Best management practices for mitigating agricultural nutrient pollution in the Mun River Basin, Thailand

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Abstract: The Mun River in NE Thailand is one of the significant tributaries of the Lower Mekong River. Its poor river quality has been reported and agricultural activities were claimed to be major causes. This study aims to assess the best management measures appropriately responsive to the nutrient pollution in the Mun River Basin's agricultural ecosystems. The data used for the analysis were acquired from field measurements during the 2018 wet season *via* satellite retrieval and secondary data collection. Linkages between land-soil datasets and hydro-water quality datasets were assessed through a canonical correlation analysis. The results suggest possible conservation measures with crop yield improvement and fertiliser cost reduction in the western basin. For the southern basin, which exhibits high sediment loading, integrated conservation measures for soil loss reduction with in-stream flow deceleration should be chosen. In the eastern basin, woody buffer strips and check dams should be prioritised. Both nutrient and sediment pollution were experienced in the middle part of the Mun River Basin and applications of low-P manure with mineral NK are recommended. Nonetheless, other soil-water conservation measures can be optionally applied to enhance the effectiveness in the watershed management.

Keywords: canonical correlation analysis; Lower Mekong River Basin; soil loss; soil-water conservation measures; water quality

The Mun River Basin is considered the largest watershed in the Lower Mekong Basin in Thailand, discharging approximately 32 280 million m^3 of water per year to the Mekong River. This accounts for ~10% of the total Mekong river flow at the Pakse station, which is located ~44 km downstream of the Mun River's confluence (Cochrane et al. 2014). Therefore, the Mun River has a role to play in maintaining the ecosystem and improving the health and well-being of the people in the Lower Mekong Basin, including Thailand, Laos PDR, Cambodia, and Vietnam.

The recent agricultural transformation in NE Thailand has been oriented towards the higher production of cash crops. Non-glutinous rice, sugarcane, maize, rubber, and specialty crops are being grown in upland fields with the implementation of modern

mechanisation and chemical fertilisers and pesticides (Rambo 2017). The adoption of soil-water conservation measures has been limited, probably due to their incompatibility with the farmers' needs. About 15% of the NE region is upland, where field crops remain the primary income source (Choenkwan et al. 2014). Para rubber (*Hevea brasiliensis* Müll. Arg.) has also become significant in some areas (Choenkwan et al. 2014). This upland has poor soils, an unpredictable rainfall, insufficient surface water for irrigation and steep slopes, etc. (Choenkwan et al. 2014). In the NE lowlands, rice (*Oryza sativa* L.) of premium-grade quality, Khao Dawk Mali 105 (KDML105) variety, mostly grown under rainfed conditions, is exposed to the risk of soil moisture shortage and low fertility (Saenya et al. 2015).

The strong association between agricultural land/ soil properties and water quality has been hypothesised. Soil properties resulting from various geophysical-chemical properties and agrarian practices can result in different water quality characteristics. Observations of the water chemistry of surface water has shown that rock-water interaction have been found to be dominant. This interaction was also observed in the wetlands of the Brahmaputra Valley, Assam, India (Dutta et al. 2016), the Barak River in NE India (Khangembam & Kshetrimayum 2019), the Jialing River and Yangtze River in China (Qin et al. 2018). Rock weathering and anthropogenic sources, including agricultural runoff and sewage sludge contributed to the poor water quality in the water samples collected from the wetlands in the Brahmaputra Valley (Dutta et al. 2016). Zhao et al. (2018) studied the relationships between the soil and water quality in the Mun River Basin. They found that the soil nutrients, mainly from non-point sources and surface runoff, were directly affecting the water quality. Yadav et al. (2019) assessed the effects of land use on the water quality in the Mun River Basin and found significant nutrient loading from urban and agricultural land use in the lower and middle parts of the basin.

This study aims to understand the spatial patterns of the associations between the land-soil properties and the hydro-water quality characteristics. Suitable soil-water conservation measures for improving the water quality are proposed. The results can be used to provide a useful tool for decision-makers to plan for soil-water conservation measures by optimising an adequate soil quality for agriculture and for improving the water quality.

MATERIAL AND METHODS

Sampling site description. The Mun River Basin, located in NE Thailand, has a total watershed area of 71 059 km^2 and consists of 31 sub-basins (HAII 2012). It is characterised by undulating highlands in the south, where the water for the basin originates (Figure 1). Water flows from the southwestern part (upper basin) toward flat terrain in the eastern part (lower basin). The Mun River confluences with the runoff from the Chi River Basin at Ubonratchathani Province.

The Mun River Basin's climate is classified as tropical savanna, influenced by the Southeast Asian Monsoon System. It exhibits an annual mean temperature of 27 °C, 73.5% relative humidity, 3.7 km/h mean wind speed, and 1 361 mm rainfall (HAII 2012). The dry season occurs from November to April, and the rainy season is from May to October. The predominant land cover in the Mun River Basin is rice paddies (55.43%), followed by forests (14.29%) and crop fields (12.06%) (HAII 2012).

The dominant soil (24.59%) exhibits a light brown, yellowish, or reddish colour with a sandy loam texture and low fertility (Department of Land Development 2020). This soil is suitable for field crops such as cassava, maize, and sugarcane. About 10.79% of the basin's soil has a sandy loam texture in the upper layer and a clayey texture in the lower layer, resulting in a long-term wetland, acidic, and low fertility soil (Department of Land Development 2020). This soil is often used for rice cultivation (HAII 2012). Another soil group (10.26%) can also grow rice in the rainy season. It has a sandy loam or loamy sand texture with an acidity and low fertility (HAII 2012; Department of Land Development 2020).

Sampling, sample preparation, and analysis. Single measurements were carried out for 77 water samples (2 L each) and 69 soil samples (~1 kg each) from July to August, the wet season, in 2018. During this period, farmers usually start cropping and applying fertilisers. The sampling locations are shown in Figure 1. The surface water samples were taken from river banks using a 2 m long hand bucket or from the middle of bridges (preferable) using a rope-handle bucket. The topsoil samples (0–15 cm) were collected within 5 km from the water sampling sites to represent the local soils in response to the water quality. In the field, we measured the water parameters, such as the pH (using an 8685 AZ pH meter, ± 0.2 resolution, AZ Instrument Corp, Taiwan),

dissolved oxygen and electrical conductivity (using a HACH HQ3d flexi multimeter, HACH Company, USA), salinity (using a KEDIDA Salt Meter, model CT-3081, Shenzhen Kedida Electronics Co. Ltd., China), and turbidity (using a HACH 2100Q Portable Turbidimeter, HACH Company). The water samples were kept under a low pH (< 2) with H_2SO_4 in an icebox until analysis in the laboratory could be performed for nitrate (NO_3-N) using the Brucine method and phosphate (PO_4-P) using a spectrometry method.

The soil samples were air-dried, sieved using a 2-mm sieve mesh and analysed for the soil texture using the hydrometer method, the soil pH (1 : 1 soil: water), the electrical conductivity (EC, 1 : 5 soil : water), the organic carbon using the Walkley and Black Method, the available phosphorus (AP) using the Bray and Kurtz Method (1945), and ammonia (NH_3-N) and NO_3-N using steam distillation methods (Bremner & Keeney 1965).

Secondary data collection. The dominant land cover, vegetation index, elevation, and steepness were assessed or averaged within a 5-km radius from the sampling points to represent their land characteristics. The details of the datasets are described below:
– The land cover type was available in the MCD12Q1 product, retrieved from the MODIS sensor onboard both the Terra and Aqua satellites for the year 2018. The data was downloaded from the Level-1 and Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Center (DAAC) website via https://ladsweb.modaps.eosdis.nasa.gov/search/ (see Figure 1).
– Normalized Difference Vegetation Index (NDVI) was available in the MOD13Q1 product, retrieved from the MODIS Terra for July 12 to 28, 2018. The data were also downloaded from the LAADS DAAC website.
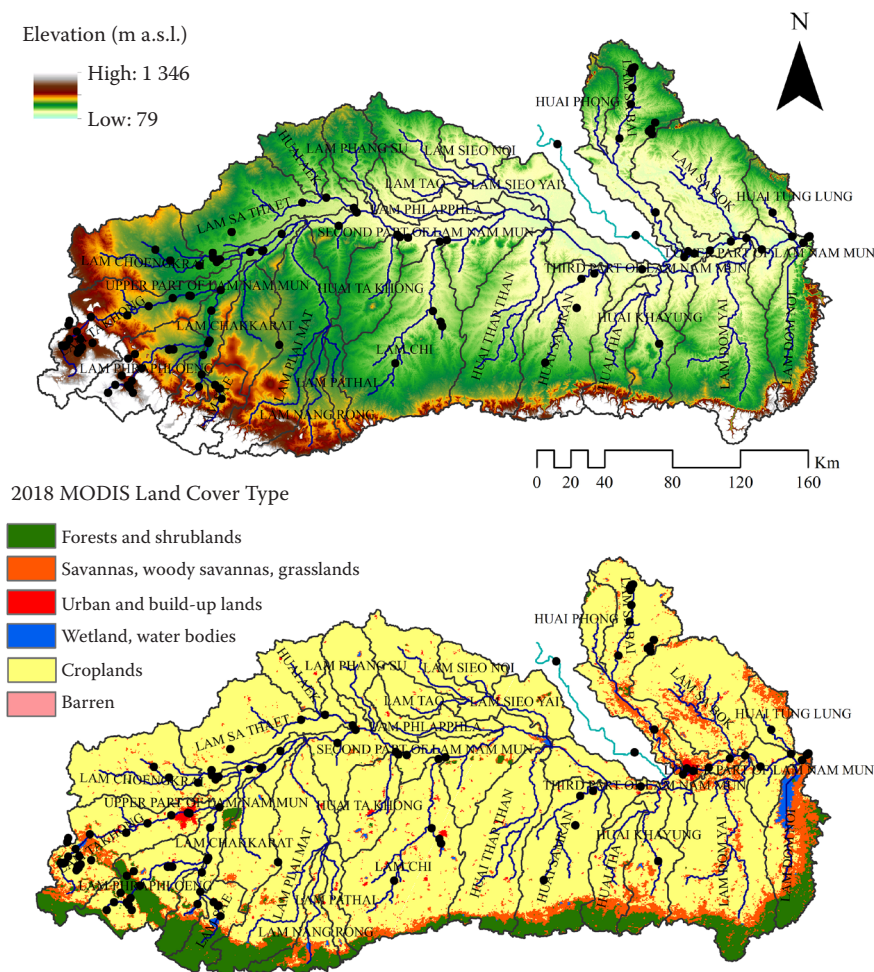

Figure 1. SRTM Digital Elevation Model (upper) and MODIS Land Cover Type map for the year 2018 (lower) of the Mun River Basin
The solid circles are the water sampling locations

– Digital Elevation Model (DEM) was retrieved from The Shuttle Radar Topography Mission (SRTM) aboard the space shuttle Endeavour and available at the USGS EarthExplorer website via https://earthexplorer.usgs.gov/. The data were in ~ 30-m resolution and later calculated for the Length-Steepness, LS, using the following Equation (Wischmeier & Smith 1978):

$$LS = \left(\frac{\lambda}{238.19}\right)^m \times \left[\left(65.41 \times \sin^2\theta\right) + \left(4.56 \times \sin\theta\right) + 0.065\right]$$

where:
λ – slope length (m),
θ – angle of the slope,
m – factor dependent on the slope 0.5 if the slope ≥ 5%, 0.45 if 4.5% ≤ slope < 5%, 0.4 if 3.5% ≤ slope < 4.5%, 0.35 if 3% ≤ slope < 3.5%, 0.3 if 1% ≤ slope < 3%, and 0.2 if the slope < 1%.

– The monthly amount of fertilisers for the different types of agricultural fields – rice, maize, and cassava – by provinces for the years 2017 to 2018, was acquired either from interviews with local farmers or retrieved from the Office of Agricultural Economics website, www.oae.goth/view/1/Home/EN-US.

Data analysis. Canonical correlations between the land/soil factors and water factors were carried out. Fourteen land/soil factors and eight water factors are listed in Table 1. In the canonical correlation analysis, pairs between the linear combinations of the land/soil factors (CANland) and the linear combinations of the water factors (CANwater) were created to maximise the correlations between both datasets. The first pair has the highest possible correlation and they are the most important. The second pair has the second-highest correlation and,

Table 1. Correlation coefficients between the first six CAN variable scores and the original variables (land-soil factors and hydro-water quality factors)

Land-soil factors	Correlation coefficients for CANland					
	CAN1	CAN2	CAN3	CAN4	CAN5	CAN6
Soil pH	−0.06	**0.64**	0.39	0.40	−0.02	**−0.26**
Soil electrical conductivity, EC	**0.72**	0.45	0.25	0.23	−0.02	0.19
Soil organic carbon, SOC	0.30	**0.69**	0.23	0.25	0.00	−0.05
Available phosphorus in the soil, AP	−0.07	**0.78**	0.38	0.29	−0.03	−0.02
Ammonia in the soil, NH$_4$-N	−0.05	−0.48	**−0.25**	**−0.66**	0.08	0.02
Nitrate in the soil, NO$_3$-N	−0.71	−0.41	−0.10	**−0.24**	**−0.23**	**−0.20**
%Clay	**0.80**	0.42	0.23	0.15	−0.05	−0.08
%Sand	−0.70	−0.59	**−0.18**	−0.16	−0.05	0.06
NDVI	**0.46**	0.27	0.14	0.06	0.18	0.53
Ratio of forests in the total land area	−0.14	0.08	0.11	0.10	−0.09	0.51
Ratio of croplands in the total land area	0.29	−0.23	0.07	−0.18	**−0.30**	0.06
Ratio of grasslands in the total land area	−0.14	0.30	0.25	0.03	0.34	−0.12
Ratio of urban and built-up lands in the total land area	−0.13	0.06	−0.06	−0.06	0.06	**−0.29**
Length-steepness, LS	−0.13	0.30	0.53	0.13	0.32	0.35
Hydro−water quality factors	correlation coefficients for CANwater					
	CAN1	CAN2	CAN3	CAN4	CAN5	CAN6
pH	−0.50	−0.48	0.60	−0.20	**−0.27**	−0.18
Dissolved oxygen, DO	−0.16	0.20	0.21	0.14	**−0.24**	0.02
Electrical conductivity, EC	**0.89**	−0.39	0.12	0.07	−0.06	−0.08
Turbidity	0.01	0.07	**−0.31**	**−0.90**	0.17	−0.24
Nitrate dissolved in the water, NO$_3$-N	0.37	**0.14**	0.35	−0.37	0.61	−0.17
Phosphate dissolved in the water, PO$_4$-P	0.24	**0.24**	−0.13	**−0.53**	**−0.44**	**−0.46**
Salinity	**0.92**	−0.23	0.21	0.08	−0.09	−0.11
Stream velocity	−0.42	−0.22	**−0.24**	0.19	0.22	**−0.77**
Canonical correlation	0.88	0.80	0.70	0.64	0.54	0.43

NDVI – normalized difference vegetation index; bold – indicates corresponding characteristics between water and land-soil and hydro-water factors and discussed in the text

therefore, they are the second most important and so on. The analysis was processed using the MATLabR2019a software.

RESULT AND DISCUSSION

The canonical correlation analysis provided six pairs of CAN variables, which are linear combinations of the land-soil factors (CANland) and linear combinations of the hydro-water quality factors (CANwater). The variables were named CANi, where i is the integral number from 1 to 6. The first CAN, CAN1, provided the highest degree of correlation ($r^2 = 0.88$), followed by the second CAN, CAN2 ($r^2 = 0.80$) and so on ($r^2 = 0.70$ for CAN3, $r^2 = 0.64$ for CAN4, $r^2 = 0.54$ for CAN5 and $r^2 = 0.43$ for CAN6). The characteristics of the CAN variables can be described in terms of the original variables (the land/soil factors or water factors) with a high correlation with the CAN variables scores, as reported in Table 1, and the spatial distribution of the six CANwater scores as shown in Figure 2.

From the coefficients in Table 2, CAN1 was less likely to represent the nutrient levels in the soil and the water, but efficiently represented the salinity problem. Since we focused on the nutrient pollution in this study, we therefore omitted CAN1 from the discussion.

High nutrient loading – positive CAN2, negative CAN5, and negative CAN6

In the entire basin, the PO_4 ranged from 0.013 to 0.236 mg/L, NO_3 ranged from 0.05 L to 0.608 mg/L, and NH_4 ranged from 0.056 to 1.652 mg/L. About 33% of the NH_4 samples exceeded the national surface water quality standard of 0.5 mg/L.

The western basin: the Lam Ta Khong and Lam Phra Phloeng Sub-Basins. The basin exhibited undulating highlands that are mainly used to cultivate maize, sugarcane, cassava, and various fruit trees – dragon fruit, mango, and custard apple, etc. The high CANwater2 in this area (Figure 2) was characterised by high PO_4 and NO_3 levels. This CANwater2 highly correlated with the CANland2, which exhibited com-
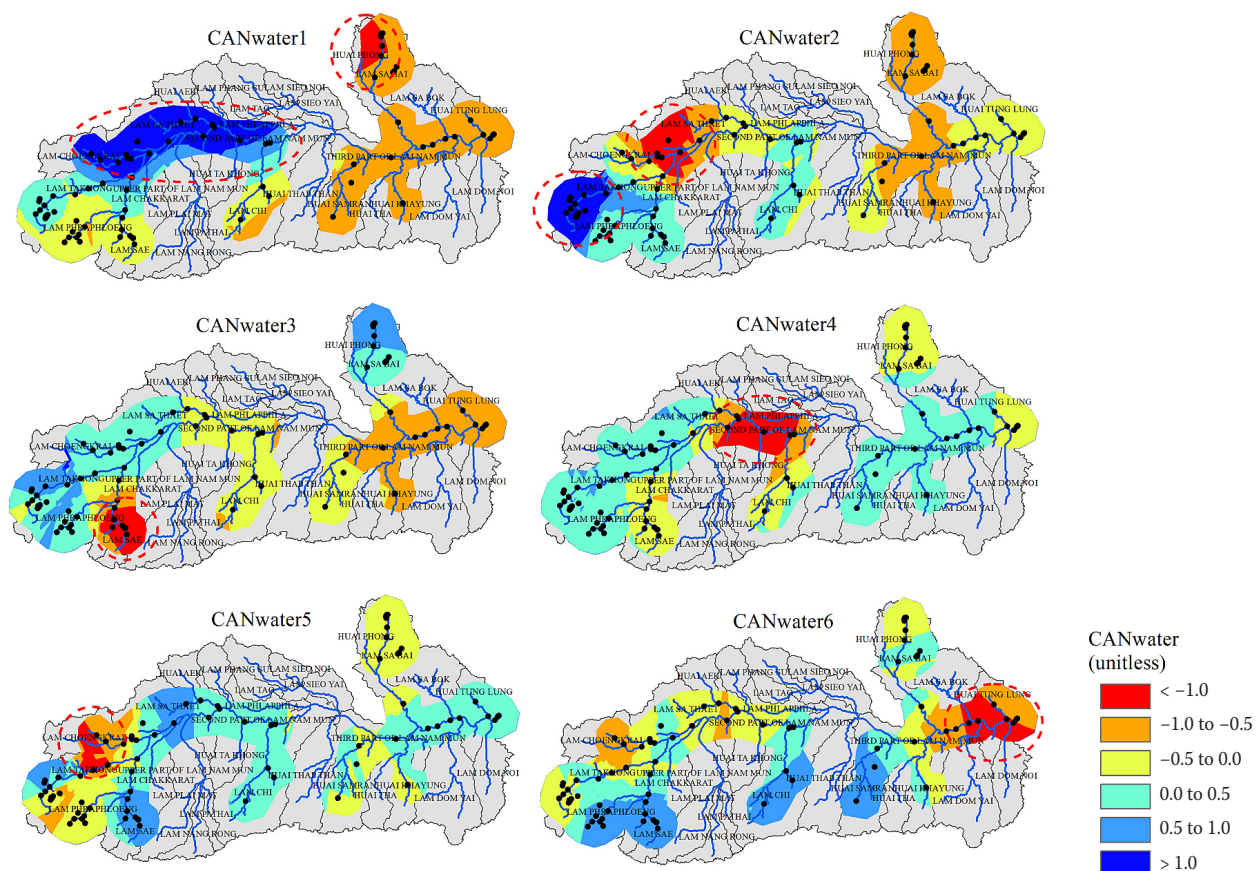

Figure 2. Canonical scores of the six CAN variables for the hydro-water quality factors

paratively high fertility – a high soil organic carbon (SOC), AP, and clay domination, but was low in soil nitrogen (see Table 1 for CANwater2).

Since it is a fertile soil, a variety of cropping, high aquatic nutrients, low-P manure with additions of mineral NK fertiliser, could be applied to reduce the fertiliser cost. Options on the soil-water conservation measures should also increase the cropping yields. Possible measures include intercropping with short-lived crops (Alcon et al. 2020), relay cropping (Tanveer et al. 2017), or strip cropping using plants with different root depths, e.g., tree crop and grass (Chen et al. 2020).

The western basin: the lower part of the Lam Ta Khong, Lam Phra Phloeng, and Lam Choengkrai Sub-Basins. The low CANwater5 in these basins (Figure 2) indicate high PO_4 and low NO_3 levels. This characterisation, associated with the low CANland5, exhibits a high fraction of cropland and a low fraction of grasslands (see Table 1 for CAN5). The predominant farmland in this area is used for rice fields. Based on the fertiliser application information, the rice cultivation in the lower Lam Ta Khong Sub-Basin required the largest amount of N addition (124.02–143.72 kg N/ha) *via* a chemical fertiliser when compared to those of the other lower reach sub-basins (117.01 kg N/ha for the middle part and

94.09 kg N/ha for the lower part). Despite the high soil N addition, the water NO_3 was still low. The low water NO_3 could be due to the high uptake rate of soil N by the rice plant. A very-low critical P level is required for rice cultivation; therefore, there were no significant differences in the rice grown in the soil with or without the P additions (Shi et al. 2015). The addition of P to the soil is, therefore, not necessary for the rice cultivation in these sub-basins.

To mitigate water pollution due to the excessive P and to maximise the crop yield, Shi et al. (2015) suggested applying a low-P manure incorporated with a mineral N and K fertiliser. Besides, we recommend the application of a filter/buffer strip using grasses due to its high soil-P fixing capacity, as suggested by Inboonchuay et al. (2019) to reduce the soil nutrient in the surface waters and groundwater (Pansak et al. 2008; Inboonchuay et al. 2019) and to increase the fraction of grassland in this agricultural ecosystem.

The eastern basin: the lower part of the Mun River Basin. The water in this basin exhibited low CANwater6 (Figure 2), representing a high PO_4 under a high flow velocity. This water characteristic was associated with a low fraction of forest and a low NDVI signal (see Table 1 for CAN6). Thus, increasing the forest fraction could effectively minimise the PO_4 discharge into the water and alleviate the

Table 2. Summary of the recommended soil-water conservation measures for the nutrient pollution mitigation in this study

Region*	Canonical variables*	Key soil-water quality issues	Recommended soil-water conservation measures		
			vegetative measures	app. of fertilisers	mechanical measures
Western	+ CAN2	high nutrient loading in hilly field crop-dominant areas	intercropping, relay cropping, strip cropping	low-P manure with mineral N and K	optional
	– CAN5	high nutrient loading in flat rice-dominant areas associated with cropping activities	filter/buffer strip		
Southern	– CAN3	high sediment loading in flat mixed-crops areas	mulching, filter/buffer strip, strip cropping	optional	contour cultivation, minimum tillage, no tillage or sub soiling, check dams
The 2nd part of the Mun River Basin	– CAN4	high nutrient and sediment loading in flat rice–dominant areas	optional	low-P manure with mineral N and K	optional
Eastern: lhe lower part of the Mun River Basin	– CAN6	high nutrient loading in flat rice-dominant areas associated with urban activities	buffer strip (woody forest is preferable)	optional	check dams

*See Figure 2

soil erosion associated with the high flow velocity in the Lower Mun River Basin. A tree filter strip measure could also increase the NDVI signal in the agricultural ecosystem, thereby resulting in a higher CANwater6. Furthermore, a series of check dams along its tributaries could effectively decelerate the stream flow and reduce the nutrient loading in the water bodies, as suggested by CANwater6. The effectiveness of the check dams can be found in many watershed management projects around the world (Abbasi et al. 2019).

High sediment loading – negative CAN3

The water turbidity in the southern basin varied from 7 to 185 (~55) NTU. The low CANwater3 found in this area was characterised by an elevated level of sediment loading, high flow velocity, and low pH. This water characteristic is associated with the CANland3, exhibiting a flat terrain (low LS) and a high NH_4 with a sandy soil.

Based on CAN3, there was no substantial contribution of the soil nutrients into the water. Thus, fertilizer management may not be highly effective. The conservation measures should be focused on minimizing the flow velocity and lowering the sediment loading into the stream. As suggested by Xiong et al. (2018), who studied global reports on soil loss controls in various slope gradients, effective measures for reducing soil loss include mulching, strip cropping, contour cultivation, no/minimum/deep tillage, and soil amendment. A series of check dams could also be introduced to reduce the in-stream flow velocity (Abbasi et al. 2019).

High nutrient and sediment loadings – negative CAN4

The water quality in the second part of the Mun River Basin exhibited 6–294 NTU turbidity, 0.053 to 0.608 mg/L NO_3, and 0.028–0.109 mg/L PO_4. The low CANwater4 in this basin had a high turbidity associated with high NO_3 and PO_4 loadings and a low stream velocity. This water characteristic correlated with soil properties of a high soil N (as both NH_4 and NO_3), but a low pH (low CANland4, see Table 1 for CAN4). The result suggests an effect of the chemical nitrogen fertiliser addition on the accelerating nitrification rate in the soil, resulting in the rapid NH_3-to-NO_3 conversion and low soil pH. The soil NO_3 could also leach into the water body.

To mitigate the water quality problem, CANwater4 suggests applications of organic sources of carbon and phosphorus into the soil. The organic carbon has a pH buffering capacity and minimises the NH_3 release from the land into the water (Parfitt & Salt 2001; Sparrius et al. 2012). The second part of the Mun River Basin exhibited a flat terrain, predominated by rice fields. A low-P manure incorporated with a mineral N and K fertiliser can be adequately applied to minimise the P loading into the water body.

The suggested soil-water conservation measures from the canonical correlation analysis were highly responsive to the local soil and water relationships during the observation periods. The measures, therefore, should prioritise tackling the local nutrient pollution issues. However, they may not respond similarly in other tempo-spatial contexts. Other soil-water conservation measures can be optionally applied to enhance the effectiveness in the watershed management.

CONCLUSION

This study proposes soil-water conservation measures in response to the agricultural nutrient pollution in the Mun River Basin, NE Thailand based on a canonical correlation analysis between the hydro-water quality factors and the land-soil factors. The study employed basin-wide information, including those acquired from field measurements during the onset of the 2018 wet season, satellite retrieval, and secondary data collection. The results suggested geographical differences in the conservation measures, as summarised in Table 2.

REFERENCES

Abbasi N.A., Xu X., Lucas-Borja M.E., Dang W., Liu B. (2019): The use of check dams in watershed management projects: Examples from around the world. Science of the Total Environment, 676: 683–691.

Alcon F., Marín-Miñano C., Zabala J.A., de-Miguel M.-D., Martínez-Paz J.M. (2020): Valuing diversification benefits through intercropping in Mediterranean agroecosystems: A choice experiment approach. Ecological Economics, 171: 106593.

Bray R.H., Kurtz L.T. (1945): Determination of total, organic, and available forms of phosphorus in soils. Soil Science, 59: 39–45.

Bremner J.M., Keeney D.R. (1965): Steam distillation methods for determination of ammonium, nitrate, and nitrite. Analytica Chimica Acta, 32: 485–495.

Chen J., Xiao H., Li Z., Liu C., Ning K., Tang C. (2020): How effective are soil and water conservation measures (SWCMs) in reducing soil and water losses in the red soil hilly region of China? A meta-analysis of field plot data. Science of the Total Environment, 735: 139517.

Choenkwan S., Fox J.M., Rambo A.T. (2014): Agriculture in the mountains of Northeastern Thailand: current situation and prospects for development. Mountain Research and Development, 34: 95–106.

Cochrane T.A., Arias M.E., Piman T. (2014): Historical impact of water infrastructure on water levels of the Mekong River and the Tonle Sap system. Hydrology and Earth System Sciences, 18: 4529–4541.

Department of Land Development (2020): 62 Soil Groups. Availabe at http://oss101.ldd.go.th/thaisoils_museum/62_soilgroup/main_62soilgroup.htm (accessed Jan 18, 2020).

Dutta S., Rekha Gogoi R., Khanikar L., Shubro Bose R., Prasad Sarma K. (2016): Assessment of hydrogeochemistry and water quality index (WQI) in some wetlands of the Brahmaputra valley, Assam, India. Desalination and Water Treatment, 57: 27614–27626.

HAII (2012): Data Collection and Analysis. The Project on Database Developments for 25 Basins and Extreme Water Simulation Models – Mun River Basin. Hydro and Agro Informatics Institute. Available at http://www.thaiwater.net/web/attachments/25basins/05-moon.pdf (accessed Jan 18, 2020).

Inboonchuay T., Chimchart B., Manoonyo J., Bootpetch S. (2019): Assessing soil erosion and nutrient losses under soil and water conservation measures in maize plantation, Khao Suan Kwang District, Khon Kaen Province. Journal of Agriculture, 35: 447–459. (in Thai)

Khangembam S., Kshetrimayum K.S. (2019): Evaluation of hydrogeochemical controlling factors and water quality index of water resources of the Barak valley of Assam, Northeast India. Groundwater for Sustainable Development, 8: 541–553.

Pansak W., Hilger T.H., Dercon G., Kongkaew T., Cadisch G. (2008): Changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand. Agriculture, Ecosystem and Environment, 128: 167–176.

Parfitt R.L., Salt G.J. (2001): Carbon and nitrogen mineralisation in sand, silt, and clay fractions of soils under maize and pasture. Soil Research, 39: 361–371.

Qin T., Yang P., Groves C., Chen F., Xie G., Zhan Z. (2018): Natural and anthropogenic factors affecting geochemistry of the Jialing and Yangtze Rivers in urban Chongqing, SW China. Applied Geochemistry, 98: 448–458.

Rambo A.T. (2017): The agrarian transformation in Northeastern Thailand: a review of recent research. Southeast Asian Studies, 6: 211–245.

Saenya J., Anusontpornperm S., Thanachit S., Kheoruenromne I. (2015): Potential of paddy soils for Jasmine rice production in Si Sa Ket Province, Northeast Thailand. Asian Journal of Crop Science, 7: 34–47.

Shi L.L., Shen M.X., Lu C.Y., Wang H.H., Zhou X.W., Jin M.J., Wu T.D. (2015): Soil phosphorus dynamic, balance and critical P values in long-term fertilization experiment in Taihu Lake region, China. Journal of Integrative Agriculture, 14: 2446–2455.

Sparrius L.B., Sevink J., Kooijman A.M. (2012): Effects of nitrogen deposition on soil and vegetation in primary succession stages in inland drift sands. Plant and Soil, 353: 261–272.

Tanveer M., Anjum S.A., Hussain S., Bolinches A.C., Ashraf U. (2017): Relay cropping as a sustainable approach: problems and opportunities for sustainable crop production. Environmental Science and Pollution Research, 24: 6973–6988.

Wischmeier W.H., Smith D.D. (1978): Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Monograph No. 537, Maryland, Department of Agriculture, Science and Education.

Xiong M., Sun R., Chen L. (2018): Effects of soil conservation techniques on water erosion control: A global analysis. Science of the Total Environment, 645: 753–760.

Yadav S., Babel M.S., Shrestha S., Deb P. (2019): Land use impact on the water quality of large tropical river: Mun River Basin, Thailand. Environmental Monitoring and Assessment, 191: 614.

Zhao Z., Liu G., Liu Q., Huang C., Li H., Wu C. (2018): Distribution characteristics and seasonal variation of soil nutrients in the Mun River Basin, Thailand. International Journal of Environmental Research and Public Health, 15: 1818.