Original Article

Application of GeoWEPP for Evaluating Sediment Yield in a Mountain Area : Agatsuma Watershed, Japan

Kharistya AMARU^{1,2} and Norifumi HOTTA³

¹ Faculty of Agricultural Industrial Technology-Universitas Padjadjaran (Jatinangor, Sumedang, Jawa Barat 45363, Indonesia)

² Graduate School of Life and Environmental Sciences-University of Tsukuba (Tennodai 1-1-1 Tsukuba, Ibaraki, Japan)

E-mail : kharistya@unpad.ac.id

³ Graduate School of Agricultural and Life Sciences, the University of Tokyo (Yayoi 1-1-1 Bunkyo-ku, Tokyo, Japan)

E-mail : hotta.norifumi@fr.a.u-tokyo.ac.jp

Sediment discharge monitoring can be used to detect sediment disasters in upstream areas in order to enable prompt countermeasures. Sediment disaster signals should be easily differentiated from ordinary sediment discharge. This study examined the application of the geospatial interface for the Water Erosion Prediction Project (GeoWEPP) for the assessment of baseline sediment discharge in a mountain watershed to allow early detection of upstream sediment disasters. When compared to detailed observation-based data from the Agatsuma watershed, GeoWEPP successfully reproduced continuous sediment discharge in subwatersheds of varying size, topography, and land use. GeoWEPP parameter settings corresponded to actual conditions and processes involved in water and sediment dynamics. Additionally, the introduction of a restrictive layer and improved settings for evapotranspiration rate were critical for predicting surface runoff and subsequent surface erosion in hillslope sections. The depth to non-erodible layer was important for determining the overall sediment discharge at the study site, as it was the only parameter that varied over time and could not be obtained from the actual depth of bed material. This parameter should be interpreted as a conceptual index that represents the spatial distribution of bed material and its erodibility, and requires an initial adjustment period. Therefore, GeoWEPP calculations should eliminate the first year in order to obtain optimal results in a mountain watershed with a significant depth of bed material in a channel section.

Key words: forested watershed, GeoWEPP, hydrological processes, sediment yield, tank model.

1. INTRODUCTION

Prediction and early warning systems are critical for the efficient mitigation of sediment-related disasters. For this reason, combinations of several approaches, including numerical simulation, hazard mapping, critical location identification, and the establishment of critical rainfall intensity thresholds, have been used to predict imminent sediment disasters [Ministry of Land, Infrastructure and Transport, 2004]. Monitoring sediment discharge can effectively detect sediment disasters in upstream areas, enabling the initiation of prompt countermeasures. Sediment disaster signals can be differentiated from ordinary sediment discharge. However, in mountain areas, sediment concentration in stream water during flood events is substantial and varies by watershed due to differences in topography, land use, and hydrological processes. Identifying sediment disaster signals requires assessing baseline sediment discharge, but it is difficult to conduct long-

term monitoring for each watershed. The application of an erosion model would assist in the detection of sediment disaster signals by revealing potential sediment discharge based on specific watershed conditions.

The Universal Soil Loss Equation (USLE) [Wischmeier and Smith, 1978] is the most widely used empirical model for predicting erosion rates [Renschler and Flanagan, 2002; Lin et al., 2002; Parveen and Kumar, 2012; Prasannakumar et al., 2012; Ganasri and Ramesh, 2016]. The USLE was developed in the United States and was calibrated with a large amount of observational data from tillage and other land uses, resulting in reliable prediction of soil loss by rainfall intensity, soil property, topographic condition, vegetation, and conservation. However, the use of empirical erosion models such as USLE may not be the best solution for assessing sediment discharge in a mountain region. These models require additional calibration when applied to mountain regions of Japan,

Fig.1 (a) Agatsuma watershed and the subwatersheds used in simulations, and (b) land cover of the 21 subwatersheds.

where conditions related to erosion vary from those of the original calibrations. Some previous research has attempted to apply USLE in forested mountain watersheds in Japan [Kitahara *et al.*, 2000 ; Karki and Shibano, 2006] ; however, more intensive calibrations are necessary for application to other regions [Chu *et al.*, 2010].

USLE predicts erosion rates on the scale of farmland or slope, making it difficult to evaluate sediment discharge in a watershed with in-stream processes. Process-based models such as GLEAMS, MEDALUS, PESERA, RHEM, SWRRB, SWAT, and WEPP [Pandey *et al.*, 2016] are often used to assess water and sediment dynamics in watersheds, instead of a simple combination of USLE and channel network (Karki and Shibano, 2006).

Many process-based models have been developed. A model in which dynamic water and sediment processes are described physically [Flanagan *et al.*, 2007] is preferable for assessing sediment discharge in mountain watersheds of Japan. Instead of calibrating parameters for empirical erosion models by accumulating *in situ* observations, the validation of physical processes implemented in a process-based model would allow for further applications [Flanagan *et al.*, 2012]. Process-based models are constructed as spatially distributed models for estimating soil erosion and sediment yield, and for identifying critical source

areas at any location within a watershed of a certain size. Although the optimal watershed size for detecting a sediment disaster upstream is smaller than for soil conservation assessments, the geospatial interface for the Water Erosion Prediction Project (GeoWEPP ; target basin size : more than 260 ha) may be more suitable than the SWAT model (target basin size : several thousand km²) or other validated and widely adapted models. Precursory applications in Japan [Osawa *et al.*, 2004 a ; Osawa *et al.*, 2004 b, Osawa *et al.*, 2008, Osawa *et al.*, 2009, Ikeda *et al.*, 2009] are another advantage of WEPP.

Although process-based models are frequently used to assess agricultural areas with moderate slopes, few studies have attempted to assess water and sediment dynamics in steep watersheds. Dun *et al.* [2009] and Zhang *et al.* [2009] introduced a key restrictive layer in WEPP to reproduce runoff in forested watersheds, but the target watershed sizes were smaller than GeoWEPP recommendations. Pieri *et al.* [2014] successfully applied GeoWEPP to a heterogeneous watershed with steep slopes and significant sediment discharge from badlands. The applicability of GeoWEPP to typical watersheds in Japan, consisting of steep, forested slopes, still needs to be assessed.

This study investigated the application of process-based models for the early detection of sediment disasters. GeoWEPP was introduced and validated with

in situ data from temporally and spatially intensive observations, including various topographic conditions and vegetation covers. After comparing the calculated and observed water and sediment discharge over several years, important parameters that affected the reproducibility of sediment dynamics were identified and described.

2. STUDY SITE AND OBSERVATIONS

2.1 Agatsuma watershed

The Agatsuma River watershed (711 km²) is located at 138.394°–138.747° east and 36.744°–36.396° north, in the Gunma Prefecture, Japan (**Fig. 1a**). The elevation ranges from 482 to 2568 m above sea level, and the topography is described by a slope average of 37.3% for the main watershed, and 47.8%, 40.7%, 28.4% and 26.8% for the branch watersheds of Shirasuna, Manza, Kuma, and Agatsuma Upper, respectively. This watershed contains two volcanos, Mt. Asama and Mt. Kusatsu-Shirane, resulting in a dominant volcanic sedimentary soil, and consequently high turbidity of fine sediment in streams following storm events [Sato *et al.*, 2000].

The watershed is mostly covered by forest (80%), and to a lesser extent farmland (6%). Most of the northern subwatersheds are completely forested. Agricultural areas of cabbage and other crops, as well as a residential area along the main channel of the Agatsuma River, are mostly distributed across the southern watershed (**Fig. 1b**).

Figure 2 displays monthly temperature and precipitation averages over 39 years (1976–2014) at the Kusatsu and Tashiro Stations (Meteorological Agency, Japan). The average annual rainfall at the Kusatsu and Tashiro Stations is 1672 mm and 1476

mm, respectively, and the average annual temperature (1979–2000) is 7.6°C and 7.2°C, respectively. The wet season is defined as monthly rainfall of more than 100 mm from April to October, and also corresponds to the vegetation growing season by temperature. Distinguishable rainfall events occur as rain fronts and typhoons in the summer from June to September. Snowfall is typically observed in the winter from December to February, and snowpack can be seen at elevated areas through May.

2.2 Observations

At the study site, flood events were monitored at 100 subwatersheds of varying size (watershed area : 0.067–224 km²), topographic condition (average gradient : 5.14–32.62°), and vegetation cover (forest percentage : 1.2–100%) from 1993 to 1997 to assess the influence of land use on suspended sediment (SS) yield [Namba *et al.*, 2007]. We used these data, consisting of coupled discharge rates and manually observed SS concentrations during flood events, to calibrate and validate GeoWEPP. The discharge rate was calculated from the cross-sectional measurement of velocity and flow depth. Stream water was collected by hand or with surface water samplers (from a bridge, in many cases) and filtered with 2-mm mesh to remove coarse sand. The sample was then vacuum-filtered in a laboratory through a 1-μm glass fiber filter, and the residue was oven-dried (105–110°C) and weighed (including organic matter) to obtain the SS concentration. There were 778 coupled discharge rates and SS concentrations for the 100 watersheds, although the timing and number of sampling events (1–34) differed by subwatershed.

We also used continuous discharge data measured from the Murakami Observatory (located along the Agatsuma River approximately 20 km downstream of the study site outlet) to calibrate a rainfall-runoff model. The rainfall-runoff model generated continuous observation-based discharge data to be compared with GeoWEPP results for each target subwatershed.

3. METHODS AND DATA

3.1 Overview of a GeoWEPP application

GeoWEPP runs as a plug-in in ArcGIS software [Flanagan *et al.*, 2011]. The WEPP model describes hillslope, channel, and impoundment processes in great detail [Ascough *et al.*, 1995]. GeoWEPP provides two options for watershed simulation : a Flowpath method for on-site assessment of soil loss, and a Watershed method for off-site assessment of sediment yield in subwatersheds based on a single representative hillslope and channel route for the watershed outlet [Renschler and Flanagan, 2002]. This study employed the Watershed method for simulating sediment yield.

Fig.2 Temperature and precipitation at Kusatsu and Tashiro Meteorological Stations.

Fig.3 Watershed discretization for WEPP [Cochrane and Flanagan, 2003].

The WEPP model accounts for sediment yields and soil losses from hillslope and channel sections at scales ranging from a single field to the entire watershed. During step one, a DEM was processed using topographic parameterization software (TOPAZ). This program can distinguish between hillslope and channel sections based on channel networks computed by the slope direction of each grid [Garbrecht and Martz, 1999]. Hillslope sections are converted to simple rectangles consisting of width, length and slope profiles (**Fig. 3**). The channel receives hillslope drainage from upstream and channel sides [Cochrane and Flanagan, 2003]. For channel calculations, the grid size was set to a similar spatial resolution to that of the DEM. The hillslope and channel sections, processed by TOPAZ, were also used as the spatial grid inputs for the GeoWEPP calculations. A stream order is allocated for channel sections in accordance with the watershed channel network.

3.1.1 Processes considered

The WEPP model describes physical processes that dictate water and sediment dynamics in a watershed, including infiltration, surface runoff, soil erosion, and sediment transport. WEPP also incorporates components for weather generation, winter processes, plant growth, residue decomposition, and irrigation [Saghafian *et al.*, 2015]. In this study, the following processes were examined to obtain optimal results.

Rainfall input is first determined by hillslope surface hydrology processes such as infiltration, depression storage, and evapotranspiration [Stone *et al.*, 1995]. Subsurface hydrological processes include subsurface lateral flow and surface and subsurface drainage routes [Savabi *et al.*, 1995]. Infiltration, surface depression storage, evapotranspiration, soil water percolation, and canopy rainfall interception are also computed in the model's channel processes [Ascough *et al.*, 1995].

The infiltration rate is calculated by the Green-Ampt Mein-Larson model (GAML) [Mein and Larson, 1973], as modified by Chu [1978]. The GAML model

is a conceptual representation of the infiltration process developed from Darcy's law [McCuen, 2016]. Excess rainfall rates are considered only when the rainfall rate is greater than the infiltration rate. Since WEPP cannot provide the boundary conditions at the bottom of the soil layer in defining the aquiclude, Dun *et al.* [2009] modified the WEPP model by introducing a restrictive layer beneath the soil that allows infiltration to contribute to subsurface lateral flow. The subsurface lateral flow is based on the mass continuity equation and is calculated from horizontal hydraulic conductivity, moisture content, and average slope angle [Savabi *et al.*, 1995]. WEPP users can choose from the Penman, Priestley-Taylor, and Penman-Monteith evapotranspiration models, depending on data availability. For peak flow computation, several options are provided based on kinematic wave models [Stone *et al.*, 1992] and the modified Rational equation [Knisel, 1980 ; Williams, 1995].

GeoWEPP divides erosion processes, driven by water flow as described above, into hillslope and channel sections. For hill slope sections, interrill and rill erosion, deposition, and SS movement based on a steady-state erosion model are considered [Foster and Meyer, 1972]. Channel erosion is computed by a steady-state sediment continuity equation from the entire channel segment distance reaching downstream, considering lateral sediment inflow from adjacent hillslopes. The sediment transport capacity in both hillslope and channel sections is computed using the Yalin sediment transport equation for non-uniform sediment delivery [Foster *et al.*, 1995 ; Ascough *et al.*, 1995].

3.1.2 Settings and parameters

The GeoWEPP model incorporates a digital elevation model (DEM) for generating topographic parameterizations for watershed simulations [Flanagan *et al.*, 2004]. We used a DEM with a resolution of 10 m from the Geospatial Information Authority of Japan. The channel network for target subwatersheds is generated from DEM using the critical source area (CSA) and minimum source channel length (MSCL) [Flanagan, 2011]. In this study, CSA and MSCL were set to 2.5 ha and 50 m, respectively. Daily precipitation and maximum and minimum temperatures at the Tashiro and Kusatsu Stations from 1979–2000 (21 years) were used to generate climate parameter (PAR) files, and the same data from 1991–2000 (10 years) were used as input data. A soil map was obtained from a land survey database administered by the Ministry of Land Infrastructure Transport and Tourism (Japan). Soil properties were identified by the Agrimesh database [National Institute for Agro-Environmental Sciences, 2009] based on a soil survey [Ministry of Agriculture, Forestry and Fisheries Production, 2008]

of soil texture, sand and clay ratio, organic matter, and CEC (cation exchange capacity). Other soil properties such as soil albedo, initial saturation level, interrill and rill erodibility, and effective hydraulic conductivity were calculated by WEPP [Flanagan *et al.*, 1995]. The soil layer thickness was set to 1000 mm, with a restrictive impervious bedrock layer below. Vegetation parameters, including a plant database, were provided by the WEPP model as rotation files. The dominant land uses at the study site were forest, bare land, dwarf bamboo (*Sasa sp.*), and cabbage. The forest parameter was set using a rotation file for 20-year-old trees, and the bare land parameter was set to a fallow rotation file with modifications for no tillage and plant growth. The *Sasa sp.* rotation file was created with an initial canopy coverage of 85%, interrill and rill coverage of 85%, and no tillage information. The cabbage rotation file was created and set for two cropping seasons, and tillage was based on Mochizuki [2007]. The influence of vegetation was also considered using the Penman-Monteith calculation. Parameters were calibrated to correspond with estimated evapotranspiration from the rainfall-runoff model introduced in Section 3.2. The crop coefficient settings for forest, grass, and agriculture (cabbage) were based on information from the Food and Agriculture Organization (United Nations) [Allen *et al.*, 1998].

3.2 Processing of observational data

We selected 21 subwatersheds (Table 1) with accompanying data from numerous field observations conducted during the study to validate the applicability of GeoWEPP. Since there was no continuous discharge record for the subwatersheds, daily discharge was estimated using a rainfall-runoff model and then compared with GeoWEPP discharge calculations. The model consists of a modified Priestley-Taylor equation [Sawano *et al.*, 2015] for effective rainfall and a tank model [Sugawara, 1995] for discharge. Figure 4 shows a schematic diagram of the tank model that contains four tanks with five horizontal outlets and three vertical outlets [Setiawan, 2003]. The first tank is responsible for surface and subsurface runoff, the second tank is for intermediate flow, the third tank is for sub-base flow, and the fourth tank only has a horizontal outlet for base flow. The modified Priestley-Taylor equation calculates dry canopy transpiration (E_d) and interception loss as wet canopy evaporation (E_w). The model was calibrated using rainfall data from 12 rainfall stations around the Murakami catchment area and continuous discharge data over 11 years from the Murakami Station. Meteorological data from the Kusatsu and Maebashi Stations were also used for evapotranspiration input data. Following calibration, the optimized parameters were integrated

in the tank models to predict discharge of the 21 selected subwatersheds based on the spatial distribution of observed rainfall. After that, the optimized tank model parameters were used for 100 subwatersheds and the rainfall runoff discharge result was validated. The SS rating curves were developed from the observed discharge and SS data for 96 subwatersheds

Fig.4 Schematic diagram of the tank model

Table 1 List of subwatersheds.

SW ID	Area (km ²)	Average slope (degree)	Landcover Percentage			Forest class
			Forest %	Crop %	Other %	
2050	2.53	7.97	23.90	75.49	0.61	F1
2043	1.38	9.19	29.11	70.47	0.43	F2
2150	1.28	12.10	34.13	65.03	0.84	F2
2161	0.37	14.82	41.71	58.23	0.06	F2
2180	18.10	14.86	47.60	39.27	13.13	F2
2160	5.29	14.82	50.35	49.52	0.13	F3
2125	2.14	18.43	65.93	32.16	1.91	F3
2120	15.41	18.43	75.41	16.27	8.32	F4
2100	22.49	30.33	80.48	4.86	14.65	F4
90	4.30	12.01	84.85	9.54	5.61	F4
2140	9.79	28.54	85.44	13.08	1.48	F4
150	3.37	18.51	85.69	7.52	6.79	F4
70	3.53	8.94	85.98	11.08	2.93	F4
2130	4.30	13.86	90.10	8.64	1.27	F4
4040	5.50	25.21	90.49	3.84	5.66	F4
2030	3.63	8.60	92.57	1.80	5.63	F4
4020	4.28	24.59	93.33	2.20	4.46	F4
3080	5.50	24.53	94.68	0.04	5.29	F4
3100	3.39	25.93	95.77	2.62	1.61	F4
4090	6.80	33.62	97.17	0.01	2.82	F4
4120	6.33	26.47	97.27	0.12	2.60	F4

after classifying the data into four forest percentage classes (**Table 1**). SS yields for 20 subwatersheds were estimated by a combination of estimated discharge and SS rating curves by forest cover classes (F 1 : 0 – 25%, F 2 : 25.1 – 50%, F 3 : 50.1 – 75%, and F 4 : 75.1 – 100%) and compared with GeoWEPP output.

3.3 Analysis

Figure 5 shows a flow chart of our analysis. Sensitivity analyses for GeoWEPP hydrological processes were conducted using a variety of soil textures (sand ratio) and depths, and with and without a restrictive layer. For other parameters, GeoWEPP was calibrated based on a comparison of annual discharge, evapotranspiration, and peak discharge of intensive rainfall events.

The sensitivity analyses of sediment yield were divided into hillslope and channel sections. For hillslope sections, interrill and rill erodibility, saturated hydraulic conductivity, and critical shear stress were examined. For channel sections, the Manning

roughness coefficient, depth to non-erodible layer of side and mid-channels, channel erodibility, and channel critical shear stress were examined. The simulation was conducted over 10 years and assessed sediment discharge for high and low annual rainfall. Sediment discharge was compared between SS yields (based on developed sediment rating curves) and GeoWEPP for the 21 subwatersheds. It is of note that GeoWEPP output should be larger than SS yields, as it contains SS yields and other bed load transport.

4. RESULT

4.1 Observations and implications

Figure 6 shows the average rainfall at the 12 stations, estimated discharge from the rainfall-runoff model, and observed discharge at Murakami Observatory from 1991 to 1993. The overall hydrograph is in good agreement, but the observed discharge occasionally exhibits irregular patterns when compared to rainfall in periods such as late 1991 and early 1993. These irregularities are possibly caused by an uneven spatial distribution of rainfall input. **Figure 7** compares the observed and estimated daily average discharges at Murakami Observatory for 11 years (1989–1999). Comparison of the observed and calculated discharge indicates that estimates are improved during intense rainfall events in summer months (**Fig. 7**). Most SS should be discharged in the summer due to a sediment rating curve that is commonly expressed as a power function, resulting in a better estimation of SS yields.

Fig. 8 compares the results between the rainfall-runoff model and observations for all 100 subwatersheds for which discharge and SS concentration data are available. Because some data were identified by only the month of observation (no

Fig.5 Flow chart of the analysis procedure.

Fig.6 Average precipitation recorded at 12 stations and the calculated and observed discharge at the Murakami Observatory for 3 years.

Fig.7 Comparison of discharge between the rainfall-runoff model and observations at the Murakami Observatory for (a) wet and (b) dry seasons.

Fig.8 Comparison of estimated discharge based on the rainfall-runoff model and observations at 100 subwatersheds in the rainfall regions of (a) Kusatsu Station and (b) Tashiro Station. The data are divided into observations 'with' and 'without' date records. For observed data without date records, the monthly average discharge was calculated for comparison.

date record), a comparison was made between data with and without date records. As shown in **Fig. 8**, the plots with date records are in better agreement than those without (for which a monthly average is calculated), suggesting increased accuracy with temporal resolution. Although **Fig. 8** shows a slightly biased correlation between observed and calculated discharge, the rainfall-runoff model reproduced the discharge at all points in the study site, as well as at the Murakami Observatory (**Fig. 7**).

As suggested by *Namba et al.* [2007], SS yields at the study site should be primarily controlled by forest coverage. **Fig. 9** shows that SS rating curves established from forest percentage estimates demonstrate good agreement between discharge and

Fig.9 A sediment rating curve is derived from 100 subwatersheds and classified into four classes of forest percentages : (a) F 1, (b) F 2, (c) F 3, and (d) F 4.

SS yields. The offset and slope of the sediment rating curve for F 4 (forest percentage : 75 – 100%) indicate the smallest and second smallest values, respectively. This supports the results by *Namba et al.* [2007], which highlighted the true detection of the forest ratio to SS discharge and stated that detection occurs only when the forest ratio is significantly high, resulting in almost no disturbance to SS source areas. In general, sediment yields can also be affected by topographical conditions and geological settings. However, at the study site, there is a strong positive correlation between forest percentage and topographic features such as gradient and Laplacian [*Namba et al.*, 2007]. This suggests the dominant control of SS discharge is by forest cover. This results in reliable SS rating curves by forest percentage.

4.2 Hydrological processes in GeoWEPP

As mentioned in Section 3.1.1, many hydrological processes can affect discharge. We conducted sensitivity analyses for each parameter and found that introducing a restrictive layer (defined as a depth to aquiclude, defined separately from soil depth) was critical for determining the overall discharge of the study site. **Figure 10** shows the influence of soil texture (sand ratio) (**Fig. 10 a**) and soil depth (**Fig. 10 b**) on the annual discharge in a watershed. The annual discharge varies widely with or without the introduction of a restrictive layer. As shown in the figure, most parameters affect the discharge only when the restrictive layer has not been introduced. After introducing the restrictive layer, discharge appears from infiltration and lateral subsurface flow without a distinct surface runoff. Because surface runoff rarely

Fig.10 Sensitivity analysis of (a) soil texture and (b) soil depth in subwatershed ID 4120 (highly forested watershed) with and without a restrictive layer.

occurs in the forested area, proper setting of infiltration rate and introducing restrictive layer are important for evaluating hydrological processes and surface erosion in forested watersheds.

In addition to the restrictive layer, it was necessary to optimize evapotranspiration parameters to adequately reproduce the hydrograph at the study site. When the Penman-Monteith equation parameter in the WEPP model is changed to correspond to the representative value for evapotranspiration from the modified Priestley-Taylor equation (see Section 3.2), the annual discharge of GeoWEPP is in agreement with the observation-based discharge (**Fig. 11**). Both discharges were slightly different in some subwatersheds with high forest coverage (classes F3 and F4). The influence of forest percentage was demonstrated more clearly by comparing the daily discharge between GeoWEPP and the rainfall-runoff model by forest class (**Fig. 12**). Disagreement was detected in F4 class watersheds only when discharge was low (**Fig. 12cd**). Although this disagreement resulted in a slight difference in annual discharge, as shown in **Fig. 11**, it did not significantly affect the prediction of SS yields. Dominant SS discharge is induced by heavy rainfall events [Hotta *et al.*, 2007], and the differences detected in low discharge scenarios would not alter the SS discharge. Ultimately, GeoWEPP was able to accurately reproduce discharge at the study site with the introduction of a restrictive layer and adjustment of evapotranspiration settings.

4.3 Sediment discharge in GeoWEPP

Sediment yields in GeoWEPP are defined at the outlet of a (sub)watershed. In addition, soil loss is

Fig.11 Comparison of annual discharge between the rainfall-runoff model and GeoWEPP from 21 subwatersheds with different forest percentages in the years with high (1742 mm in 1993) and low (1470 mm in 1995) annual rainfall.

Fig.12 Comparison between the rainfall-runoff model and GeoWEPP for daily discharge of subwatersheds by forest percentage and rainfall region for (a) F2-Tashiro, (b) F3-Tashiro, (c) F4-Kusatsu, and (d) F4-Tashiro.

calculated for each hillslope and channel section to delineate contributions to sediment yield. GeoWEPP provides annual average and daily/event sediment yields. Soil loss is available on an annual basis.

Figure 13 shows the daily sediment discharge of a forested watershed (subwatershed ID : 4120) as calculated by GeoWEPP, and SS discharge based on 10 years of observations. These optimized results show an apparent overestimate for the first year but good correspondence during the following nine years.

Fig.13 (a) Daily precipitation, daily sediment yield based on GeoWEPP, observation-based estimates of SS yield, and (b) ratio of the annual sediment yield and the SS yield (calculation/observation) at subwatershed ID 4120.

Disagreement was observed in the first year at all subwatersheds, regardless of watershed size, topography, or land use (**Table 1**).

Figure 14 compares the GeoWEPP and observation-based results of 20 subwatersheds in years with high (1742 mm in 1993) and low (1470 mm in 1995) annual rainfall for the 10-year period. The results in

Fig.14 Comparison of annual sediment yields between observation-based estimates and GeoWEPP based on 20 subwatersheds with differing forest percentages (F 2-F 4) in the years with high (1742 mm in 1993) and low (1470 mm in 1995) annual rainfall. The coefficients of determination were determined on the 1 : 1 line.

both years were not influenced by the disagreement in the first year. The F 1 forest class did not compare further since the coefficient determination of suspended sediment rating curve (**Fig. 9**) was low and the data was not sufficient.

The low values of the coefficient of determination for F 3 and F 4 in **Fig. 14** can be explained from the following: The SS yields (horizontal axis) do not vary when compared to the GeoWEPP results (vertical axis). The SS yields were also obtained using SS rating curves that were classified into four forest classes. Discharge values were obtained from the tank model using identical settings and parameters.

Despite a significant dispersion, the results for watersheds with low forest percentages (F 2 and F 3) are distributed around a 1 : 1 line, suggesting that GeoWEPP results and SS yields are not systematically different. However, GeoWEPP results are clearly higher than observation-based SS yields for forested watersheds (F 4).

Sensitivity analyses of hillslope sections provide insights for understanding overestimates in forested watersheds. **Figure 15** shows the relationship between soil loss and the WEPP surface erosion parameters in hillslope sections of subwatersheds with high and low forest percentage, respectively. Of those parameters, rill erodibility and initial saturated hydraulic conductivity affected soil loss significantly, but only when the forest percentage was low. Soil loss remained low regardless of parameter values in fully forested subwatersheds, a result of diminished surface runoff on a forested floor during rainfall events in both

Fig.15 Sensitivity analysis in hillslope sections at subwatershed ID 4120 (high forest percentage) and ID 2050 (low forest percentage) for (a) interrill erodibility, (b) rill erodibility, (c) initial saturated hydraulic conductivity, and (d) critical shear stress.

GeoWEPP calculations and actual situations. These results also suggest that the overestimates in **Fig. 14** were not induced by erosion processes in hillslope sections.

Figure 16 presents the results of a sensitivity analysis for parameters related to sediment dynamics in channel sections. Whereas the contribution and sensitivity vary by parameter as shown in **Fig. 16**, all results show the same pattern of the highest sediment yields in the first year, suggesting that parameter values did not contribute to the disagreement in the first year (**Fig. 13**). The parameters were 0.04 for Manning roughness coefficient for bare soil in channels, 0.5 and 0.1 m for depth to non-erodible layer at mid and side-channels, and 0.0006 s/m for channel erodibility. As mentioned in Section 3.1, channel sections have a stream order. In GeoWEPP, dominant river bed material is defined by the stream order: rock for the first order, gravel for the second order, and earth for the third through fifth orders. The channel critical shear stress was determined to be 100, 10, and 2 N/m² for rock, gravel, and earth, respectively. These results suggest that sediment discharge values remain comparable throughout the study period, with the exception of the first year (**Fig. 16**). These default parameters were assigned for all subwatersheds. The only exception was the depth to non-erodible layer, which could be modified so that the GeoWEPP calculation would correspond with the observation-based SS discharge. It is difficult to practically define the representative depth of deposition in channel

Fig.16 Sensitivity analysis in channel sections of subwatershed ID 4120 for (a) Manning roughness coefficient, (b) depth to non-erodible layer at mid-channel, (c) channel erodibility factor, and (d) channel critical shear stress.

sections.

5. DISCUSSION

5.1 Accuracy and reliability of results

This study examined the applicability of GeoWEPP in a mountain watershed by comparing its results to observational data. The first issue to consider is that observation-based data consists of SS discharge only, while the GeoWEPP output contains SS discharge and bed load transport. Because monitoring bed load transport is more difficult than monitoring SS discharge, the total sediment load estimation is often based on SS discharge alone [e.g., *Milliman and Syvitski, 1992*] or assumes a constant fraction of bed load transport [*Whipple and Tucker, 2002*]. *Turowski et al. (2010)* found that the fraction of total load made up of bed load is 30–50% for sand bed rivers and approximately 1% for gravel bed rivers, contradicting previous reports of 10–20%. The bed load fraction will require further examination, as it can be affected by watershed size, topography, and land use. However, this study validated output from GeoWEPP by comparing it to SS discharge, representing an acceptable first approximation.

For more accurate validation, the depth to non-erodible layer should be more precisely determined. GeoWEPP is a steady-state model, but most processes related to water and sediment dynamics are based on physically described sub-models. Therefore, when model parameters are assigned to reflect actual conditions, the results should accurately reflect reality,

as shown in section 4.3. Only the depth to non-erodible layer was determined through optimization, and it was consequently assigned the default value of 0.5 m. The results would be improved if the depth to non-erodible layer could be determined so that it incorporates the actual depth of bed material. Because bed load transport originates from the river bed, whereas SS is largely generated from hillslope sections, adjustment of the depth to non-erodible layer would effectively partition the total sediment load. However, accurate configuration of the depth to non-erodible layer is difficult to achieve.

For sediment yields in hillslope sections, reproducing hydrological processes is important for obtaining optimal results. No significant disturbances, such as intensive landslides, have occurred recently at the study site, resulting in no distinguishable point sources of sediment discharge [Namba *et al.*, 2007]. Evaluation of surface erosion in a hillslope sections and sediment transport in channel sections will be required to reproduce sediment dynamics in watersheds. Considering that surface runoff is not significant in a forested hillslope several meters in length [Gomi *et al.*, 2008] and the resolution of DEM used was 10 m, infiltration rate should accurately reflect actual conditions. Introducing a restrictive layer enables the generation of river discharge, even when most of the rainfall has been infiltrated [Dun *et al.*, 2009]. An accurate evapotranspiration rate improves results as well. Despite the use of identical structures and parameters for all subwatersheds in the rainfall-runoff model, the results from this study showed good agreement (Fig. 8), suggesting that observations from the rainfall-runoff model can be used to validate GeoWEPP. GeoWEPP was less effective for reproducing base flow in highly forested watersheds (Fig. 12), but the reproducibility of annual discharge was not affected (Fig. 11), suggesting that direct runoff is well-estimated. For hydrological processes, GeoWEPP sufficiently predicted SS discharge, which is largely controlled by direct runoff.

GeoWEPP overestimated sediment yields when the forest percentage was high (Fig. 14). As shown in Fig. 15, soil loss from forested hillslopes was significantly less than that from other land uses, mainly due to the high permeability of forest soil and minimal surface runoff. The sediment yield overestimates in Fig. 14 are likely governed by channel processes. Most importantly, the reproducibility of GeoWEPP sediment yields is influenced by the depth to non-erodible layer parameter setting.

5.2 Depth to non-erodible layer in channel sections

We suspect that the discordance between GeoWEPP and observation-based results for the first year (shown in Fig. 13) was the result of the depth to non-erodible

layer parameter. Figure 16 presents the initial values of parameters related to channel processes. Among those parameters, Manning roughness, channel erodibility and critical shear stress maintain the initial values. Only the value of the depth to the non-erodible layer is temporally altered in GeoWEPP since the depth of the bed material changes with erosion and deposition. Therefore, the significant and systematic change of sediment yields from the first to second year cannot be explained by any parameter other than the depth to non-erodible layer. A single value of the depth to non-erodible layer is given for a target watershed. Because bed material depth varies spatially in an actual watershed, the single representative value should be interpreted as the average or conceptual depth.

When considering bed material depth at a certain point, a constant rate of erosion or deposition should apply for the same shear stress regardless of the bed material depth if particle size is uniform. However, our results indicate that the rate changed with depth. In GeoWEPP, initial bed load material with uniform depth is re-allocated through erosion and deposition processes, resulting in the spatial distribution of channel bed deposition. When a channel reaches bedrock, GeoWEPP widens the channel and reduces the erosion rate [Ascough *et al.*, 1995]. Because intensive channel bed erosion should be limited to specific domains along the channel according to the topography and other conditions, the overall erosion rate should decrease and become stable over time (one year in this study). This is the source of the discrepancy in the first year of this study (Figs. 13 and 16). The depth to non-erodible layer is an index, in combination with the spatial distribution of bed material deposition and a changing erosion rate. Therefore, this parameter is difficult to ascertain based on *in situ* measurements alone.

Previous reports [e.g., Dun *et al.*, 2009; Zhang *et al.*, 2009] changed the depth to the non-erodible layer values from the default (0.5 m) to several centimeters so that temporal changes in the erosion rate would be negligible due to the limited sediment storage. The erosion rate should decrease rapidly following the initiation of calculations. This setting can be effective to avoid unexpected sediment dynamics in GeoWEPP, especially when assessing hydrological processes, since it can limit sediment sources. However, in mountainous watersheds where sediment storage along channel sections is a dominant sediment source [Koi *et al.*, 2008], GeoWEPP may overestimate sediment discharge in the first years after model initialization. Due to this, it is necessary to begin calculations several years prior to the target period to adjust the model to initial conditions. This initialization stage

then needs to be removed. Limited previous research, such as *Pieri et al.* [2014], introduced this “spin-up process”; however details regarding setting the depth to the non-erodible layer were not provided. *Pieri et al.* [2014], applied GeoWEPP to a watershed with significant erosion, and due to this, a spin-up period may have been needed for proper redistribution of initial sediment deposition as discussed above.

Additionally, characteristics of sediment dynamics vary between supply-limited and transport-limited watersheds [*Hotta and Koi*, 2011]. Armoring and destruction, by which sediment discharge patterns are altered before and after a flood event, would also be associated with specific watersheds. Therefore, investigation of target watershed sediment supply conditions should be conducted in advance, as this will result in more accurate GeoWEPP predictions.

6. CONCLUSION

This study explored the application of GeoWEPP for assessing the baseline sediment discharge in a mountain watershed for the early detection of upstream sediment disasters. Comparison with detailed data from intensive observations in the Agatsuma watershed revealed that GeoWEPP successfully reproduced the continuous sediment discharge in subwatersheds of varying size, topography, and land use. The parameter settings corresponding to actual conditions and processes enabled the reproduction of water and sediment dynamics. For surface runoff and subsequent surface erosion in hillslope sections, the introduction of a restrictive layer and evapotranspiration rate optimization were critical for reproducing hydrological processes. The depth to non-erodible layer parameter, which varies with time and cannot be obtained from the actual depth of bed material, governed the overall sediment discharge at the study site. This parameter should be interpreted as a conceptual index that represents the spatial distribution of bed material and erodibility, and will require an adjustment period. Therefore, GeoWEPP calculations should eliminate the first year as a spin-up process in order to obtain better results in a mountain watershed where the depth of bed material is dominant in a channel section.

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