Effect of Land Use Change Driven by Economic Growth on Sedimentation in River Reach in Southeast Asia

— A Case Study in Upper Citarum River Basin —

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Abstract

The recent rapid population and economic growth in Southeast Asia has brought about drastic socio-economic changes, such as urbanization and an agricultural shift. Urbanization consists of concentrating a population from a rural to an urban area and expanding urban areas, which pushes farmland outward. The current development diagram generates and accumulates disaster risk as an extensive risk; however, the relationship between developmental progress and the increase in disaster risk must be determined for sustainable development to be achieved.

We assessed the effects of land-use changes driven by economic growth on sedimentation in a river reach of the upper Citarum River basin in Indonesia. The land-use changes in the 20 years from 1990 to 2010 were driven by economic growth and urbanization around Bandung city and are typical for Southeast Asia. Urbanization was characterized by expansion of the urban area, replacement of paddy fields, and cultivation of forest into upland fields for cash crops. As a result, sediment runoff from the hillside to the plate increased from 0.17 Mton year⁻¹ to 0.24 Mton year⁻¹, and sediment deposition on the plate increased from 0.11 Mton year⁻¹ to 0.13 Mton year⁻¹. This amount corresponded to about 30% of the sediment dredged for flood control in 2013. These results indicate that the land-use changes had a direct impact on humans under the heavy rainfall and a wide plate with steep hillside characteristics of Southeast Asian islands. We revealed the relationship between developmental progress and increased disaster risk. The results suggest that forest cultivation and the increased flood risk in the urban area were directly connected through land-use driven by rapid economic growth and urbanization.

Key words: Dredging, Economic growth, Land use change, Sediment, SWAT.

1. Introduction

The recent rapid population and economic growth in Southeast Asia has brought about drastic socio-economic changes, such as urbanization and an agricultural shift. Urbanization consists of concentrating a population from a rural to an urban area and expanding urban areas, which pushes farmland outward. The current development diagram generates and accumulates disaster risk as an extensive risk; however, the relationship between developmental progress and the increase in disaster risk must be determined for sustainable development to be achieved (UNISDR, 2015).

Prior to widespread farming and deforestation, sediment discharge was estimated to less than half the present level (Milliman and Syvitski, 1992). At the global scale, population growth provides a meaningful surrogate measure of change in land cover such as land clearance for agriculture and other facets of land disturbance, to which can be attributed the key driver of increased sediment loads (Walling, 2006). Annual suspended sediment

yields in many developing countries in Southeast Asia were increasing at a rate of 1.6 times the rate of population increase because of forest clearance and land use change in the 20th century (Abernethy, 1990). Recent progress in the market economy has shifted agriculture from self-sufficient farming to commercial farming (Burgers *et al.*, 2005), resulting in changes in land use, such as forest cultivation, which accelerates soil erosion (Valentin *et al.*, 2008).

Many studies have investigated the effects of land-use changes on the ecological consequences (Zhao *et al.*, 2006). For example, 50% of the coral reef in the Pacific region is in danger and half of that has been impacted by the anthropogenic environmental load from the landsphere (Burke *et al.*, 2011). In particular, soil and nutrients flowing from the land can lead to a loss of diversity in coral reef ecosystems (Fabricius, 2005). On the other hand, there are few studies which have investigated the effects of increased sediment loads on the human society. Some studies have assessed the impact of human activity on the amount of sediment flow which is essential to conserve coastal lines (*e.g.* Syvitski *et al.*, 2005; Auerbach *et al.*, 2015), but deposition of sediment in a river reach, which directly affects human life as a flood risk, has not been evaluated. The purpose of this study was to evaluate the effects of land use derived from economic growth on sediment

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balance, particularly focusing on deposition in a river reach using a case study in the Upper Citarum river basin where this typical change in land use has occurred.

2. Methodology

2.1 Study Area

The Citarum River basin is the largest river basin in West Java. It is 350 km long with a catchment area of about 6,600 km² (Fig. 1). The Saguling, Cirata, and Jatiluhur storage dams were built on this river and are used for hydropower, irrigation water supply, and as a fishery. The water supplies the capital of Jakarta, which is 80% dependent on the Citarum River basin for water (Loebis and Syamman, 1993). The climate is tropical, and clear, rainy, and dry conditions occur throughout the year. Annual mean precipitation is about 1,600 mm year⁻¹ and >80% of all precipitation is concentrated in the rainy season of October–April. Bandung,

the third largest city in Indonesia, is located in the upper stream region of the Citarum River. Bandung city is surrounded by a steep hill, which spreads out in to a flat area at the bottom of the Bandung basin. Bandung city suffers from frequent flood damage. One of the major factors affecting flood risk is sedimentation in the river reach, but the effect of hillside erosion has not been evaluated quantitatively (UCBFM, 2012). In this study, the target area was the upper Citarum River basin, which is about 1,740 km² (Fig. 1).

The paddy field is a very unique use of land in East and South-east Asia that is usually located in a flat area and functions as a flood plain (Agus *et al.*, 2006). Recent economic growth and urbanization have brought about land-use changes, which accelerate sediment yield from steep slopes and drainage from flat areas, and that are typical in Southeast Asia (Burgers *et al.*, 2005). Land use maps of the upper Citarum River in 1990 and 2010 are shown

Fig. 1. Target area in Citarum river basin. (a) Location of Citarum River basin: water runs from the southeast to the north. The upper Citarum River basin is colored by yellow. (b) Outline of the upper Citarum River basin: water from the hillside go through the plate and reach the Nanjung station.

Fig. 2. Land use map in upper Citarum river basin in (a) 1990 and (b) 2010.

Fig. 3. Change of land use ratio from 1990 to 2010 in (a) the whole watershed, (b) the hillside and (c) the plate.

in Fig. 2. Red portion for urban area has expanded to the east and south with increase of upland field around replacing forest and paddy fields. The changes of accumulated area for each land use in the two decades are shown in Fig. 3. On the plate, paddy fields has been developed into urban area by 46 km², which represents 18% of the plate, while 62 km² of paddy fields and 129 km² of forest have been replaced by 109 km² of upland fields and 82 km² of urban area. As a whole, 7% of the upper Citarum River has been developed into urban area from forest and 6% of it has been replaced by upland fields from paddy fields.

2.2 SWAT Model

The Soil and Water Assessment Tool (SWAT) is a hydrological process-based model (Neitsch *et al.*, 2009). This model can be used to predict the impact of land-management practices on water, sediment, and agricultural chemical yields in large complex watersheds with different soils, land uses, and management conditions over long periods of time. Some studies have applied SWAT to analyze the effects of land use changes on sediment runoff in Southeast Asia (Khoi and Suetsugi, 2014a; 2014b; Memarian *et al.*, 2014), but the effects on sediment dynamics, particularly sedimentation in a river reach, have not been evaluated. We employed ArcSWAT ver. 2012.10_1.13 in this study.

The hydrological processes in SWAT comprise a land phase and a routing phase. By partitioning the watershed into sub-basins for the tributary catchments, SWAT was used to calculate water and sediment runoff from the land into the river in each sub-basin. Water balance and material dynamics were calculated in hydrologic response units (HRUs), which are lumped land areas within the sub-basin composed of unique land cover, soil, and topography.

Sediment yield in each HRU was calculated using the modified universal soil loss equation (MUSLE) (Williams, 1975), which was modified from the universal soil loss equation (USLE) (Wischmeier and Smith, 1978). The rainfall runoff factor in the USLE, which is a function of the amount and intensity of rainfall, is replaced by a function for the amount and intensity of water runoff, which enables the equation to be applied to a larger scale than simply a farming field.

$$sed = 11.8 \cdot (q_{peak} \cdot Q_{surf} \cdot area_{hru})^{0.56} K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot GFRG \quad (1)$$

where sed is sediment yield (metric tons d⁻¹), Q_{surf} is surface runoff volume (mm ha⁻¹ d⁻¹), q_{peak} is peak runoff rate (m³ s⁻¹), $area_{hru}$ is area of an HRU (ha), K_{USLE} is the USLE erodibility factor (0.013 metric ton m² hr (m³ metric ton cm)⁻¹), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and $GFRG$ is the coarse fragment factor.

Deposition and degradation of sediment in the river reach were calculated by comparing the maximum and current concentrations of sediment.

$$sed_{dep} = \begin{cases} conc_{sed} - conc_{sed, mx} & \cdot V & conc_{sed} > conc_{sed, mx} \\ conc_{sed, mx} - conc_{sed} & \cdot V \cdot K_{CH} \cdot C_{CH} & conc_{sed} < conc_{sed, mx} \end{cases} \quad (2)$$

where sed_{dep} is the amount of sediment deposited (metric tons), $conc_{sed}$ is the current concentration of sediment (kg L⁻¹), $conc_{sed, mx}$ is the maximum concentration of sediment (kg L⁻¹), V is the volume of water in the reach (m³), sed_{deg} is the amount of sediment re-entrained (metric tons), K_{CH} is the channel erodibility factor, and C_{CH} is the channel cover factor. The maximum concentration was calculated using the stream power equation (Bagnold, 1977).

$$conc_{sed, mx} = SPCON \cdot v^{SPEXP} \quad (3)$$

where $SPCON$ is a coefficient, v is the peak channel velocity (m s⁻¹), and $SPEXP$ is an exponent. The peak channel velocity v is calculated:

$$v = \frac{q_{ch, pk}}{A_{ch}} \quad (4)$$

where $q_{ch, pk}$ is the peak flow rate (m³ s⁻¹) and A_{ch} is the cross-sectional area of flow in the channel (m²). The peak flow rate $q_{ch, pk}$ is defined as:

$$q_{ck, pk} = PRF \cdot q_{ck} \quad (5)$$

Where PRF is the peak rate adjustment factor and q_{ch} is the aver-

age rate of flow ($\text{m}^3 \text{s}^{-1}$).

In this study, the amount of sediment deposited in a sub-basin was defined as net deposition, which is the difference between the amount of sediment deposited and that of sediment re-entrained in the river reach segment. The amount of sediment deposited can take a negative value when degradation is dominant.

A further description of hydrological and sediment transport processes can be found in the SWAT theoretical documentation (Neitsch *et al.*, 2009).

2.3 Simulation Settings

The watershed was delineated based on ASTER GDEM ver. 2 (ASTER GDEM, 2011), a product of the Ministry of Economy, Trade, and Industry, Japan and the National Aeronautics and Space Administration. Spatial resolution was resampled from 30 to 100 m in the original data. The catchment area unit was set to 10 km^2 , and 116 sub-basins were used. The plate and hillside were defined based on the average slope in each sub-basin; the slope of the plate was $<3\%$, and the hillside slope was $>3\%$. The spatial distributions of the plate and hillside sub-basins are shown in Fig. 1. Thirty plate sub-basins were used in an area of 251 km^2 , which was 14% of the whole target area.

HRUs were defined based on a soil map, a land use map, and topography. The Digital Soil Map of the World and Derived Soil Properties ver. 3.6 (FAO-UNESCO, 2007) was used as the soil map. The original vector data were converted to a 100-m grid raster. Land use maps were prepared using satellite images; Landsat images were used for the 1990 map, and Aster images were used for the 2010 map; both were resampled at 100-m resolution (Fig. 2). The correspondence of the land use category in Fig. 2 to the SWAT code is listed in Table 1. The mean slope in each sub-basin was adopted as the topographical parameter. The total number of HRUs was 275 for 1990 (LU1990) and 303 for 2010 (LU2010). This difference in the number of HRUs resulted from the land-use changes.

Weather input data from Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE) ver. 1101 (Yatagi *et al.*, 2012) were adopted for precipitation, and the Climate Forecast System Reanalysis (CFSR) by the National Centers for Environmental Prediction (Fuka *et al.*, 2013) was used for temperature, solar radiation, relative humidity, and wind speed. APHRODITE uses a 0.25° grid, and CFSR uses a 0.3° grid.

The agricultural management was set based on local information. The upland field management referred to in Harashina *et al.* (2003), in which vegetables are harvested three times/year and paddy rice is planted twice annually, was used, as reported by a field survey in the Cianjur region. Both target regions were located in the Citarum River basin. The other parameters were set as

default value.

The SUFI-2 algorithm under the SWAT-Calibration and Uncertainty Procedure interface was used for the sensitivity analysis and calibration (Abbaspour, 2014). Sensitivity analysis and calibration were performed for the parameters listed in Table 2. The parameters were selected after referring to the discharge parameters in Khoi and Suetsugi (2014a) and after constitutive Eq. 1 to Eq. 5 which describe sediment dynamics.

The calibration was performed along the two procedures: 1) Calibration of the parameters related to the river discharge for monthly data from January 1995 to September 1999 and 2) Calibration of the parameters related to the sediment flow for monthly data from January 2001 to December 2003. The monitoring station was at Nanjung, which was the target area outlet in this study and the inlet to Saguling Dam Lake (Fig. 1). The source used for river discharge data was Balai Besar Wilayah Sungai and that for sediment concentration was Badan Pengendalian Lingkungan Hidup Daerah. Data of sediment flow were interpolated by the relation to the river discharge in the dry and rainy season respectively because of few number of observation data. LU1990 and LU2010 were used for the flow and sediment parameters, respectively. The parameter ranges were optimized with 95% confidence interval of the best solution, after 1,000 iterations in a step to maximize the objective function bR^2 , which is the coefficient of determination R^2 multiplied by the coefficient b of the regression line. This function accounts for discrepancies in magnitude and fluctuation. The parameter ranges were updated until the model outputs satisfied the criteria in Moriasi *et al.* (2007), using the Nash–Sutcliffe efficiency (NSE) value (Nash and Sutcliffe, 1970), percent bias ($PBIAS$) (Gupta *et al.*, 1999), and the ratio of the root mean square error ($RMSE$) to the standard deviation of the measured data (RSR) (Singh *et al.*, 2004).

NSE is computed as follows:

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2} \quad (6)$$

where Y_i^{obs} is the i th observation, Y_i^{sim} is the i th simulated value, Y^{mean} is the mean of observed data and n is the total number of observations. NSE ranges between $-\infty$ and 1.0, with $NSE = 1.0$ being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas $NSE < 0.0$ indicates that the mean observed value is better predictor than the simulated value (Moriasi *et al.*, 2007).

$PBIAS$ is calculated as follows:

Table 1. Correspondence table of each land use/cover category to the SWAT code.

Land use category	SWAT code	Description	Initial CN2 value
Paddy field	RICE	Rice	81
Upland field	AGR	Agricultural Land-Row Crops	85
Forest	FRSE	Forest-Evergreen	70
Urban	URHD	Residential-High Density	72

Table 2. Sensitivity and best value of the calibrated parameters.

Parameter	Description	t-Stat		Best value
		Discharge	Sediment	
<i>Discharge parameters</i>				
ALPHA_BF	Base flow recession constant	28.11	0.33	0.34
CH_K2	Effective hydraulic conductivity of channel (mm hr ⁻¹)	-18.73	-0.43	20
GWQMN	Threshold water depth in the shallow aquifer for base flow (mm)	-1.49	-2.63	1,300
ESCO	Soil evaporation compensation coefficient	12.26	0.49	0.97
SOL_AWC	Available water capacity (mm)	-6.96	-0.12	-0.50*
GW_REVAP	Groundwater revap coefficient	-3.16	0.08	0.08
SOL_K	Saturated soil conductivity (mm hr ⁻¹)	3.61	1.19	0.27*
CH_N2	Manning's n value	0.66	0.09	0.21*
SOL_Z	Soil depth (m)	-3.19	0.17	-0.40*
CN2_RICE	Curve Number II value for RICE	5.94	-4.45	35
CN2_AGR	Curve Number II value for AGR	3.88	-0.67	98
CN2_FRSE	Curve Number II value for FRSE	2.59	-18.74	49
CN2_URHD	Curve Number II value for URHD	-1.57	-1.99	98
<i>Sediment parameters</i>				
SPCON	Linear parameter in Eq. 3.		-0.96	0.004
SPEXP	Exponent parameter in Eq. 3.		-1.05	1.34
PRF	Peak rate adjustment factor in Eq. 5.		-0.32	0.05
USLE_P_RICE	Support practice factor for RICE		-1.00	0.69
USLE_P_AGR	Support practice factor for AGR		-28.52	0.07
USLE_C_RICE	Minimum value of cover and management factor for RICE		-29.75	0.12
USLE_C_AGR	Minimum value of USLE cover and management factor for AGR		-34.94	0.02
USLE_C_FRSE	Minimum value of USLE cover and management factor for FRSE		0.07	0.39
USLE_C_URHD	Minimum value of USLE cover and management factor for URHD		-21.47	0.003

*Parameter value is multiplied by (1+given value)

Values of t-Stat for Discharge and Sediment are the result from comparing with observed data of river discharge and sediment flow, respectively.

$$PBIAS = \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})}{\sum_{i=1}^n (Y_i^{obs})} \right] * 100. \quad (7)$$

The optimal value of *PBIAS* is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias and negative values indicate model overestimation bias (Gupta *et al.*, 1999).

RSR is calculated as the ratio of the root mean square error and standard deviation of measured data as shown in equation (7):

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2}}. \quad (8)$$

RSR varies from the optimal value of 0, which indicates zero *RMSE* or residual variation and therefore perfect model simulation, to a large positive value. The lower *RSR*, the lower *RMSE*, and the better the model simulation performance.

The best parameters were applied to the calculations. The validation was performed for the river discharge and sediment flow of

the river water at Nanjung station, from January 2004 to December 2006, after a comparison with the criteria in Moriasi *et al.* (2007).

In this study, the effects of different land uses were compared with the sediment balance determined by LU1990 and LU2010. The calculation period was 12 years (1995–2006) with a 5-year spin up, and the same weather forcing was applied to assess the effects of differences in land use. In particular, the increased sediment yield from the hillside where forest was widely cultivated into an upland field and the sediment deposition in the river reach on the plate were estimated.

3. Results and Discussion

3.1 Model Calibration and Validation

The sensitivity analysis results for the parameters and optimized values are shown in Table 2. In terms of the river discharge calculation, the most sensitive parameter was *ALPHA_BF*, which is the base flow recession constant, followed by the absolute values of *t*-stat for *CH_K2*, *ESCO*, and *SOL_AWC*, in that order. These parameters were related to local soil characteristics and river reach managements, but not to land use. *CN2* is a representative parameter corresponding to land use, but was the less sensitive of the parameters listed in Table 2, indicating that river discharge in this basin was not very sensitive to the land use change. This is because the sensitivity analysis in this study was per-

Fig. 4. Comparison between model output and observed data at Nanjung station. (a) Calibration period for river discharge: from January 1995 to September 1999. (b) Calibration and validation for sediment flow: calibration from January 2001 to December 2003; validation from January 2004 to December 2006.

formed in monthly step of time. The monthly hydrological circulation on the ground was mainly explained by soil water and river routing processes rather than infiltration and surface runoff which were strongly affected by land use. On the other hand, the t-stat values for sediment calculation indicate that, instead of parameters for sediment routing in the river reach, *CN2s* were the most sensitive next to the USLE parameters which are key factor accounting for the sediment yield in each land use. This was attributed to the characteristics of sediment dynamics that the erosion occurs only in rainfall events and it takes short time, such as a few days, sediment runoff from each land use reaches the outlet.

Water and sediment in paddy field is very comprehensive and some previous studies have developed a sub-model to assess the daily dynamics in a field to small watershed scale (Xie and Cui, 2011; Sakaguchi *et al.*, 2014). The purpose of this study is, however, the assessment of the effect of decadal land use change on the water and sediment dynamics. The value of *CN2_RICE* was optimized up to 35 such a low value indicates a high retention capacity of paddy field which could be attributed to the leveled and terraced structure.

The numbers of calibration steps of a 1,000 iteration were two for river discharge and three for sediment flow. Monthly river discharge and sediment flow of the calculation and observation at Nanjung station are shown in Fig. 4. The line of calculation indi-

cates the SWAT output using the best parameters after calibrations. The interannual and annual variations in river discharge were well simulated during the calibration and validation periods. At the last step for discharge calibration (Fig. 4(a)), *RSR* ($= 0.67$) and *NSE* ($= 0.55$) were rated as satisfactory, and *PBIAS* ($= -0.4\%$) was rated as very, whereas for sediment flow (Fig. 4(b)), *RSR* ($= 0.66$) and *NSE* ($= 0.56$) and *PBIAS* ($= 31.6\%$) were rated as satisfactory. As a result of validation for sediment flow, *RSR* ($= 0.92$) and *NSE* ($= 0.15$) were rated as unsatisfactory and only *PBIAS* ($= 31.6\%$) was rated as satisfactory. These values indicated that calculation results were valid for annual average, and were not valid but preferable to a constant value of the observation average for monthly variation. In this study, uniform crop calendars were applied to each land use but the actual crop calendars differ from even in the field scale due to adequate water availability and warm temperature all year.

3.2 Changes in Sediment Runoff and Deposition

The spatial distributions of annual average sediment yield from each subbasin are shown in Fig. 5. In the west and southwest region, sediment yield from some subbasins in the hillside, which was almost equal to zero in 1990, was increased up to several ton ha^{-1} , where land use changed from forest to upland fields in Fig. 2. On the other hand, in the plate, regardless of a remarkable change of land use, that paddy field was replace into urban area by 18%

Fig. 5. Spatial distribution of sediment yield from subbasins in a) LU1990 and b) LU2010. The hillside is covered by diagonal stripe.

Fig. 6. Comparison of sediment yields from each subbasin between LU1990 and LU2010. (a) Subbasins plotted on the upper/lower side of the 1:1 line indicate that sediment yield from the subbasins increased/decreased from 1990 to 2010. (b) Line within box means median; bottom and top of each box, 25th and 75th percentiles; horizontal lines outside box, 10th and 90th percentiles.

of the plate area, most subbasins stayed at the same level. This is because the topography in the plate is flat and the value of LS_{USLE} is very small (Eq. 1). Comparison of sediment yields in each subbasin between LU 1990 and LU2010 are shown in Fig. 6. Average sediment yield from 27 upland catchments in Southeast Asia, which include a catchment in Indonesia, was reported as 3.4 ± 4.6 $\text{ton ha}^{-1} \text{yr}^{-1}$ (Valentine *et al.*, 2008) and all the value of sediment yield from the subbasins were included the range except one subbasin in the hillside. The different trends of the sediment yield in the hillside and plate were revealed (Fig. 6(a)). Some hillside subbasins which were plotted near the vertical axis mainly corresponded to the subbasins in the west and southwest region where land use changed remarkably. While most subbasins were plotted

upper portion than 1:1 line as a whole, it should be worthy of remark that the range from median to 75 percentile relatively shrieked to that to 25 percentile. The potential or maximum sediment yield is given by the climate, soil and topographic condition (Eq.1) and such trend of median values should imply that the situation was getting close to the potential.

The total sediment balances in LU1990 and LU2010 are shown in Fig. 7. The land-use change on the hillside increased sediment yield from $0.26 \text{ Mton year}^{-1}$ to $0.39 \text{ Mton year}^{-1}$ and sediment runoff to the plate from $0.17 \text{ Mton year}^{-1}$ to $0.24 \text{ Mton year}^{-1}$. While total sediment flow into Saguling Dam Lake, which is located downstream of the target area, increased by $0.05 \text{ Mton year}^{-1}$, sediment deposition on the hillside increased from 0.10

Fig. 7. Sediment balance in the plate and hillside sub-basins in a) LU1990 and b) LU2010. Y, D and R indicate sediment yield, deposition and runoff to the downstream respectively.

Mton year⁻¹ to 0.16 Mton year⁻¹ and on the plate increased from 0.11 Mton year⁻¹ to 0.13 Mton year⁻¹. Actually, the sediment deposition in the river reach has been a serious problem in the target area and the local government conducts several dredging projects in and around Bandung city every year, as is necessary to maintain urban functions by increasing channel drainage capacity. According to Ministry of General Work and Public Housing of Indonesia (2016), the dredged amount in 2013 was 410,000m³ in total. Assuming the density of sediment water is equal to 2.0 ton m⁻³, the amount of sediment which was estimated to deposit on the plate annually corresponded up to 27% to 32% of the dredged sediment. Furthermore, increased sediment deposition on the hillside should be increasing the flood risk around the plate.

4. Conclusion

We assessed the effects of land-use changes driven by economic growth on sedimentation in a river reach of the upper Citarum River basin in Indonesia. The land-use changes in the 20 years from 1990 to 2010 were driven by economic growth and urbanization around Bandung city and are typical for Southeast Asia. Urbanization was characterized by expansion of the urban area, replacement of paddy fields, and cultivation of forest into upland fields for cash crops. As a result, sediment runoff from the hillside to the plate increased from 0.17 Mton year⁻¹ to 0.24 Mton year⁻¹, and sediment deposition on the plate increased from 0.11 Mton year⁻¹ to 0.13 Mton year⁻¹. This amount corresponded to about 30% of the sediment dredged for flood control in 2013. These results indicate that the land-use changes had a direct impact on humans under the heavy rainfall and a wide plate with steep hillside characteristics of Southeast Asian islands. We revealed the relationship between developmental progress and increased disaster risk. The results suggest that forest cultivation and the increased flood risk in the urban area were directly connected through land-use driven by rapid economic growth and urbanization. And also the results imply that there is possibility to improve economic efficiency toward sustainable development by harmonized activities among stake holders such as governments, private companies and farmers.

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References

- Abbaspour KC, 2014: SUFI-2. In *SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs – A User Manual*. Swiss Federal Institute of Aquatic Science and Technology Eawag, pp.20-56.
- Abernethy CL, 1990: The use of river and reservoir sediment data for the study of regional soil erosion rates and trends, *the International Symposium on Water Erosion, Sedimentation and Resource Conservation*. 9-13 October, and Dehradun, India, pp.1-19.
- Agus F, Irawan I, Suganda H, Wahyunto W, Setiyanto A, Kundarto M, 2006: Environmental multifunctionality of Indonesian agriculture. *Paddy and Water Environment* **4**, 181-188.
- ASTER GDEM, 2011. Available from <http://www.jspacesystems.or.jp/ersdac/GDEM/J/3.html> (Accessed April 5, 2016).
- Auerbach LW, Goodbred Jr SL, Mondal DR, Wilson CA, Ahmed KR, Roy K, Steckler MS, Small C, Gilligan JM, Ackerly BA, 2015: Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change* **5**(2), 153-157.
- Bagnold RA, 1977: Bedload transport in natural rivers. *Water Resources Research* **13**, 303-312.
- Burgers P, Ketterings, QM, Garrity DP, 2005: Fallow management strategies and issues in Southeast Asia. *Agriculture, Ecosystems and Environment* **110**, 1-13.
- Burke L, Reynter K, Spalding M, Perry A, 2011: Regional Summaries. In *Reefs at Risk Revisited*. World Resources Institute, Washington, DC, USA, pp.48-65.
- Fabricius KE, 2005: Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* **50**, 125-146.
- FAO-UNESCO, 2007: Digital Soil Map of the World, GeoNetwork, Food and Agriculture Organization of the United Nations. Available from <http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116>. (Accessed April 5, 2016).
- Fuka DR, Walter MT, MacAlister CA, Degaetano AT, Steenhuis TS, Easton ZM, 2013: Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrological Processes*, Published online in Wiley Online Library.
- Gupta HV, Sorooshian S, Yapo PO, 1999: Status of automatic calibration for hydrologic models: Comparison with multilevel

- expert calibration. *Journal of Hydrologic Engineering* **4**(2), 135-143.
- Harashina K, Takeuchi K, Tsunekawa A, Arifin HS, 2003: Nitrogen flows due to human activities in the Cianjur–Cisokan watershed area in the middle Citarum drainage basin, West Java, Indonesia: a case study at hamlet scale. *Agriculture Ecosystems and Environment* **100**, 75-90.
- Khoi DN, Suetsugi T, 2014a: The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. *Hydrological Processes* **28**, 640-652.
- Khoi DN, Suetsugi T, 2014b: Impact of climate and land-use changes on hydrological processes and sediment yield –a case study of the Be River catchment, Vietnam. *Hydrological Sciences Journal* **59**(5), 1095-1108.
- Loebis J, Syamman P, 1993: Reservoir operation conflict in Citarum river basin management. *Proceedings of the Yokohama Symposium*. Yokohama, Japan, pp.455-459.
- Memarian H, Balasundram SK, Abbaspour KC, Talib JB, Sung CTB, Sood AM, 2014: SWAT-based hydrological modeling of tropical land-use scenarios. *Hydrological Sciences Journal* **59**(10), 1808-1829.
- Milliman JD, Syvitski JPM, 1992: Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *The Journal of Geology* **100**(5), 525-544.
- Ministry of General Work and Public Housing of Indonesia, 2016: *Infrastructure rehabilitation for flood controlling in Citarum river in 2013, Quantity and Cost*, Balai Besar Wilayah Sungai (BBWS) Citarum, Bandung, pp.2.
- Moriassi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel R D, Veith TL, 2007: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers* **50**, 885-900.
- Nash JE, Sutcliffe JV, 1970: River flow forecasting through conceptual models. Part I-a discussion of principles, *Journal of Hydrology* **10**, 282-290.
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR, 2009: *Soil and Water Assessment Tool theoretical documentation version 2009*, Texas Water Resources Institute, College Station, Texas, USA, pp.647.
- Sakaguchi A, Eguchi S, Kato T, Kasuya M, Ono K, Miyata A, Tase N, 2014: Development and evaluation of a paddy module for improving hydrological simulation in SWAT. *Agricultural Water Management* **137**, 116-122.
- Singh J, Knapp HV, Demissie M, 2004: Hydrologic modeling of the Iroquois River watershed using HSPF and SWAT. *Illinois State Water Survey Contract Report 2004-08*, pp.24.
- Syvitski JP, Vörösmarty CJ, Kettner AJ, Green P, 2005: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* **308**(5720), 376-380.
- UCBFM, 2012: *Upper Citarum Basin Flood Management, flood Management Strategy*, pp.40-42.
- UNISDR, 2015: *Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR), pp.247-266.
- Valentin C, Agus F, Alamban R, Boosaner A, Bricquet JP, Chaplot V, de Guzman T, de Rouw A, Janeau JL, Orange D, Phachomphonh K, Phai DD, Podwojewski P, Ribolzi O, Silvera N, Subagyo K, Thiebaux JP, Toan TD, Vadari T, 2008: Run-off and sediment losses from 27 catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. *Agriculture, Ecosystems and Environment* **128**, 225-238.
- Walling DE, 2006: Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology* **79**, 192-216.
- Williams JR, 1975: Sediment Routing for Agricultural Watersheds. *the Water Resources Bulletin* **11**(5), 965-974.
- Wischmeier WH, Smith DD, 1978: Predicting rainfall erosion losses, In *Agriculture Handbook*, Agricultural Research Service, Washington, DC, USA, Handbook number 537, pp.58.
- Xie X, Cui Y, 2011: Development and test of SWAT for modeling hydrological processes in irrigation districts with paddy rice. *Journal of Hydrology* **396**(1), 61-71.
- Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A, 2012: APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges, *Bulletin of the American Meteorological Society*, published on line. Available from <http://journals.ametsoc.org/doi/full/10.1175/BAMS-D-11-00122.1> (Accessed April 5, 2016).
- Zhao S, Peng C, Jiang H, Tian D, Lei X, Zhou X, 2006: Land use change in Asia and the ecological consequences. *Ecological Research* **21**(6), 890-896.