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 —

Keigo NODA a, †, Koshi YOSHIDA b, Hiroaki SHIRAKAWA c, Ussep SURAHMAN d and Kazuo OKI a

a Institute of Industrial Science, the University of Tokyo, Komaba 4-6-1, Meguro-ku 153-8505, Japan
b College of Agriculture, Ibaraki University, Chuo 3-21-1, Ami, Ibaraki 300-0393, Japan
c Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
d Faculty of Technology and Vocational Skills Education, Indonesia University of Education, Jalan Setiabudhi No. 229, Isola, Sukasari, Kota Bandung, Jawa Barat 40154, Indonesia

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 be 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 landspace (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
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 into 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 Southeast 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 in Fig. 2.

![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.](image1)

![Fig. 2. Land use map in upper Citarum river basin in (a) 1990 and (b) 2010.](image2)
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 Stetsugi, 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.

\[
sed = 11.8 \left( \frac{q_{\text{peak}} \cdot Q_{\text{surf}} \cdot \text{area}_{\text{hru}}}{P_{\text{USLE}} \cdot LS_{\text{USLE}} \cdot GFRG} \right)^{0.56} K_{\text{USLE}} \cdot C_{\text{USLE}} \cdot P_{\text{USLE}} \cdot \text{USLE to topographic factor, } LS_{\text{USLE}} \text{ is the USLE erodibility factor (0.013 metric ton m}^2 \text{ hr} \cdot (\text{m}^3 \text{ metric ton cm})^{-1}), \text{C}_{\text{USLE}} \text{ is the USLE cover and management factor, } P_{\text{USLE}} \text{ is the USLE support practice factor, and } GFRG \text{ is the coarse fragment factor.}
\]

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

\[
sed_{\text{dep}} = \begin{cases} \text{conc}_{\text{sed}} - \text{conc}_{\text{sed, mx}} & \text{if conc}_{\text{sed}} > \text{conc}_{\text{sed, mx}} \\ V \cdot \text{SPEXP} & \text{if conc}_{\text{sed}} < \text{conc}_{\text{sed, mx}} \end{cases}
\]

\[
\text{conc}_{\text{sed, mx}} = \text{SPCON} \cdot v^{\text{SPEXP}}
\]

where \( \text{SPCON} \) is a coefficient, \( v \) is the peak channel velocity (m s\(^{-1}\)), and \( \text{SPEXP} \) is an exponent. The peak channel velocity \( v \) is calculated:

\[
v = \frac{q_{\text{ch, pk}}}{A_{\text{ch}}}
\]

where \( q_{\text{ch, pk}} \) is the peak flow rate (m\(^3\) s\(^{-1}\)) and \( A_{\text{ch}} \) is the cross-sectional area of flow in the channel (m\(^2\)). The peak flow rate \( q_{\text{ch, pk}} \) is defined as:

\[
q_{\text{ch, pk}} = PRF \cdot q_{\text{ch}}
\]

Where \( PRF \) is the peak rate adjustment factor and \( q_{\text{ch}} \) is the aver-

---

**Fig. 3.** Change of land use ratio from 1990 to 2010 in (a) the whole watershed, (b) the hillside and (c) the plate.
age rate of flow (m³ 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 km², 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 km², 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 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 bR², which is the coefficient of determination bR² 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:

\[
NSE = 1 - \frac{\sum_{i=1}^{n} \left( \frac{Y_{i}^{\text{obs}} - Y_{i}^{\text{sim}}}{Y_{i}^{\text{mean}}} \right)^2}{\sum_{i=1}^{n} \left( \frac{Y_{i}^{\text{obs}} - Y_{i}^{\text{mean}}}{} \right)^2}
\]

where \(Y_{i}^{\text{obs}}\) is the \(i\)th observation, \(Y_{i}^{\text{sim}}\) is the \(i\)th simulated value, \(Y_{i}^{\text{mean}}\) 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>
<thead>
<tr>
<th>Land use category</th>
<th>SWAT code</th>
<th>Description</th>
<th>Initial CN2 value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy field</td>
<td>RICE</td>
<td>Rice</td>
<td>81</td>
</tr>
<tr>
<td>Upland field</td>
<td>AGRR</td>
<td>Agricultural Land-Row Crops</td>
<td>85</td>
</tr>
<tr>
<td>Forest</td>
<td>FRSE</td>
<td>Forest-Evergreen</td>
<td>70</td>
</tr>
<tr>
<td>Urban</td>
<td>URHD</td>
<td>Residential-High Density</td>
<td>72</td>
</tr>
</tbody>
</table>
Table 2. Sensitivity and best value of the calibrated parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>t-Stat</th>
<th>Best value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPHABF</td>
<td>Base flow recession constant</td>
<td>28.11</td>
<td>0.33</td>
</tr>
<tr>
<td>CHK2</td>
<td>Effective hydraulic conductivity of channel (mm hr⁻¹)</td>
<td>-18.73</td>
<td>-0.43</td>
</tr>
<tr>
<td>GWQMN</td>
<td>Threshold water depth in the shallow aquifer for base flow (mm)</td>
<td>-1.49</td>
<td>-2.63</td>
</tr>
<tr>
<td>ESCO</td>
<td>Soil evaporation compensation coefficient</td>
<td>12.26</td>
<td>0.49</td>
</tr>
<tr>
<td>SOLAWC</td>
<td>Available water capacity (mm)</td>
<td>-6.96</td>
<td>-0.12</td>
</tr>
<tr>
<td>GWREVAP</td>
<td>Groundwater revap coefficient</td>
<td>-3.16</td>
<td>0.08</td>
</tr>
<tr>
<td>SOLK</td>
<td>Saturated soil conductivity (mm hr⁻¹)</td>
<td>3.61</td>
<td>1.19</td>
</tr>
<tr>
<td>CHN2</td>
<td>Manning’s n value</td>
<td>0.66</td>
<td>0.09</td>
</tr>
<tr>
<td>SOLZ</td>
<td>Soil depth (m)</td>
<td>-3.19</td>
<td>0.17</td>
</tr>
<tr>
<td>CN2RICE</td>
<td>Curve Number II value for RICE</td>
<td>5.94</td>
<td>-4.45</td>
</tr>
<tr>
<td>CN2AGR</td>
<td>Curve Number II value for AGRR</td>
<td>3.88</td>
<td>-0.67</td>
</tr>
<tr>
<td>CN2FRSE</td>
<td>Curve Number II value for FRSE</td>
<td>2.59</td>
<td>-18.74</td>
</tr>
<tr>
<td>CN2URHD</td>
<td>Curve Number II value for URHD</td>
<td>-1.57</td>
<td>-1.99</td>
</tr>
</tbody>
</table>

| Sediment        |                                                  |        |            |
| 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_PRICE      | Support practice factor for RICE                 | -1.00  | 0.69       |
| USLE_PAGR       | Support practice factor for AGRR                 | -28.52 | 0.07       |
| USLE_CRICE      | Minimum value of cover and management factor for RICE | -29.75 | 0.12       |
| USLE_CAGR       | Minimum value of USLE cover and management factor for AGRR | -34.94 | 0.02       |
| USLE_CFSE       | Minimum value of USLE cover and management factor for FRSE | 0.07  | 0.39       |
| USLE_CURHD      | 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.

$$\text{PBIAS} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{Y_{i}^{\text{obs}} - Y_{i}^{\text{sim}}}{Y_{i}^{\text{obs}}} \right) \times 100.$$  \hspace{1cm} (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).

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \sqrt{\frac{\sum_{i=1}^{n} (Y_{i}^{\text{obs}} - Y_{i}^{\text{sim}})^2}{\sum_{i=1}^{n} (Y_{i}^{\text{obs}} - Y_{\text{mean}})^2}}.$$  \hspace{1cm} (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 ALPHABF, which is the base flow recession constant, followed by the absolute values of t-stat for CHK2, ESCO, and SOLAWC, 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-
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, \( CN_2 \)s 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 \( CN_2\_RICE \) 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 indicates 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%
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. Aver age sediment yield from 27 upland catchments in Southeast Asia, which include a catchment in Indonesia, was reported as 3.4-4.6 ton ha$^{-1}$ 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 hillsid e. 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 Mton year$^{-1}$ to 0.39 Mton year$^{-1}$ and sediment runoff to the plate from 0.17 Mton year$^{-1}$ to 0.24 Mton year$^{-1}$. While total sediment flow into Saguling Dam Lake, which is located downstream of the target area, increased by 0.05 Mton year$^{-1}$, sediment deposition on the hillside increased from 0.10

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

![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.](image)
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 410,000m\(^3\) 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.

Acknowledgement

This research was supported by the Environment Research and Technology Development Fund (1E-1104), Kurita Water and Environment Foundation Grant, and Green Network of Excellence-environmental information (GRENE-ei) funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References


Fuka DR, Walter MT, MacAlister CA, Degattaeno 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


