximately 2 cm. Areas of high erosion losses occur along ridgelines in several headwater areas.

5. Summary and conclusions

A new perspective for the analysis of soil erosion losses at the watershed scale is presented. A three-tiered approach is proposed including: (1) impairment ranking based on topography and land use; (2) lumped parameter mean annual soil loss mapping using the RUSLE model; and (3) a fully-distributed dynamic watershed analysis using the TREX model. The first tier is used as a screening tool to identify sub-watersheds prone to surface erosion. The second tier provides quantitative information on gridded areas prone to higher mean annual erosion losses. The third tier provides a detailed dynamic simulation on flood propagation and erosion losses on the entire watershed. The three-tiered approach was tested on the entire Nakdong River basin covering 23,384 km^2 to evaluate the erosion risk for all 226 sub-basins. The first two tiers identified the 1815 km^2 Naesung Stream as having the greatest erosion risks. The third tier demonstrated that the TREX watershed model can simulate sediment transport from upland areas to the mouth during severe rainstorms. The most erodible upland areas and the river reaches most likely to cause stream bed degradation can be identified with and without flood control infrastructure. The three tiered approach is therefore recommended for soil erosion losses risk assessment at the watershed scale.

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