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論文内容の要旨

Chapter 1 Background and Objectives

The most common and widespread land use and land cover (LULC) changes across the globe are deforestation, agricultural expansion, and urbanization. The LULC changes caused by anthropogenic activities significantly affect the hydrological characteristics of the landscape. Moreover, it also was recognized as capable of greatly accelerating soil erosion. In Cambodia, the LULC changes happened dramatically in the last 2 decades which was mainly due to population growth, agricultural expansion, and economic and urban development.

Therefore, the research interests have been focused on the impacts of LULC changes on hydrological characteristics and soil erosion in Stung Sangkae Catchment, as the impacts threaten sustainable development in agriculture and local livelihoods if the targeted catchment is not properly restored through deep consideration. Accordingly, this study attempted to examine 1) What the changes of LULC and its hydrological characteristics were in the Stung Sangkae Catchment from 2002 to 2015 by the SWAT model; 2) What the soil erosion severeness was in the catchment from 2002 to 2015 by RUSLE model; 3) Based on the impacts of LULC changes on stream flow and soil erosion, how seasonal flow or soil erosion is mitigated in the catchment thought implementing countermeasures of reforestation or agroforestry practices; and 4) How the public perception on the importance of conservation strategies against flood/drought and soil loss in the catchment is deepened.

Chapter 2 Research Site Description

The Stung Sangkae Catchment (605,170 ha), which is the third-largest tributary of the Tonle Sap Basin River system, is located at the upper north-western part of Cambodia between 12°130-13°240 N and 102°350-103°420 E. The topography is level within the floodplain region and rough with slopes at the upland portion of the catchment having elevations extending from 4 m at the most reduced point to 1,413 m a.s.l at the most noteworthy point. The catchment is characterized by distinctive topographical conditions, from flat plains to rugged areas. The main river that flows through the catchment, Sangkae River, lies between the tributaries of the Tonle Sap Great Lake in the upper western part of the catchments. The length of the river is approximately 250 km. Based on meteorological data collected from six weather stations in 2007-2018, the average annual precipitation in the study area is 1,388 mm and varied from 1,308 mm at Moung Ruessei Station to 1,577 mm at Samlout Station with little change during the year. The major soil types in the catchment are (1) Luvisols (34.0%) which are a type of soil in which highly active clay migrates from the top part of the profile, usually gray, and is deposited in the B layer, usually brown; (2) Nitisols (27.4%) which are mainly deep, well-drained soils with a stable structure and high nutrient content; (3) Gleysols (27.3%) which are wetland soils, which in the natural state are continuously water-saturated within 50 cm of the surface, for extended periods; and (4) Acrisols (11.3%) which are clay-wealthy soils which can be fairly vulnerable to erosion covering the area. In the catchment, floods, drought, and soil erosion have been happening severely.

The Stung Sangkae Catchment, located in Battambang Province, is recognized by the Royal Government of Cambodia (RGC) as an important area for agricultural investment and development. Agriculture is the main local economic activity and the main source of livelihood in the catchment. Agricultural production, in particular paddy rice production, has had significant expansion and intensification. Consequently, the catchment has experienced intensive LULC changes, particularly in the last 20 years, especially the transformation of forest land to agricultural land. Additionally, the focus has been paid to drought and flooding as well as soil erosion happening severely more in the catchment.

Accordingly, for solving facing problems in the catchment, a study on the impacts of LULC changes on hydrological characteristics and soil erosion was conducted, as the impacts threaten sustainable development in agriculture and local livelihoods if the targeted catchment is not properly restored. The impacts of LULC changes from 2002 to 2015 on the changes of hydrological characteristics, especially stream flow and soil erosion in the Stung Sangkae Catchment was analyzed, while three scenarios of reforestation or agroforestry to mitigate the excess fluctuation of stream flow and soil erosion loss in the catchment were implemented. The land use developed by the Japan International Cooperation Agency (JICA) in 2002 and land cover (Land Cover Maps of LMB) developed by Mekong River Commission (MRC) in 2015 were used in the study integrating with SWAT model and RUSLE model.

Chapter 3 Impacts of Land Use and Land Cover Changes on Hydrological Responses and Soil Erosion in Stung Sangkae Catchment in 2002-2015 by SWAT model

Based on LULC dynamics for the study periods from 2002-2015 in Stung Sangkae Catchment, the results showed that the catchment experienced a rapid conversion of forests to agricultural upland, paddy rice fields, and others. The cultivated lands (upland fields and paddy rice fields) occupied almost 50% of the total land area in the catchment in 2015, which increased from 20% in 2002, while forest cover (evergreen, deciduous, and mixed forest) occupied 43% in 2002 and declined to 30% in 2015. Among the LULCs, the areas under upland fields increased from 4.2% to 25.2%, which is the highest compared to other land use, followed by paddy rice fields that increased from 15.3% to 23.9% between the years 2002 and 2015.

The SWAT results showed that in the Stung Sangkae Catchment, the LULC changes have slightly impacted on hydrological characteristics, particularly streamflow due to the conversion from the forest area, shrubland, and grassland to agricultural upland, paddy rice, and urban area. Moreover, it was indicated that the increase of bare land and upland fields resulted in a slight increase in annual and seasonal stream flow remarkably in the catchment.

The mean annual stream flow increased in the range of approximately 0.1 m^3/s to 104 m^3/s and the highest mean annual flow changes increased by approximately 0.8 m^3/s along the mainstream of Stung Sangkae River, especially at the downstream catchment, while the soil loss was increased from 13.4 t/ha/y to 22.1 t/ha/y. The soil erosion maps also showed that 74.5% of the surface area of the Stung Sangkae Catchment is exposed to a low to moderate risk of erosion (<10 t/ha/y) and 17.4% basin is at severe risk. The most affected areas are in the west of the catchment where the upland fields were expanded.

The simulation performances for the monthly flow were reasonably good (R^2 =0.58, NSE = 0.55 and PBIAS = 5 including dam construction) and (R^2 = 0.64, NSE = 0.62 and PBIAS = 15 excluding dam construction). Therefore, these calibrated parameters can be used for further future hydrological and environmental studies in the Stung Sangkae Catchment without the need to perform a sensitivity analysis. Moreover, the applicability of the SWAT model in simulating the stream flow and sediment dynamics of the Stung Sangkae Catchment has been validated based on the satisfactory values of the statistical measures of the model efficiency.

Hence, the results of the model simulation provide confidence for the further application of the model to assess the hydrological response analysis due to spatial and temporal variability of the catchment characteristics having minimal bias within the Stung Sangkae Catchment. Moreover, the approach used in this research simply evaluates the contributions of individual LULC classes to the total hydrological responses, providing quantitative information for decision-makers to make better options for land and water resource planning and management.

Chapter 4 Impact of Land Use and Land Cover Changes on Soil Erosion in Stung Sangkae Catchment in 2002-2015 by RUSLE Model

The Revised Universal Soil Loss Equation (RUSLE) model integrated within a Geographic Information System (GIS) was further used to verify the result of soil loss in the catchment from the SWAT model in chapter 3. This research aimed to estimate the total amounts of soil loss in Stung Sangkae Catchment using the RUSLE model based on national LULC maps of JICA 2002 and MRC 2015.

Based on the assessment of LULC dynamics, the forest lands decreased significantly during the investigated period, notably a massive shift in deciduous and mixed forest converted to upland fields, paddy rice fields, and other types of land use. In terms of the soil loss in the catchment, the results indicated that the average soil loss was 4.6 t/ha/y and 14.4 t/ha/y for 2002 and 2015, respectively. The calculated total soil loss in the 2002 and 2015 periods was 2.8 million t/y and 8.7 million t/y, respectively. The spatial distribution of soil loss by land use types showed that the highest erosion happened to agricultural land (36.2 t/ha/y in 2002 and 48.5 t/ha/y in 2015) was recorded in upper parts of the catchment, particularly sub-catchments 11, 12, 14, 16, 18 and 19 which was agreed with the corn experimental field.

It is recommended that priority should be given to erosion hot spot areas, and appropriate soil and water conservation practices should be adopted to restore degraded lands. Therefore, it is necessary to integrate protection measures at the farm level and targeted areas of high risk of erosion, mainly the degraded lands along steep slopes, to limit the conversion of forest areas for agriculture and minimize the rate of erosion where the land is bare or with low vegetation cover.

Chapter 5 Effects of Reforestation or Agroforestry on Hydrological Responses in Stung Sangkae Catchment

From the results of Chapters 3 and 4, LULC changes slightly impacted stream flow and significantly affected soil erosion in the catchment. Hence, some scenarios of reforestation or agroforestry practices were applied to investigate its effects on streamflow and soil erosion, such as scenario 1) all areas of forest land (mixed and deciduous forest) are revived, while the other types of land use remain the same (15% in the area applied reforestation or agroforestry for achieving 30% in forest area), scenario 2) the area of agricultural upland was reforested for converting to agroforestry, while the other types of land use are the same (25% in the area applied reforestation or agroforestry for achieving 40% in forest area), and scenario 3) all the mixed forest, deciduous forest, and agricultural upland were revived (40% in the area applied reforestation or agroforestry for achieving 55% in forest area), while the other types of land use remain the same. The scenarios were based on the Royal Government of Cambodia (RGC) to maintain at least 50% of its land under forest cover to contribute to the country's Sustainable Development Goals by 2030.

The results of simulated stream flow by the SWAT model for the whole catchment of baseline land use in 2015 and three proposed scenarios showed the slight effects of reforestation or agroforestry on stream flow, especially seasonal stream flow. The results indicated that the discharge of seasonal stream flow of three scenarios decreased in the wet season (May-Oct.) and increased in the dry season (Nov.-April) compared with the baseline land uses. For the percentage of seasonal stream flow changes in scenarios 1, 2 and 3, they decreased in the wet season at about 1.4%, 3.4%, and 3.3%, and increased in the dry season at about 2.9%, 0.8%, and 0.4%, respectively. The increased stream flows are remarkably important for water resource management in the dry season and for flood reduction and soil conservation in the wet season.

However, the results of the reforestation scenarios significantly showed that 25% of reforestation in the catchment can prevent soil erosion. Reforestation beyond 25% in the catchment is not recommended from a view of soil erosion prevention, as there was no remarkable difference in preventing soil erosion under 25% reforested and under 40%.

Chapter 6 Deeping Public Perception on the Importance of Conservation Strategies against Flood/Drought and Soil Loss

Additional assessment of soil fertility changes and flood/drought was assessed through farmers' perceptions through household survey (HS) of 200 respondents (100 HS at the upstream and 100 HS at the downstream of Stung Sangkae catchment) in 2021. To overcome the problem of data scarcity and evaluate soil erosion in a relatively short period, a unique approach for assessing land degradation from the standpoint of farmers was used. It was based on farmer assessments and observations of changes in their fields. These changes were expressed as soil and productivity loss through visible and comprehensible indicators by the farmers. For the field survey, four districts were selected from each ecological zone (2 districts at the upstream and 2 districts at the downstream catchment). The villages were selected based on their agricultural practices and accessibility. Of the total participants in focus group discussion (FGDs), 35% of respondents were female. The FGDs consisted of a mixture of closed- and open-ended questions.

The results of the HS showed that during the last 18 years from 2002 to 2020, soil fertility declined significantly. In general, the soil fertility in the catchment declined from a low decline to a very strong decline at the upstream and the downstream of the catchment, respectively. In the catchment, mostly the soil fertility occurred from a fair decline to a strong decline, while the rate of soil fertility tended to slightly increase from a fair decline to a strong decline of 33% to 36% and 40% to 43 % at the upstream and downstream catchment, respectively. In contrast, the rate of a very strong decline in soil fertility mainly happened at the upstream catchment rather than at the downstream catchment, which was 18% and 11%, respectively. However, based on the FGD, the farmers responded that their agricultural yield only slightly declined during the study period. This was because the amounts of chemical fertilizer consumption were used more than before to sustain the yield of their products.

The catchment mostly experienced low drought at the upstream and downstream catchment in 2002 and 2015; however, in 2020 the catchment experienced extreme drought rather than low drought in the catchment, particularly in the lowland catchment. At the upstream and downstream catchment, the flooding occurred at a moderate level. In 2002, the flooding occurrence at the upstream catchment (42%) was higher than at the downstream catchment (33%); however, in 2015-2020 the flooding experienced at the downstream catchment, while the rate of flooding also increased from moderate to the extreme level, particularly in 2020. Farmers confirmed that they experienced not only drought but also flooding while there was water released from the Sek Sok multi-purpose dam at the upstream catchment.

Chapter 7 Conclusions and Recommendations

In this research, the national LULC maps of JICA 2022 and MRC 2015 were used to evaluate their impacts on the hydrological characteristics and soil erosion in Stung Sangkae Catchment. It was shown that the forest lands decreased significantly during the investigated period, especially a massive shift in deciduous and mixed forest converted to upland fields, paddy rice fields, and other types of land use. The upland fields increased 21% from 4.4% in 2002 to 25.2% in 2015, while the forest land occupied 43% in 2002 and declined to 30% in 2015 for a whole catchment area (605,170 ha). The statistical agreement of R^2=0.64, NSE=0.62, and PBIAS=15 (without dam construction period) and R^2=0.58, NSE=0.55, and PBIAS=5 (with dam construction period) for the SWAT model is found to be satisfactory for the Stung Sangkae Catchment. As of the 2002-2015 period, even though the LULC was significantly changed, the streamflow was slightly increased; however, soil erosion significantly impacted which was 13.4 t/ha/y in 2002 and 22.1 t/ha/y in 2015. The highest mean annual flow changes increased by approximately 0.8 m^3/s along the mainstream of Stung Sangkae River, especially downstream, while medium mean annual flow increased by 0.3 m^3/s across a whole catchment.

For the soil erosion analysis with the RUSLE model, the average soil loss from the catchment was 4.6 t/ha/y in 2002 and 14.4 t/ha/y in 2015, while the highest erosion area was found in parts of the upland of the Stung Sangkae Catchment, mainly due to agricultural land expansion, steep slopes, and degradation of the vegetation. Both models could capture reasonable soil loss agreement compared with the experimental corn field, while countermeasures of reforestation or agroforestry of 25% can slightly reduce streamflow, but significantly prevent erosion in the catchment.

It could be concluded that the approach used in this research simply evaluates the contributions of individual LULC classes to the hydrological characteristic, providing quantitative information for decision-makers to make better options for land and water resource planning and management. It can be widely applied to a variety of catchments, where time-sequenced digital land cover data are available, and to predict hydrological consequences of LULC changes. 25% of reforestation or agroforestry can decrease the stream flows in the wet season and increase them in the dry season which is more important for water resource management in the dry season and for flood reduction in the wet season and could significantly prevent soil erosion, while the reforestation more than 25% is not recommended in the catchment.

The outcomes of farmers' perceptions on soil fertility changes and flood/drought indicated that the rate of a very strong decline in soil fertility observed in the upstream catchment at 18% and in the downstream catchment at 11%.

As mentioned above, this study has been conducted to evaluate the impacts of land use and land cover changes on hydrological characteristics and soil erosion in Stung Sangkae catchment, Cambodia. Although the Royal Government of Cambodia (RGC) has a direction to maintain at least 50% of its land under forest cover to contribute to the country's Sustainable Development Goals by 2030, the outcomes of this study indicated the area of agricultural upland is reforested for converting agroforestry (25% in area applied reforestation or agroforestry for achieving 40% in forest area) was very meaningful to decrease the stream flows in the wet season and increase them in the dry season, as well as to eliminate soil erosion remarkably.

和文要約

本研究は，カンボジア国スツゥン サンカェ流域における土地利用と被覆の変化が水文特性および土壌侵食に与える影響を SWAT モデルと RUSLE モデルを用いて，植林やアグロフォレストリーによる土壌保全効果を定量的に評価したものである。この研究対象地では，農業的発展を背景に森林域の開発が進み，結果として過去 20 年間に顕著な土地利用と被覆の変化が生じている。そこで，土地利用と被覆の変化が水文特性および土壌侵食に与える影響を SWAT モデルと RUSLE モデルを用いて一定の精度でシミュレーションするとともに，対象地に植林やアグロフォレストリーを進め，現有の森林面積（25%）と合わせて森林率 40%を達成することにより，流域の流出特性の変化が期待できることを示した。特に，土壌侵食に対しては有意に土壌流亡量の抑制効果が発現できることを示した。現在，同国政府は森林率 50%の目標値を策定しているが，この目標値について根拠が示されていなかった。そのため，本研究の成果から植林やアグロフォレストリーによって森林率を 40%に回復することで十分に保全効果を発現できる可能性を示した。

審 査 報 告 概 要

本研究は，カンボジア国スツゥン サンカェ流域における土地利用と被覆の変化が水文特性および土壌侵食に与える影響を SWAT モデルと RUSLE モデルを用いて，植林やアグロフォレストリーによる土壌保全効果を定量的に評価したものである。この研究対象地では，農業的発展を背景に森林域の開発が進み，結果として過去 20 年間に顕著な土地利用と被覆の変化が生じている。そこで，土地利用と被覆の変化が水文特性および土壌侵食に与える影響を SWAT モデルと RUSLE モデルを用いて一定の精度でシミュレーションするとともに，対象地に植林やアグロフォレストリーを進め，現有の森林面積（25%）と合わせて森林率 40％を達成することにより，流域の流出特性の変化が期待できることを示した。特に，土壌侵食に対しては有意に土壌流亡量の抑制効果が発現できることを示した。現在，同国政府は森林率 50％の目標値を策定しているが，この目標値について根拠が示されていなかった。そのため，本研究の成果から植林やアグロフォレストリーによって森林率を 40％に回復することで十分に保全効果を発現できる可能性を示した意義は大きい。

以上のように，本研究は，カンボジア国における流域の土地利用と被覆の変化が流出特性や土壌侵食量への影響を評価し，さらに流域での植林やアグロフォレストリーの導入による森林率の回復に科学的な根拠を与えるなど有益で新規性のある知見を得たことから，審査員一同は博士（農学）の学位を授与する価値があると判断した。