QUANTITATIVE EVALUATION OF WATER AND SUBSTANCES CYCLE IN THE UPPER RIVER BASIN OF KUSHIRO MIRE BY USING SWAT MODEL

HIROKI OHASHI

OYO corporation, Saitama-City, Japan, oohashi-hiroki@oyonet.oyo.co.jp

MAKOTO NAKATSUGAWA

Muroran Institute of Tecnology, Muroran-City, Japan, mnakatsu@mmm.muroran-it.ac.jp

ABSTRACT

The purpose of this paper is to evaluate water and substances (sediment, nitrogen and phosphorus) runoff mechanism quantitatively in Kuchoro River watershed located in the upper river basin of Kushiro mire. We applied SWAT model, which is sufficiently calibrated to this objective area, to understand runoff mechanism of water and substance cycle in 1940 to 2017. Main results of this study are 1) Substances flowed out from not only Pasture area but also highland area because of rapid surface water flow occurrence and 2) development and river straighten in upper watershed would be influenced to the environment of Kushiro Mire. These results will contribute to evaluate water and substances cycle in whole Kushiro mire and to propose efficient countermeasures for preserving the natural environment in Kushiro River.

Keywords: Water and substances cycle, SWAT, Nature Restoration, Kushiro mire, Quantification

1. INTRODUCTION

For Kushiro Mire, registered in the Ramsar Convention in 1980, the Kushiro Wetland Nature Restoration Committee has been organized to restore and conserve the condition of the mire at the time of Ramsar registration because of its rapid qualitative and quantitative changes in recent years (Kushiro Wetland Nature Restoration Committee, 2005). The most basic and important action for this issue is to understand the mechanism of water and substances cycle in Kushiro Mire. In particular, inflects of flow-in volume of water and substances play the key roles in the mire, so it is important to study water and substances runoff mechanism of upper watershed in understanding the present mire conditions, predicting the future change of environment, and proposing effective countermeasures.

There are three typical methods for quantifying the runoff mechanism of water and substances, namely, 1) Pollutant load factor method (e.g. Miura, 2004; Ota, 2002), 2) Rating Curve for Pollutant loads method (e.g. Kurihara, 2012), and 3) distributed or semi-distributed hydrological runoff model (Yangwen, 2001; Shimizu, 2017). In pollutant load factor method, discharging load is calculated from pollutant load per unit area of each land use and areas of each land use in watershed. This method is very simple but difficult to consider topographical factor and climate factor directly. In Rating Curve for Pollutant loads method, discharging load is calculated by using an approximate equation made from the relationship between the observed load and river flow rate. This method is reliable in calculating present load. But in other conditions, for example, in past or future, this method is unwarrantable because it is difficult to consider load occurrence and movement process. It indicates that it is difficult to evaluate load runoff mechanism of watershed by using Rating Curve for Pollutant loads method as well.

On the other hand, the distributed or semi-distributed hydrological runoff model is complicated and not easy to use, but suitable for quantification of water and substances runoff mechanism. There are extensive applications of such runoff model to understand and predict the water and substance cycle in large scale watershed (Yangwen, 2001; Shimizu, 2017). In this study, we used SWAT model developed by the USDA Agricultural Research Service (USDA-ARS) (Arnold, 1998) for the following reasons:

1. SWAT can simulate behavior of both dissolved and suspended substances.

2. SWAT is open source program and has many databases for reference made by researchers all over the world.

3. SWAT has some examples applied for quantifying the runoff mechanism of water and substances in mire (Yang, 2008; Ndomba, 2010; Liu 2018).

SWAT is a semi-distributed hydrological runoff model. It has more than 100 parameters and uses some empirical formulas in the material circulation process. It means that we need to understand and calibrate the

physical values of empirical formulas and verify these input parameters by using observation data, referential database and advanced studies. In Japan, SWAT was applied in the Abashiri River basin (Somura,2009), Shibetsu River basin (Jiang, 2011), Mukawa and Sarukawa River basin (Mizugaki, 2018), etc. These studies indicate that SWAT is applicable to the condition in Japan. However, few study has been done to apply SWAT model to evaluate discharging load mechanism in mire and discuss about performance of model in mire in Japan.

In this study, we first calibrate SWAT model using observed dataset in Kushiro mire, and then applied to simulate long-term water and substance cycle in the objective area. Based on the calculation results, possible efficient countermeasures to preserve the natural environment of the mire is discussed.

2. METHODS

2.1 Study area

Figure 1 shows the location of study area. The Kushiro Wetland, about 26,000 ha, is the largest wetland in Japan, and partly (5,012 ha) became a national monument in 1967 and a Japan's first Ramsar site in 1980. The expansive wetland catchment supports diverse, important wildlife, including native populations of the Japanese crane (Grus japonensis), Siberian salamander (Salamandrella keyserlingii), and Sakhalin taimen (Hucho perryi), as well as provides water storage, filtering function, flood control, and aesthetic and recreational opportunities. Kuchoro river, target watershed in this study, is one of tributaries of Kushiro Mire. It locates in the northwest of Kushiro Mire and watershed area is 12,700 ha (length is about 25km and width is about 5km) in narrow shape. Figure 2a shows the topographic map of Kuchoro watershed. The distribution of altitude is 5m to 750m. There are three observation points measuring river flow rate and concentration of SS, nitrogen and phosphorus, namely, Nakakuchoro-bridge in the upper watershed, Sakai-bridge in the middle watershed, and Hikari-bridge in the
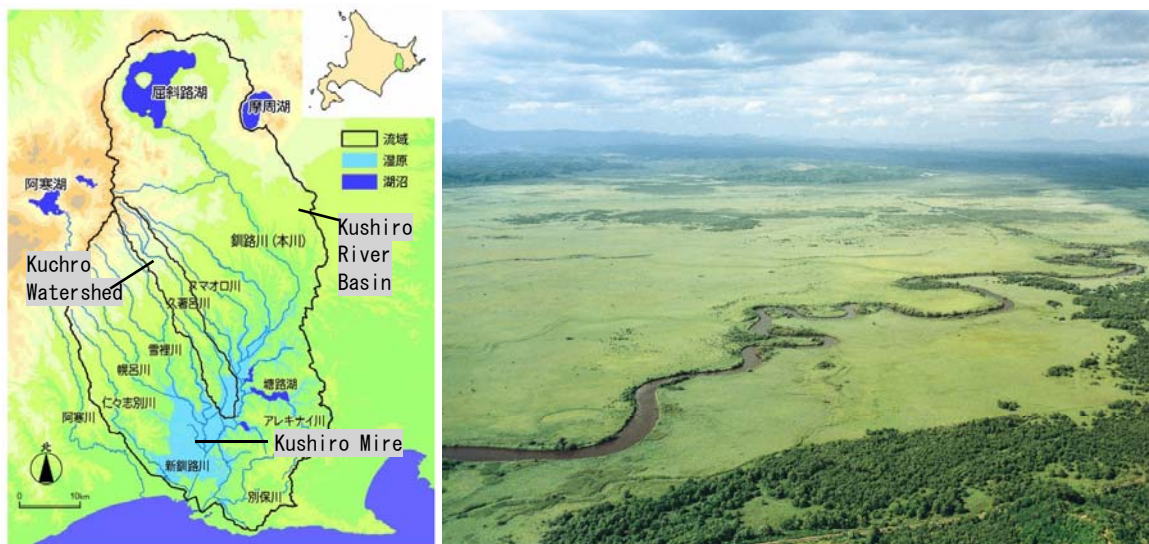

Figure 1. Study area within the Kushiro Mire and Kuchoro watershed (Source of left side figure: Kushiro Wetland Nature Restoration Committee, 2005)
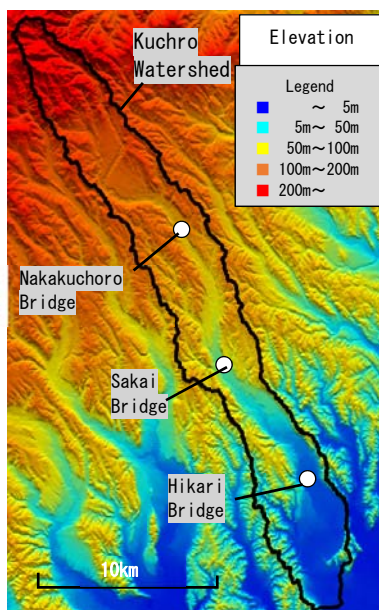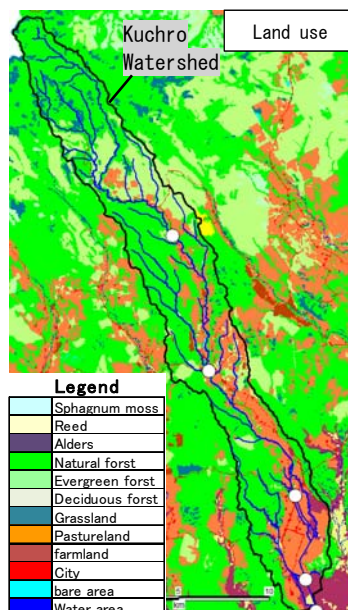

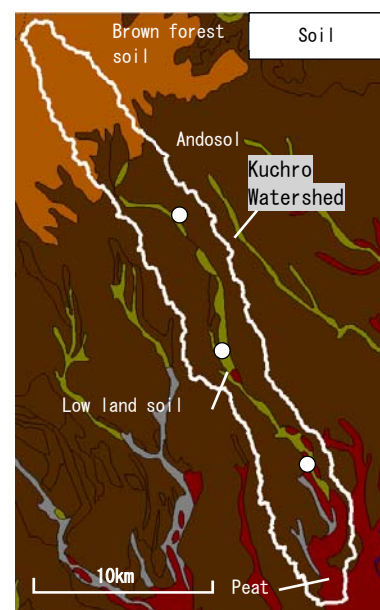Figure 2a. Topographic map   Figure 2b. Land use map   Figure 2c. Soil map

lower watershed. Figure 2b shows the distribution of land use in Kuchoro watershed. The area covered with forest (69%), pasture (24%), wetlands (5 %), and city (2%). Figure 2c show the distribution of soil in Kuchoro watershed. There are brown forest soil (19%) in the upper watershed, Andosol (72%) in the middle watershed, peat (5%) in the lower watershed, and Low land soil (4%) along river.

2.2 Overview of SWAT

2.2.1 Model preparation

SWAT divide study area into 2 types of small regions which are called SUBBASINs and HRUs (Hydrological Response Unit). SUNBASINs, divided by surface topography, are the units of calculation of channel routing processes. HRUs, divided by slope, landuse and soil attributes, are the units of calculation of runoff processes. In SWAT, discharging rate of water, sediment, and nutrients into main channel form each HRU are calculated in each SUBBASIN. After that, distributions of water flow rate and sediment and nutrients loading rate in main channel are calculated considering channel routing processes. Figure 3a and figure3b show the SUBBASINs and the HRUs in this study.
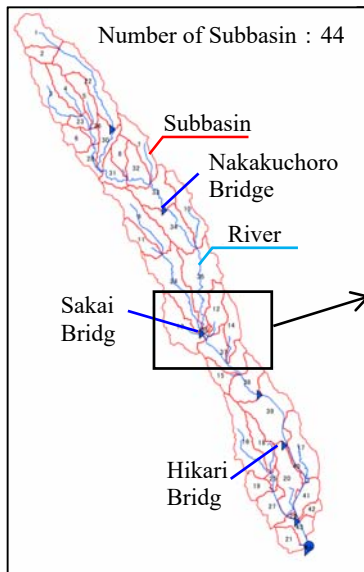

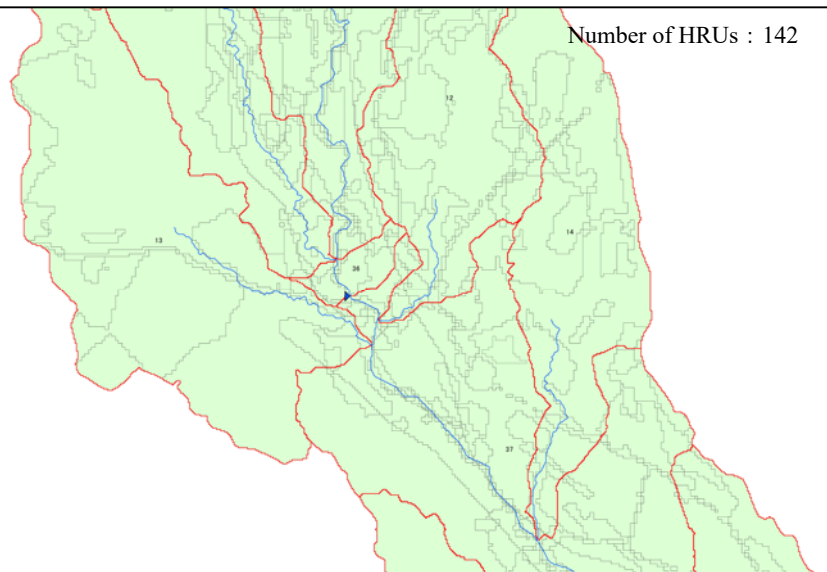Figure 3a. Subbasins map in this study   Figure 3b. HRUs map in this study

2.2.2 Modeling of water cycle in SWAT

Water cycle processes in SWAT is simulated mainly by five steps as shown in figure 4 with blue colored texts. First step generate precipitation, Second step separate precipitation into surface runoff water and infiltration water by SCS-CN (Curve Number method) (SCS, 1972) or Green and Ampt Infilteration method (Green &Ampt, 1911). Surface runoff water move to river according to the modified rational formula. Third step separate
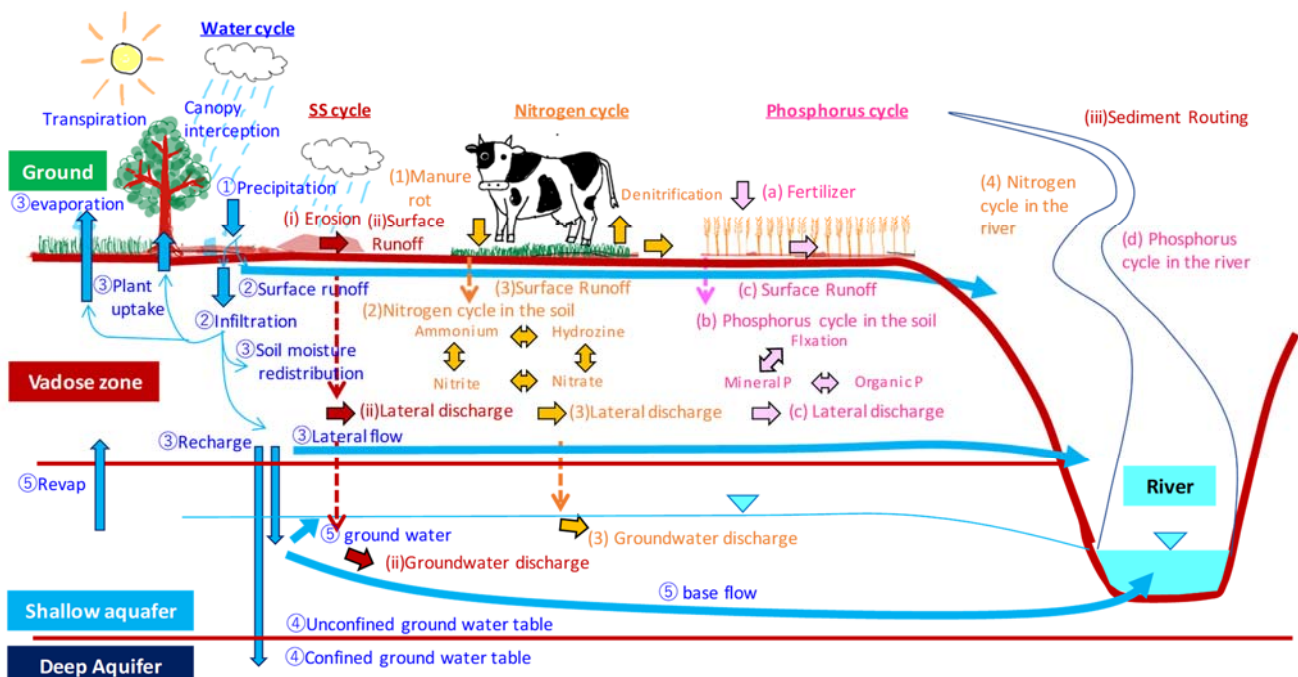

Figure 4.   Water and substances cycle modeled in SWAT

3

infiltrated water into evapotranspiration water, plant uptake water, lateral flow water, soil moisture redistribution water, and recharge water by physical or Empirical formulas in each process. Forth step separate recharged water into shallow aquifer (unconfined) water and Deep aquifer (confined) water. And last step separate shallow aquifer water into ground water, base flow water, and revap water.

2.2.3 Modeling of sediment cycle in SWAT

Sediment cycle simulation in SWAT is composed of three processes, (i) erosion, (ii) overland (include underground) flow, and (iii) channelized river flow as shown in figure 4 with brown colored texts. In erosion process, sediment yield on given day is mainly calculated from surface runoff volume, peak runoff rate and soil erodibility by using the modified universal soil loss equation (Williams, 1995). In overland flow process, the sediment produced by erosion process above are discharged into main channel by lateral flow and ground water flow. Sediment load is calculated from concentration of sediment factor given by user. Travelling time is determined from lateral flow rate and groundwater flow rate. In channelized flow, degradation or deposition of sediment occur depending on stream power. It is calculated from peak flow rate in channel by using 4 type physical equations.

2.2.4 Modeling of nitrogen cycle in SWAT

Nitrogen cycle simulation in SWAT is composed of four processes, (1) load, (2) nitrogen cycle in the soil, (3) transportation, and (4) in-stream nutrient process as shown in figure 4 with orange colored texts. In load process and nitrogen cycle in the soil process, we can set up plant operation, harvest operation, grazing operation, and fertilizer operation. In addition, chemical, physical, and biological changes like mineralization, decomposition, nitrification, ammonia volatilization, denitrification, atmospheric deposition, fixation are modeled. In transport process, nitrate and Organic nitrogen move with water. Nitrate is transported by surface runoff, lateral flow and percolation. Organic nitrogen is transported by surface runoff with eroded sediment. In-stream nutrient process, nitrogen transformation is considered in simulation.

2.2.5 Modeling of phosphorus circulation in SWAT

Phosphorus cycle simulation in SWAT is almost same with nitrogen cycle simulation as shown in figure 4. Organic phosphorus and mineral phosphorus are transported with eroded sediment by surface runoff and soluble phosphorus in soil water is transported by lateral flow.

3. RESULTS & DISCUSSION

3.1 Input data

3.1.1 Spatial data

Input spatial data are terrain, land use and soil distribution as shown in figure 2, figure 3, and figure 4. Each source is shown in table 1.

3.1.2 Meteorological data

Input meteorological data are precipitation, air temperature, solar radiation, wind speed, and relative humidity provided by Japan Meteorological Observatory. Locations of observation stations are shown in figure 1 and summarized in table 1.

3.2 Calibration and Validation

The model is validated by using the observed data at some stations shown in figure 2. In this study, for the lack of complete observed data at these stations, we validate the discharge at Hikari-bridge, and sediment, total nitrogen and total phosphorus load at Nakakuchoro-bridge, Sakaki-bridge and Hikari-bridge, respectively. The

Table 1. Summary of data used for model setting up and sources

DATA	DESCRIPTION	SOURCE
SPATIAL	Terrain	10m mesh DEM ,2000, Geospatial Information Authority of Japan
	Land use	Satellite image, 2000, Survey report
	Soil map	Fundamental Land Classification Survey, 1:200000, 1977, Ministry of Land, Infrastructure and Transport
METEORO LOGICAL	Precipitation Temperature Solar radiation	AMEDAS Turui, 2002-2017, Japan Meteorological Observatory
	Wind speed Relative humidity	AMEDAS Kushiro, 2002-2017, Japan Meteorological Observatory

model parameters are calibrated using the dataset taken during 2002 to 2014, and the model performance is discussed by predicting the water and substance cycle during 2015 to 2017.

3.3 Model performance

3.3.1 Reproduction of river flow rate

Figure 5 shows the observed (gray colored line) and simulated (orange colored line) daily river flow rate with daily precipitation (blue colored line). We find that our results agree mostly with observation data. When the reproducibility is expressed by Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), NSE = 0.72 during the calibration period and NSE = 0.73 during the validation period. The value is in the category of good in the reproducibility evaluation table by NSE value.
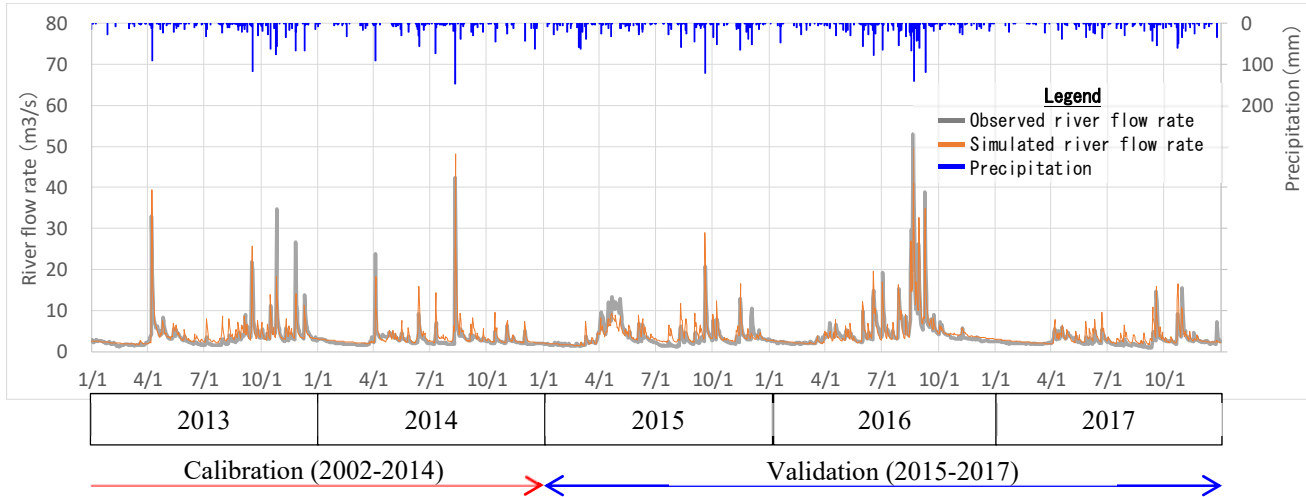

Figure 5. Comparison between observed and simulated daily river flow rate at Hikari-bridge (2013-2017)

3.3.2 Reproduction of load

Figure 6 shows comparison between observed (orange colored marker) and simulated (blue colored marker) relationship of river flow rate and sediment load volume at Nakakuchoro-bridge, Sakai-bridge, and Hikari-bridge. These figures indicate that the model reasonably predicts the observed water discharge - sediment transport relation at all the observed stations. Table 2 shows comparison between observed and simulated yearly sediment, all nitrogen, and all phosphorous load value at Hikari-bridge averaged 2002-2017. The differences between observed data and simulated data were 5%～13%.

Figure 6. Comparison between observed and simulated relationship of river flow rate and sediment load volume

Table 2. Comparison between observed and simulated yearly sediment, all nitrogen,
and all phosphorous load value at Hikari-bridge (average from 2002 to 2017)

	CALCULATED FROM OBSERVED DATA	SIMULATION RESULTS
SS (TON)	9198	8820
T-N(KG)	106360	92986
T-P(KG)	9294	9294

3.4 Model parameter sensitivity

Table 3 shows comparison of input parameter between this study and other study. It is difficult to verify the model parameters calibrated in this study distinctly because of shortage of study cases, but there is no unusual input value compared to others.

Table 3. Comparison of input parameters

	Defalt	This study	Soumura (2009)	Shimizu (2013)	Kubo (2015)	Ndomba (2010)	YANG (2008)
Location	-	Japan	Japan	Japan	Japan	Rwanda	Canada
Target	-	Mire	River	River	River	Mire	Mire
SFTMP	1	0.2	4.2		-2.92		0.5
SMTMP	0.5	-0.8			0.25		2.5
SMFMX	4.5	1.6					6.5
SMFMN	4.5	1.6					1.5
TIMP	1	0.84	0.2				0.35
SNOCOVMX	1	1			651		
SNO50COV	0.5	0.5			0.38		
SURLAG	4	2	0.96	1.2		0.7	1
CN2	-	35～92	-7.7	40～89	1	62	
CH_N(1)	-	0.4	0.4		0.6		
CANMX	-	5	3.5	7.66		12	
SOL_Z	-	250	19.4				
SOL_K	-	0.58-3.6		0.6-154.4		11.4-18.54	
ESCO	0.95	0.95	1	0.61		0.01	0.45
GW_DELAY	0	180			15		
ALPHA_BF	-	1	1	1.2		0.01	
RCHRG_DP	-	0	0		0.61		
CH_N(2)	-	0.3		0.3		0.3-0.5	
CH_K(2)	-	0.01		81		2.5	

3.5 Distribution of sources of substances

Figure 7 shows the substances yield volume per unit area of subbasin simulated by SWAT with land use map. Total phosphorus yield volume per unit area were distinctly related to the distribution of pasture area. On the other hand, the subbasin of high sediment and total nitrogen yield volume per unit area distributed at pasture area and highland area. It can be explained that high substances yield at pasture is caused by fertilization because there is few phosphorous in nature. In terms of high sediment and total nitrogen yield at high land, it can be presumed that high slope and much precipitation are casing high surface runoff flow and strong erosion.
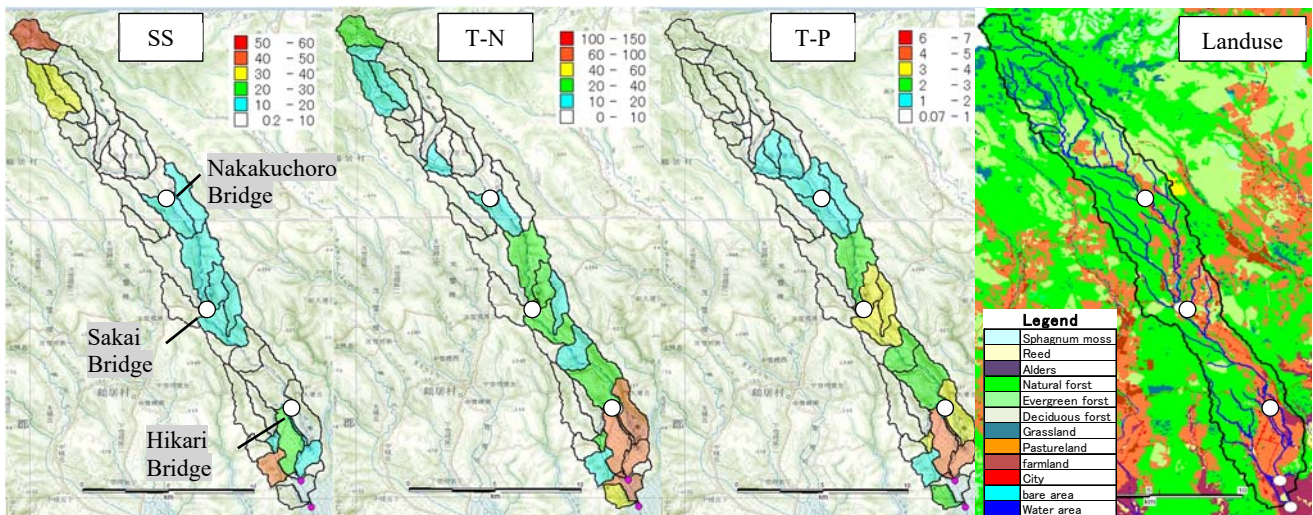

Figure 7. The substances yield volume per unit area of subbasin simulated by SWAT with land use map

3.6 Prediction of transition of substances runoff

To predict a transition of substances load caused by the past changes of environment, landuse and etc, we simulated substances runoff in Kuchoro watershed under the past land use and precipitation conditions. In this simulation, we divided 1940-2017 into five stages by land use, river straighten condition and farmland development condition as shown in figure 8. 1st stage, from 1940 to 1959, is a natural condition of this area since the development (e.g., river improvement works) started at 1959. Second, third and fourth periods are all

under the extensive development of this basin. Last stage (1990-2017) is the current situation (i.e., after the development).

Figure 8 shows the simulated sediment load in each stage with water quality observation data at Kusiro river. According to results, sediment load became maximum in 3rd stage. And it is close agreement with transition of river water quality in Kushiro river. These suggest two things. One is that development speed and the river straighten in the upstream watershed have a great effect on the Kushiro Mire condition. And another is SWAT model may be useful to evaluate water and substances cycle in the Kushiro Mire.
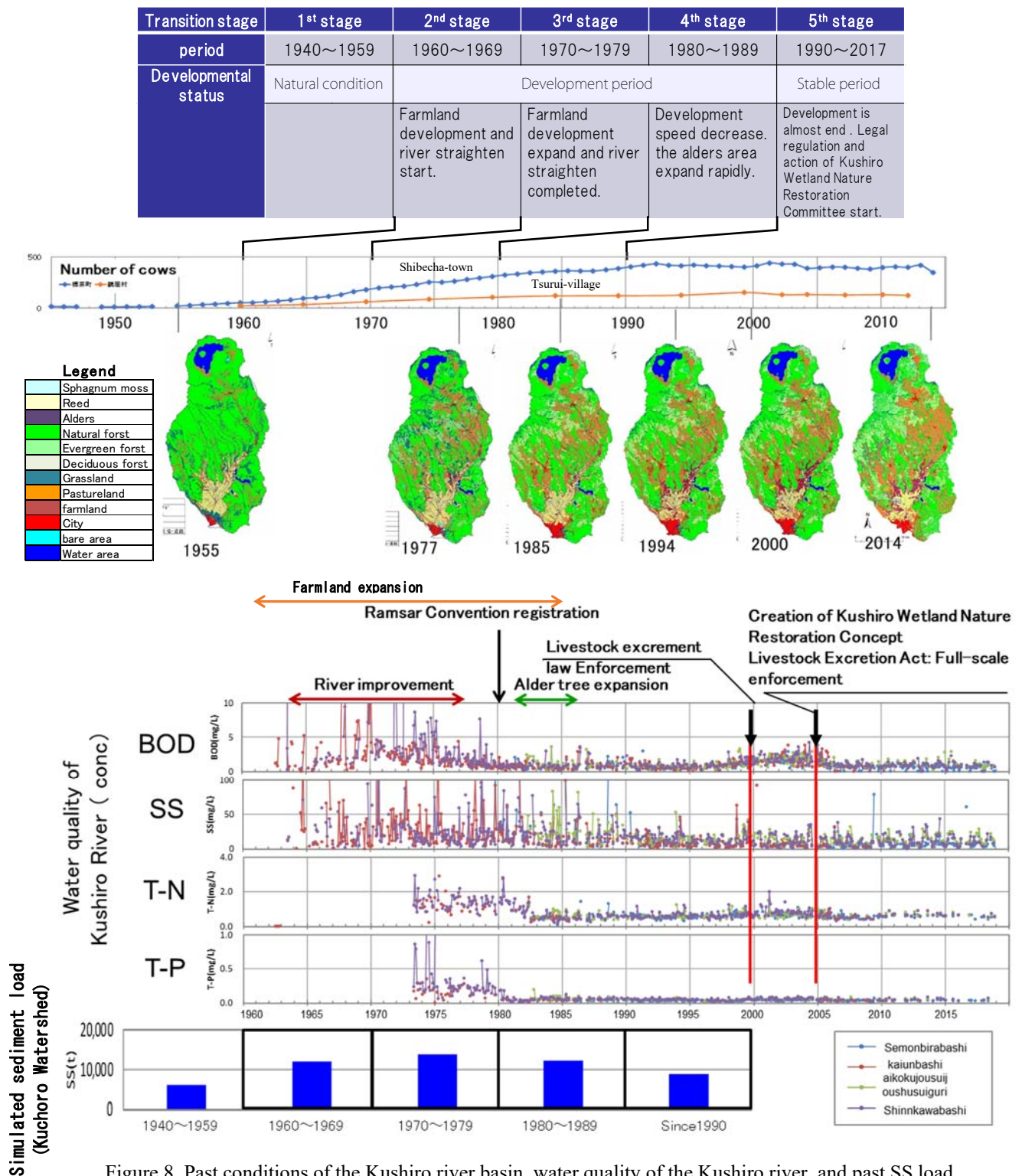
Transition stage	1st stage	2nd stage	3rd stage	4th stage	5th stage
period	1940～1959	1960～1969	1970～1979	1980～1989	1990～2017
Developmental status	Natural condition	Development period			Stable period
		Farmland development and river straighten start.	Farmland development expand and river straighten completed.	Development speed decrease. the alders area expand rapidly.	Development is almost end . Legal regulation and action of Kushiro Wetland Nature Restoration Committee start.

Figure 8. Past conditions of the Kushiro river basin, water quality of the Kushiro river, and past SS load

4. CONCLUSIONS

In this study, we used a SWAT model to evaluate water and substances (SS, nitrogen and phosphorus) runoff mechanism in Kuchoro River watershed located in the upper river basin of Kushiro mire. By using SWAT model, we predicted the distribution of substances load sources and transition of substances load in the past. The findings obtained are as follows:

1. The SWAT model, which is sufficiently calibrated using the observed data in this river basin, can qualitatively reproduce the water and substance cycles in Kushiro River basin.

2. It is difficult to verify the validity of input model parameters calibrated here distinctly because there are few study cases.

3. The model prediction suggested that substances load is produced not only in pasture area but also in highland area because of much precipitation and high surface runoff flow rate.

4. The model results in terms of past water and substance transport simulation indicate that transition of substances load is related to development speed in upper watershed and countermeasures like legal regulation and action of Kushiro Wetland Nature Restoration Committee.

REFERENCES

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. (1998). Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resour. Assoc.* 34(1): 73-89.

Green, W. H. and G.A. Ampt. (1911). Studies on soil physics, 1. The flow of air and water through soils. *Journal on Agricultural Sciences* 4:11-24

Jia, Y., Ni, G., Kawahara, Y and Suetsugi, T. (2001). Development of WEP model and its application to an Urban watershed, Hydrological processes, 15, pp. 2175–2194.

Jiang, R. (2011). Modeling the water balance processes for understanding the components of river discharge in a non-conservative watershed, Transactions of the ASABE, 54(6), pp. 2171-2180.

Kudo, M. (2015). Application SWAT model to forest basin by using GIS. 126th meeting of *The Japan Forest Society* Conference Paper.

Kushiro Wetland Nature Restoration Committee. (2015). Action plan to restore Kushiro Wetland.

Kurihara, S., Tada, A., and Tanakamaru, H. (2012). Some considerations in estimating diffuse loads with rating curve. *Journal the Japanese society of irrigation, drainage and rural engineering,* pp. 600-601.

Liu, Y. (2018). Development of an Integrated Modelling System for Evaluating Water Quantity and Quality Effects of Individual Wetlands in an Agricultural Watershed. Water 2018, 10, 774.

Miura, S., Aisaki, M., and Matsusige, K. (2004). Nutrien loading management in Lake Kasumigaura basin using GIS – Evaluatin of estimate C, N, O loading in divided small river basin. *Journal Society of environmental Science Japan* 17(2), pp. 109-119.

Mizugaki, S. (2018). Validity of discharge and parameters associated with groundwater in the hydrological model SWAT for the Mukawa River and the Saru River, northern Japan. Abstracts, *Japan Geoscience Union meeting.*

Nash, E. J. and Sutcliffe, V. J. (1970). River flow forecasting through conceptual models: Part 1. A discussion of principles. *Journal of Hydrology*, 10(3), pp. 282-290.

Ndomba, M. P. (2010). Application of SWAT in Natural Wetland Catchments. A Case of Rugezi Catchment in Rwanda. *Nile Basin Water Science & Engineering Journal*, 3(3), pp. 1-13.

Ota, Y. and Nakatsugawa, M. (2002). Study on water quality loads including flood events related to land use in catchment area. *Annual journal of hydraulic engineering, JSCE*, 46, pp. 887-892.

Shimizu, Y. (2013). Applicability of SWAT Model for Estimation of Phosphorus Discharge in a Suburban Catchment. *J. Japan Soc. Hydrol. and Water Resour.* 26(3), pp. 153 – 173

Shimizu, Y., Onodera, S., and Matumori, K. (2014). Estimating nitrogen flux from a watershed using hydrological model - an overview of recent achievements and future directions -. *Journal of Japanese Association of Hydrological Sciences* 44(4), pp. 207-223.

Soil Conservation Service Engineering Division. (1972). Section 4: Hydrology in National Engineering Handbook. SCS.

Somura, H. (2009). Sensitivity analysis of hydrologic and suspended sediment discharge in the Abashiri River Basin, Hokkaido Region, *Japan International agricultural engineering journal 2009*, 18, pp. 27-39.

Williams, J.R. (1995). Chapter 25: The EPIC model. In V. P. Singh(ed.) Computer models of watershed hydrology. Water Resources Publications. p. 909-1000.

Yang, W. (2008). Water Quantity and Quality Benefits from Wetland Conservation and Restoration in the Broughton's Creek Watershed. A Research Report Submitted to Ducks Unlimited Canada.