Integrating Landscape Metrics and Hydrologic Modeling to Assess the Impact of Natural Disturbances on Ecohydrological Processes in the Chenyulan Watershed, Taiwan

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Introduction

- Land use and land cover are the results of interaction among natural environment and human activities, and its distribution can reflect the anthropogenic types and decision behavior.
- Many metrics and indices have been developed to characterize the landscape composition and spatial configuration in a categorical map.
- Quantitative analysis of how landscape changes influence the watershed streamflow and sediment exports by using hydrological models is needed to provide support for identifying the critical areas that require appropriate management and also can suggest for future land use management and allocation.

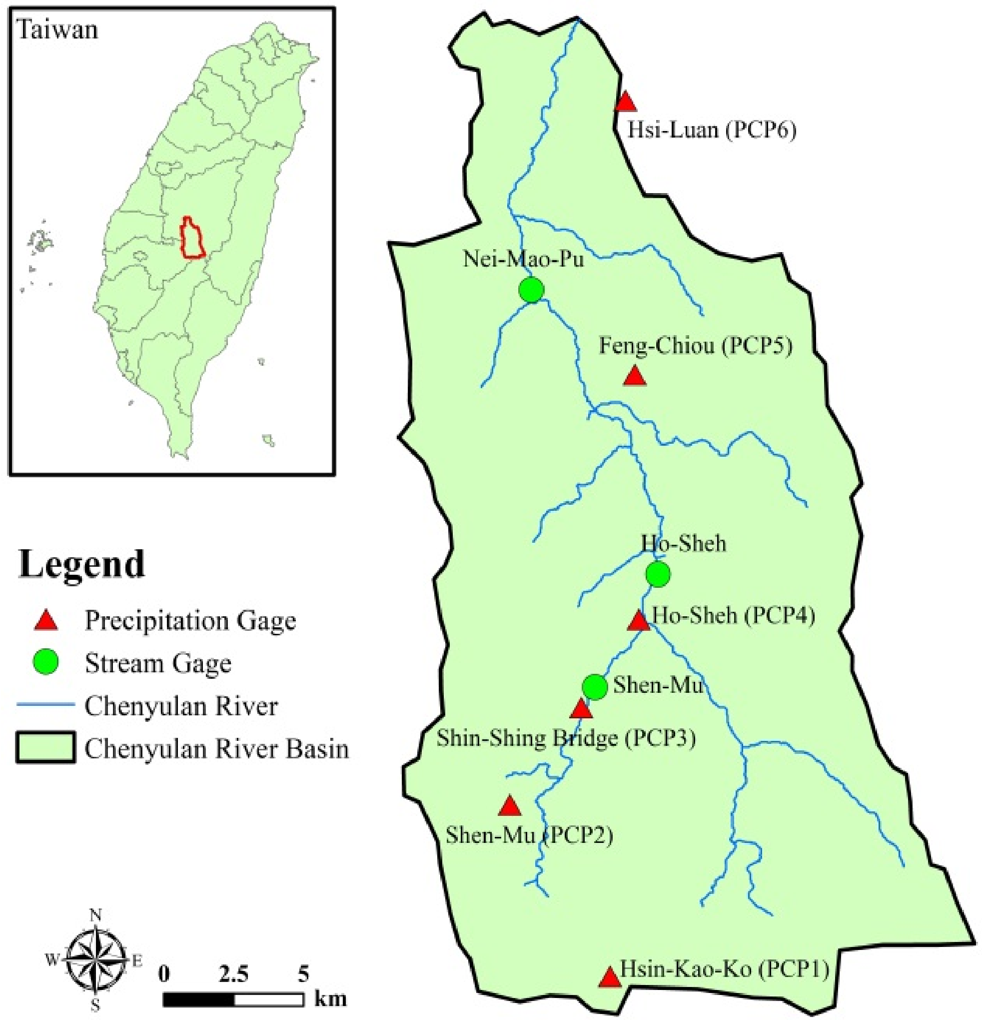
Objectives

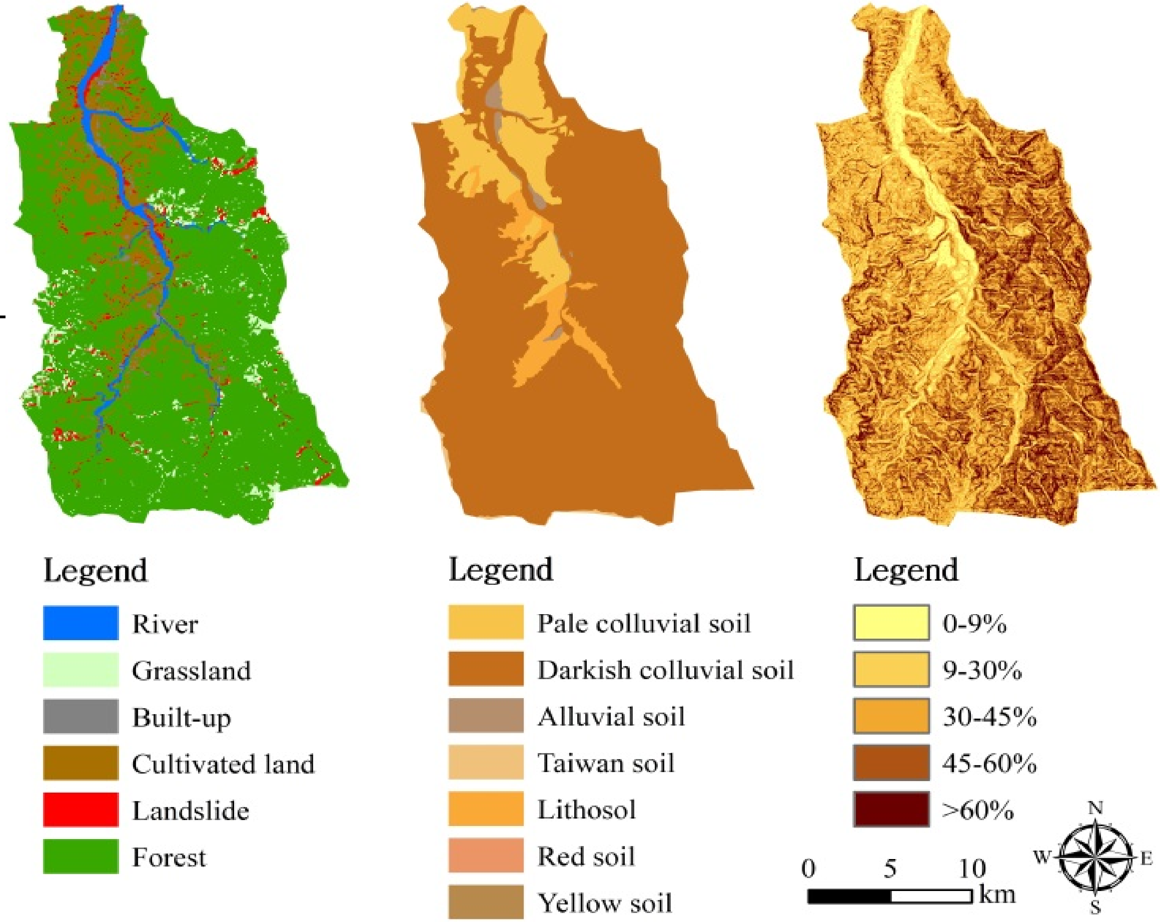
- To analyze the change in spatial patterns of the Chenyulan watershed during 2008-2013 by using FRAGSTATS.
- To apply the SWAT model to evaluate the impact of land cover change on the watershed responses.
- To establish the relationships between landscape metrics, water yield and sediment yield.

Study site: Chenyulan watershed

Area: 449 km^2

1 weather station (PCP2),
5 automated precipitation gages (PCP1, PCP3, PCP4, PCP5, PCP6),
3 gages of streamflow and sediment export (Shen-Mu, Ho-Sheh, Nei-Mao-Pu)





- More than 70% of watershed is covered by forest, and cultivated lands are distributed mostly in the valley region.

- Darkish colluvial soil is dominated (82.38%) in the watershed, followed by pale colluvial soil (12.29%), lithosol (4.19%), alluvial soil (0.89%), Taiwan clay (0.22%), yellow soil (0.03%), and red soil (0.002%)

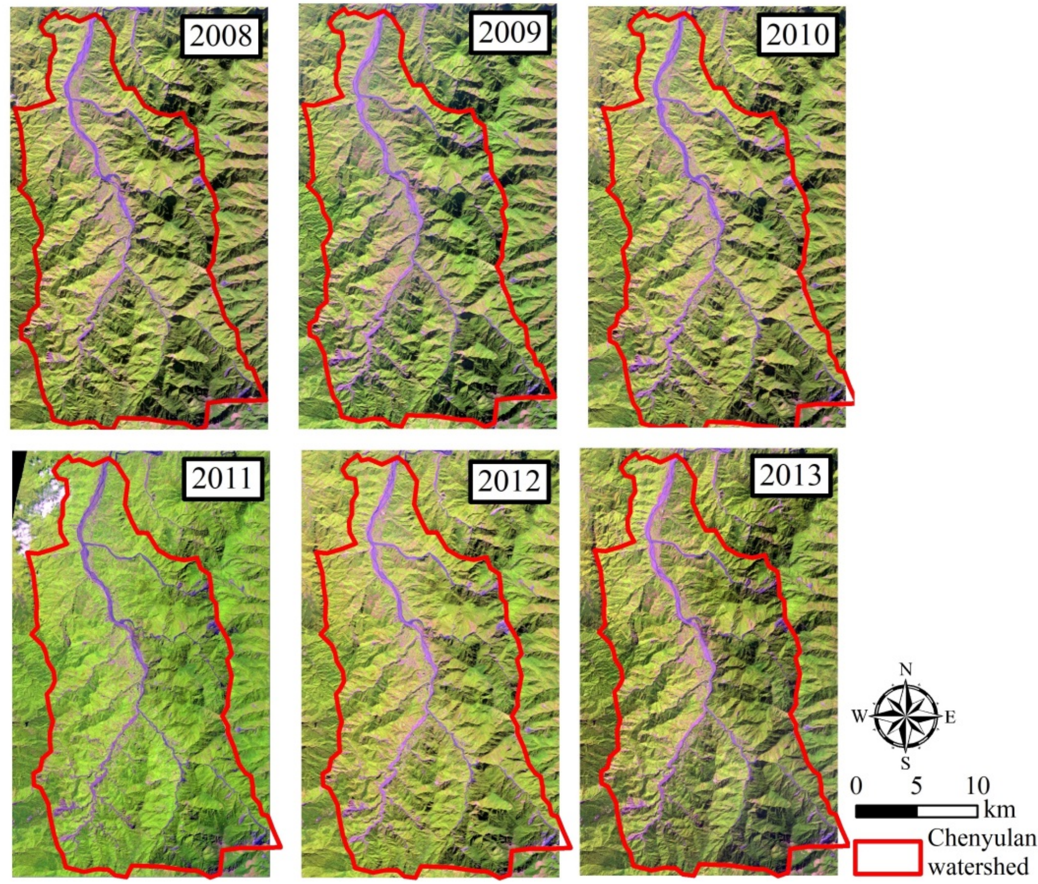
- Major area (49.58%) is of slope greater than 60%, followed by slope of 45-60% (19.60%), 30-45% (15.14%), 9-30% (12.38%), and 0-9% (3.30%)

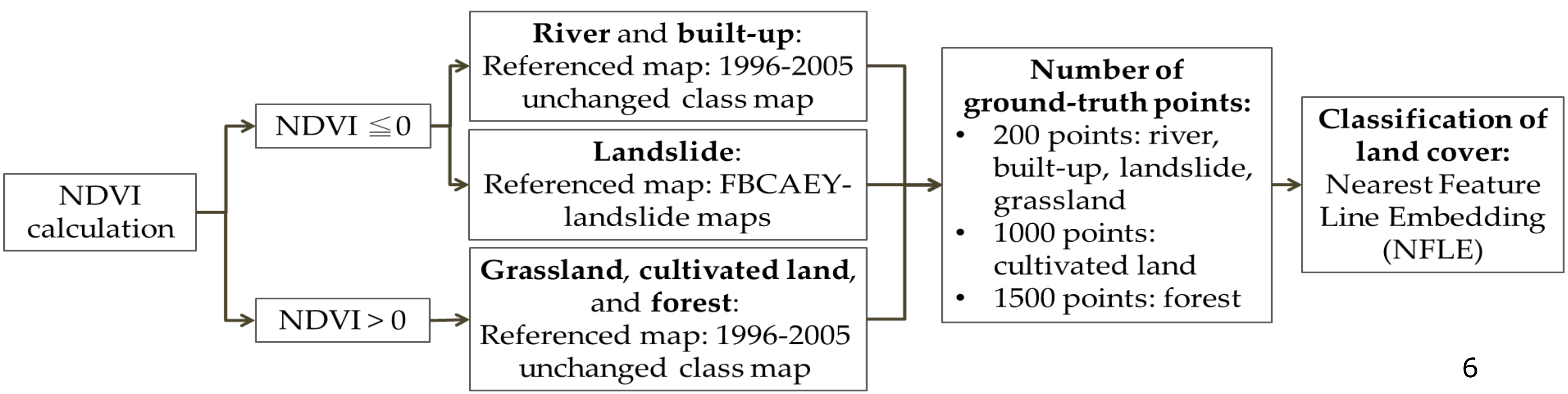
Methodology

- Image processing:

NDVI=(NIR-R)/(NIR+R),

NIR: the Near Infrared Reflectance;
R: the Red (visible) Reflectance





○ Landscape metrics:

Landscape composition was quantified by the proportion of each land cover types. Configuration metrics included: (1) patch-based metrics: patch density (PD) and area-weighted mean patch area (AREA_AM); (2) shape metrics: edge density (ED) area-weighted mean radius of gyration (GYRATE_AM), and area-weighted mean shape index (SHAPE_AM); (3) aggregation metrics: aggregation index (AI) and splitting index (SPLIT).

Landscape metrics	Description	Unit	Range
Patch density (PD)	The number of patches of the land cover class divided by total landscape area (m^2), multiplied by 10,000 and 100	N/100ha	PD>0, constrained by cell size
Area-weighted mean patch area (AREA_AM)	The sum of patch area multiplied by the proportional abundance of the patch	m^2	AREA_AM > 0, without limit
Edge density (ED)	The sum of the lengths of all edge segments of the patch, divided by the total landscape area (m^2), multiplied by 10,000	m/ha	ED ≥ 0, without limit
Area-weighted mean radius of gyration (GYRATE_AM)	The sum of the radius of gyration multiplied by the proportional abundance of the patch	m	GYRATE_AM > 0, without limit
Area-weighted mean shape index (SHAPE_AM)	The sum of the SHAPE[1] value for each patch multiplied by the proportional abundance of the patch	-	SHAPE_AM ≥ 1, without limit
Aggregation index (AI)	For the same land cover class, the sum of cell number of neighbor patch divided by maximum cell number of neighbor patch, multiplied by the proportional abundance of the patch (%)	%	0 ≤ AI ≤ 100
Splitting index (SPLIT)	The total landscape area (m^2) squared divided by the sum of patch area (m^2) squared	-	1 ≤SPLIT≤ number of cells in the landscape squared

SWAT model: Land cover update module

- Two land cover scenarios: constant land cover (CLC) which assumes that land cover remains constant since 2005, and updated land cover (ULC) which represents the dynamic land cover during 2008-2013.
- lup.dat file, which lists the order of changing dates of each land cover; the HRU fraction (HRU_FR) files of different land cover of concern.

Model calibration and validation

- The model performance was evaluated by using four statistical measures, including coefficient of determination (R^2), Nash-Sutcliffe efficiency coefficient (NSE), percent bias (PBIAS), and RMSE-observation standard deviation ratio (RSR)

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right]$$

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

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

where Y^{obs} is the measured value; Y^{sim} is the simulated value; Y^{mean} is the average of measured value.

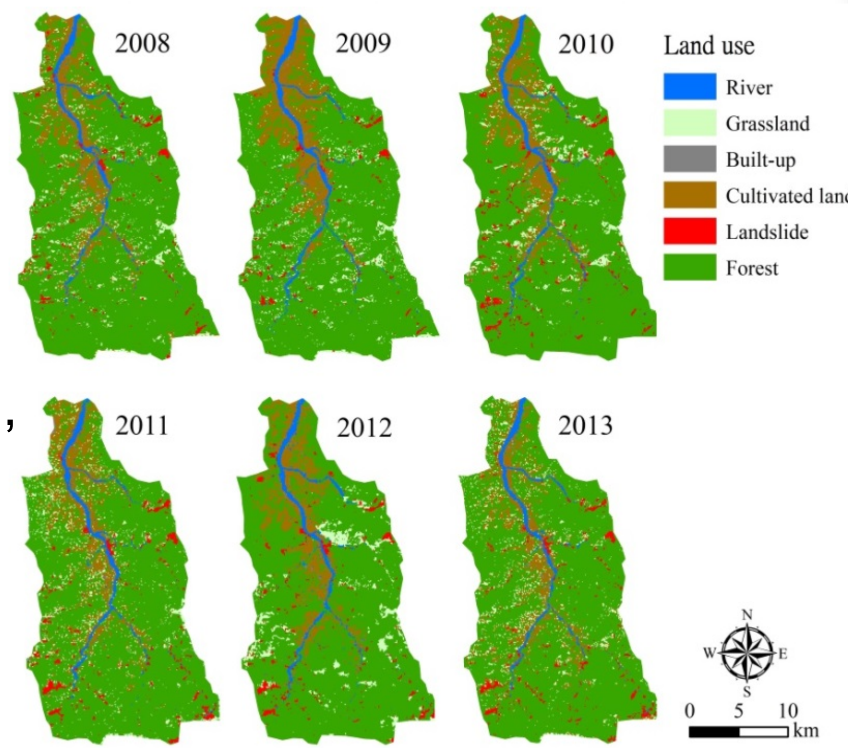
Results

○ Classification results:

Assessment indexes of classification accuracy

Year	2008	2009	2010	2011	2012	2013
Overall accuracy	82.22%	83.74%	81.00%	81.81%	77.80%	73.70%

- Forest is the major land cover, occupying 74.45-76.75% of the watershed.
- Cultivated lands are usually developed along the streams, with the area between 11.87-14.05% of the watershed, and tend to be decreased and aggregated during the study period.
- Landslide was increased from 2.00% in 2008 to 2.73-3.11% during 2010-2013.



Landscape metrics analysis: Landscape level

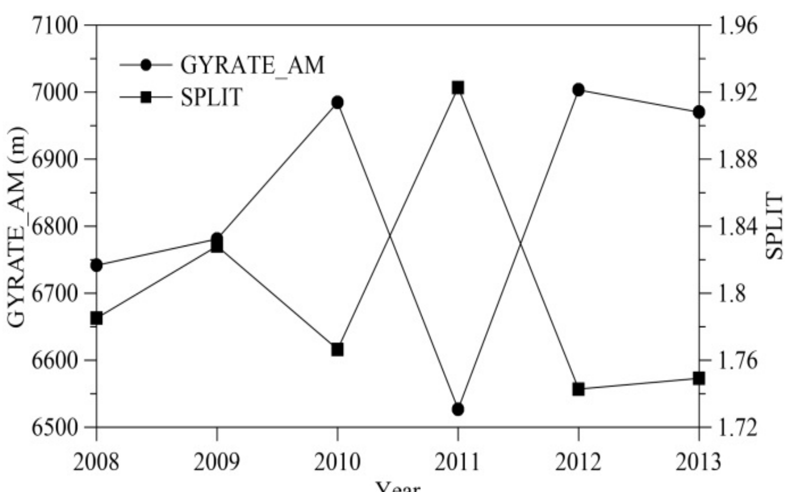
- There is a strong positive relationship between PD and ED, indicating more numbers of patches would have longer edge lengths. Both large values of PD and ED show a high level of fragmentation.
- The increasing SHAPE_AM from 2008 to 2013 indicated the patch shapes were less compacted.
- → a positive relationship between SHAPE_AM, PD and ED were found.

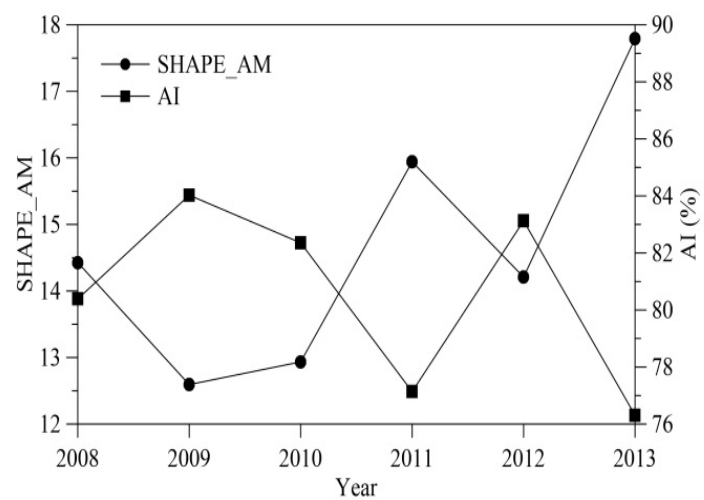
Metrics[1]	PD	AREA_AM	ED	GYRATE_AM	SHAPE_AM	AI	SPLIT
PD	1						
AREA_AM	-0.319	1					
ED	0.968**[2]	-0.283	1				
GYRATE_AM	-0.396	0.931**	-0.335	1			
SHAPE_AM	0.879*[3]	-0.036	0.930**	-0.094	1		
AI	-0.969**	0.282	-1.000**	0.335	-0.930**	1	
SPLIT	0.321	-1.000**	0.286	-0.935**	0.041	-0.285	1

** indicates a significant relationship at a level of $p < 0.01$.
* indicates a significant relationship at a level of $p < 0.05$.

○ Landscape metrics analysis: Landscape level

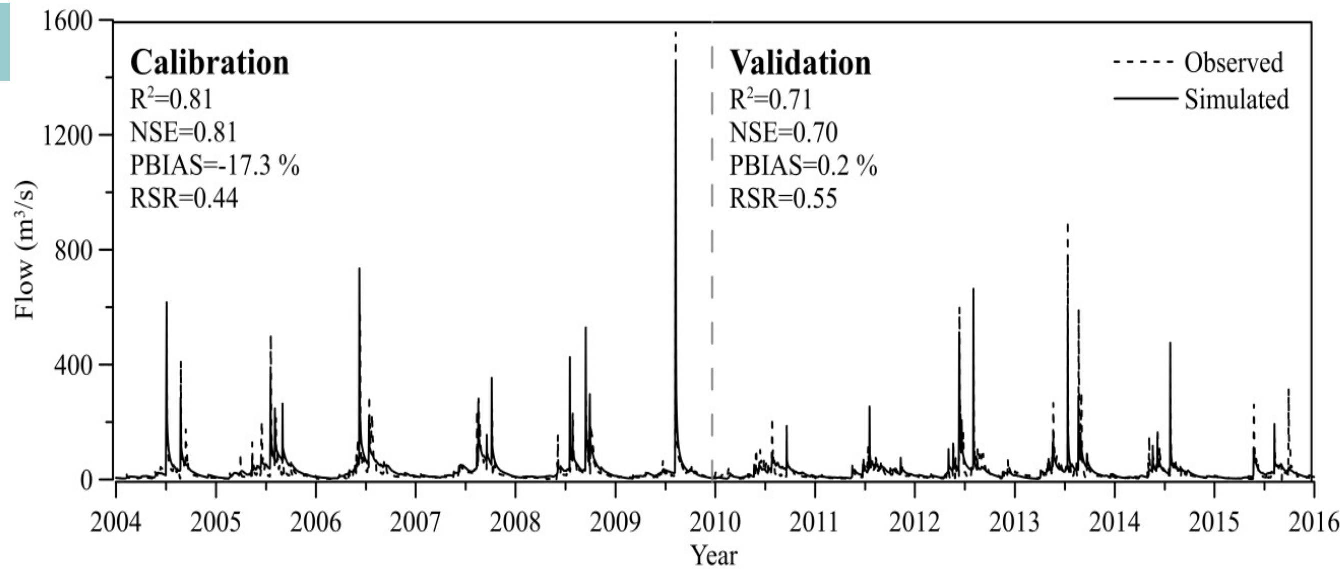
- GYRATE is equal to the mean distance between each cell and the centroid of that patch. GYRATE has a zero value when the patch consists of only one pixel.
- → GYRATE_AM is sensitive to the patch area (AREA_AM)
- SPLIT is negatively correlated with GYRATE_AM and AREA_AM, while AI is negatively correlated with PD and SHAPE_AM.
- As the process of fragmentation of a land cover patch begins with reduction in the patch area and an increase in proportion of edge-influenced patch area.



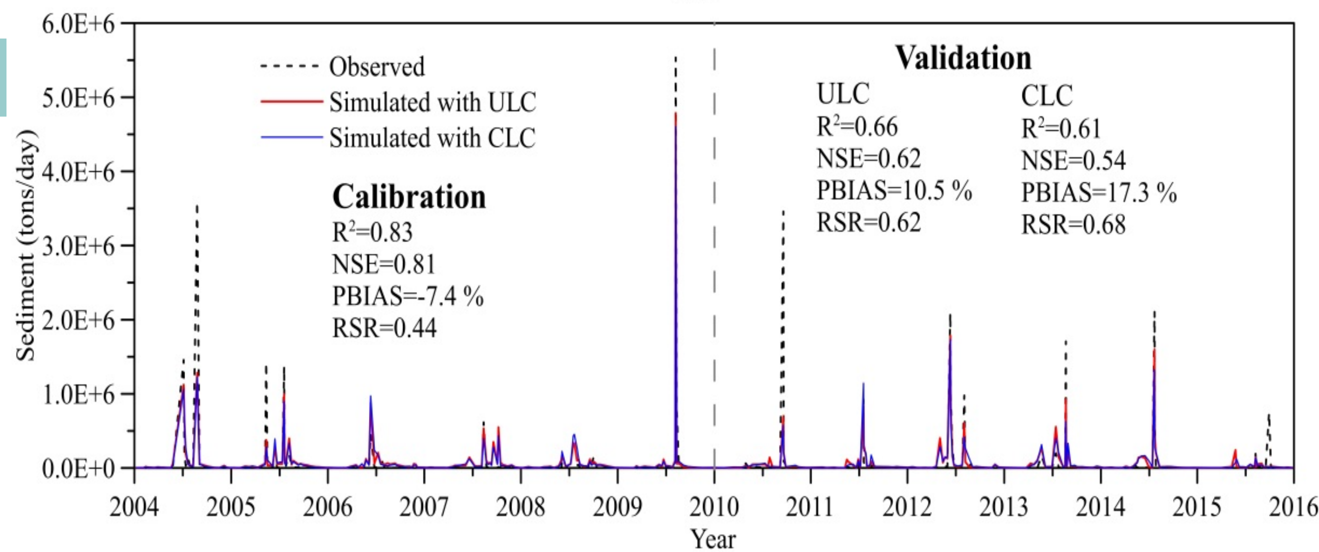


SWAT results: Model calibration and validation

daily streamfow

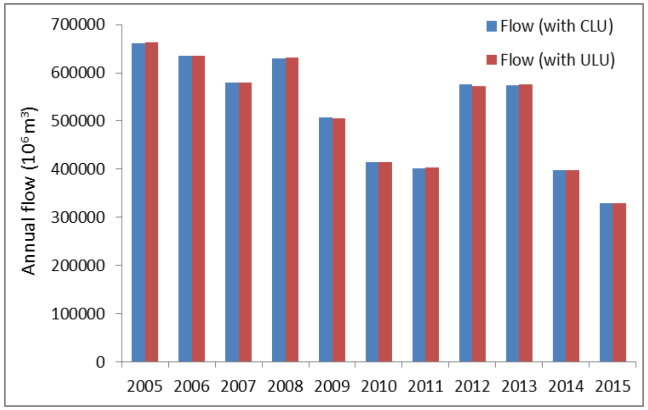


daily sediment

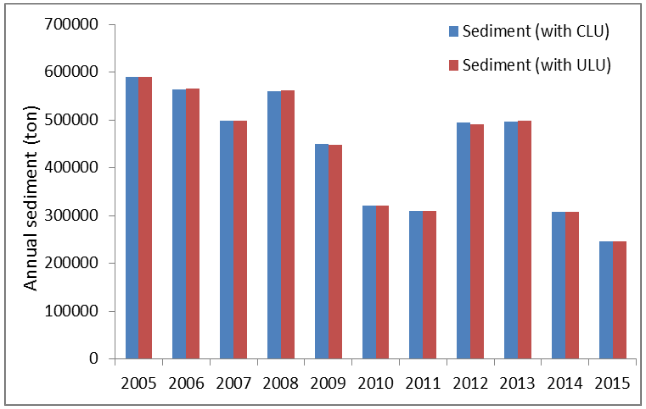


SWAT results: simulation results

- Annual flow simulation was dominated by the rainfall, leading a similar trend of sediment loadings during 2005-2015.
- The biggest difference between two land cover scenarios was found in 2008 and 2012.
- During 2008-2009, higher precipitation in 2008 magnified the impact of difference between 2005 and 2008 land covers.
- Since 2009, land cover had more impact than the rainfall as the model read the 2008 land cover until December 2nd, 2009 and then read the 2009 land cover afterward.



(a) annual flow (m^3)



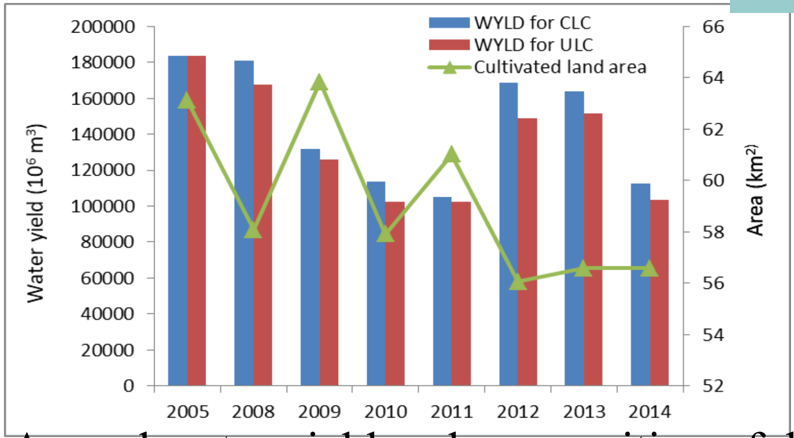
(b) annual sediment (ton).

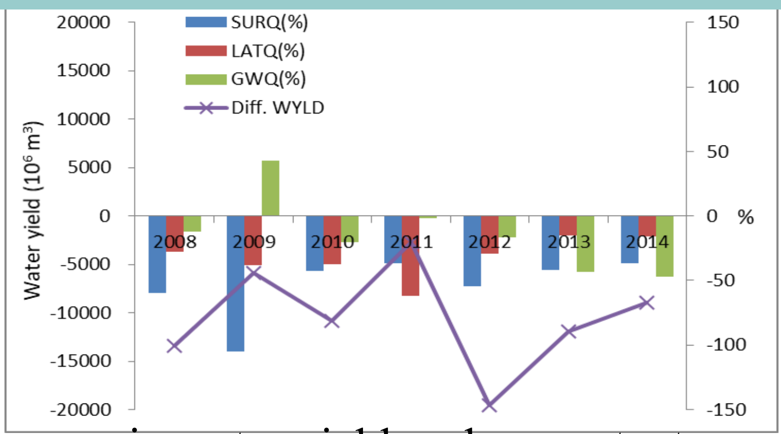
Discussion:

Impact of land cover change on ecohydrological processes

- Land cover patterns affect ecohydrological processes and component of water yields, while the proportions of land cover types control the erosion rates within the watershed.
- For both land cover change scenarios, the average compositions of water yield from cultivated land, forest and grassland during 2005 and 2008-2014 were similar.

Cultivated land: surface runoff (50.92%), lateral flow (14.45%) and groundwater recharge (34.63%)



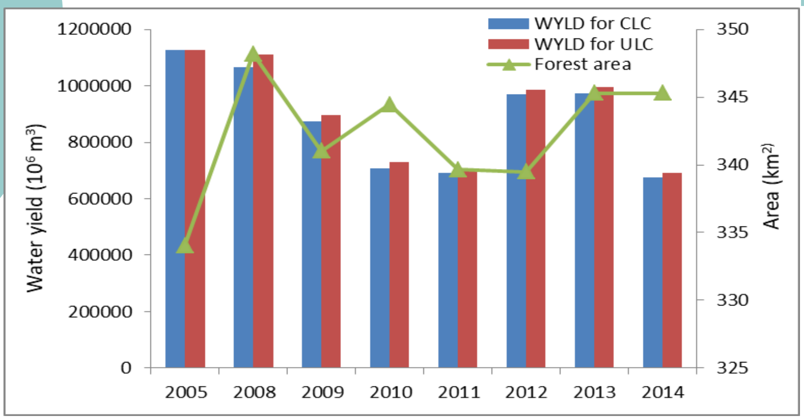


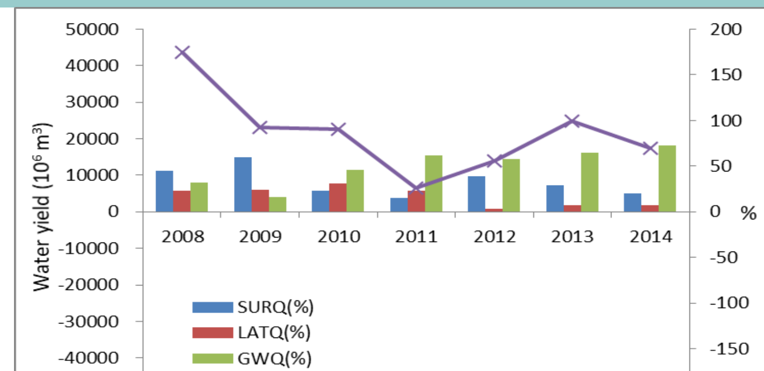
Annual water yield and composition of difference in water yield under constant land cover (CLC) and updated land cover (ULC) scenarios.

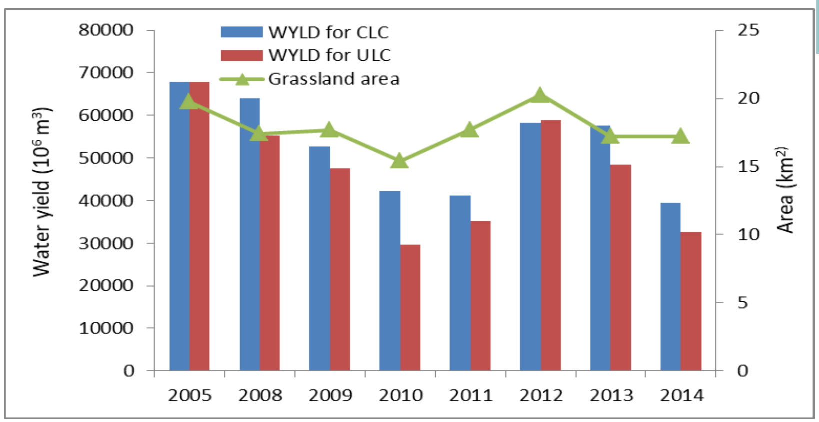
Discussion:

Impact of land cover change on ecohydrological processes

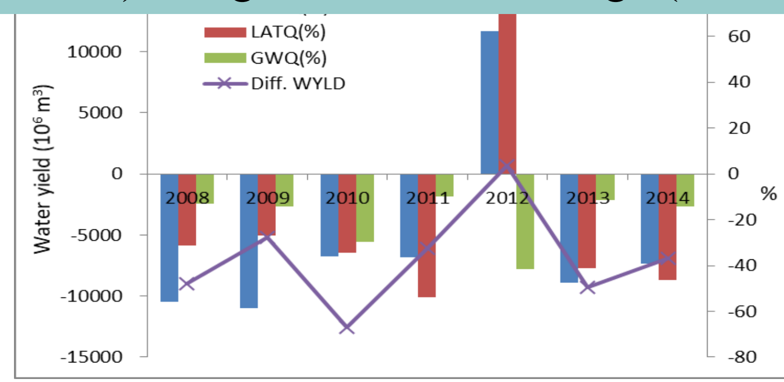
Forest: surface runoff (34.69%), lateral flow (32.62%) and groundwater recharge (32.69%)







Grassland: surface runoff (44.30%), lateral flow (31.37%) and groundwater recharge (24.33%)

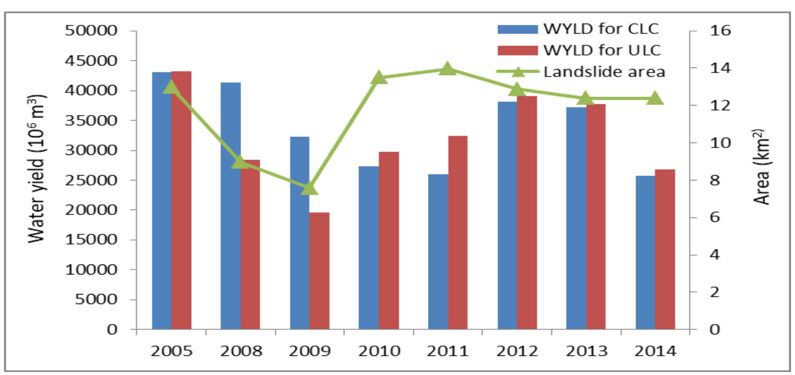


Annual water yield and composition of difference in water yield under constant land cover (CLC) and updated land cover (ULC) scenarios.

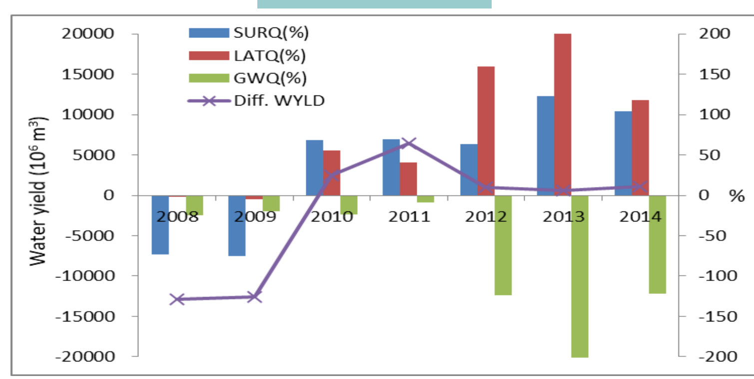
Discussion:

Impact of land cover change on ecohydrological processes

- Land cover change had slightly impacts on water yields generated from landslide and built-up.
- The contribution of lateral flow was increased and groundwater recharge was decreased for land cover change scenario compared to the constant land cover scenario, indicating the increasing pore water pressure, groundwater exfiltration from the bedrock, hydraulic uplift pressure from below the landslide caused by landslide.



Landslide



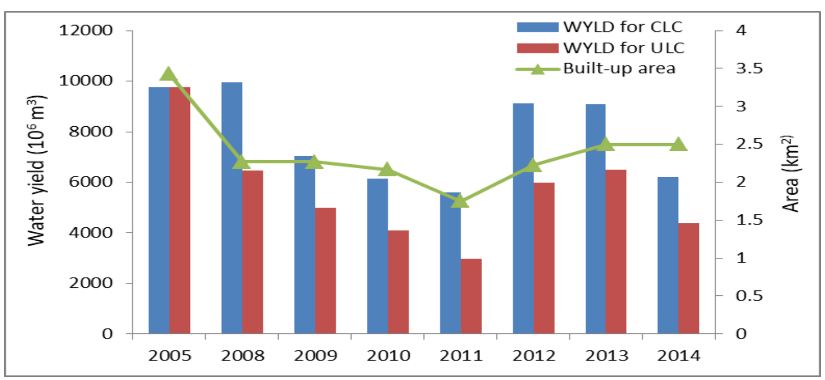
Annual water yield and composition of difference in water yield under constant land cover (CLC) and updated land cover (ULC) scenarios.

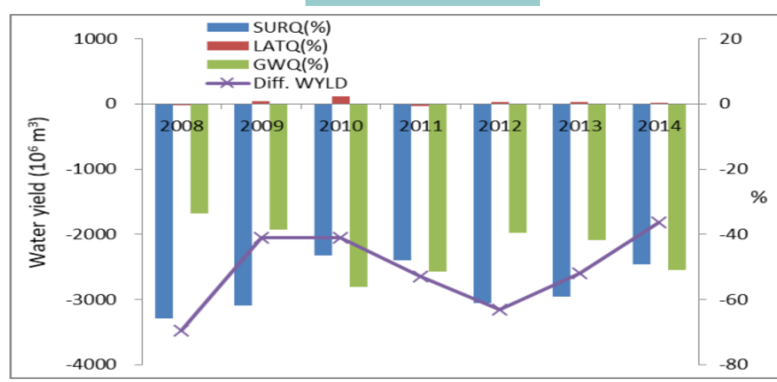
Discussion:

Impact of land cover change on ecohydrological processes

- Built-up primary consisting of impervious surface increases surface runoff and prevents groundwater to recharge to the land.
- Therefore, decreases in surface runoff (-46.45% ~ -65.80%) and groundwater recharge (-33.68% ~ -56.05%) were the two major contributions to the change in built-up water yield between land cover scenarios

Built-up





Annual water yield and composition of difference in water yield under constant land cover (CLC) and updated land cover (ULC) scenarios.

Discussion:

Relationship between landscape metrics and watershed responses

- The higher patch density (PD) and edge density (ED) of grassland, cultivated land and forest generated less water.
- AI metric were positively correlated with water yield from forest and sediment yield from landslide, while AI had a negative relationship with water yield and sediment yield from the cultivated lands.

(a) Water yield

Land cover	PD	AREA_AM	ED	GYRATE_AM	SHAPE_AM	AI	SPLIT
Grassland	-.271**	0.1025	-.278**	0.1007	0.0054	0.2052	-0.0382
Built-up	-0.1534	0.0599	-0.0848	0.0302	-0.0161	-0.0815	0.0613
Cultivated land	-.207*	-0.1702	-.341**	-.270**	-.252**	-.421**	.375**
Landslide	-0.0030	0.0158	0.0829	0.0558	0.1030	0.0625	-0.0625
Forest	-.282**	.394**	-.350**	.353**	0.0314	.304**	-0.1547

(b) Sediment yield

Land cover	PD	AREA_AM	ED	GYRATE_AM	SHAPE_AM	AI	SPLIT
Grassland	0.0240	0.0944	0.0622	0.1102	0.0613	0.0182	-0.1205
Built-up	-0.0805	-0.0328	-0.0836	-0.0018	0.0035	-0.0468	-0.0842
Cultivated land	-.228**	-0.0849	-.377**	-.216*	-.223*	-.431**	.327**
Landslide	0.1777	0.1796	.349**	.281**	.341**	.238*	-0.1639
Forest	-0.0156	-0.0541	.213*	0.0442	.257**	-0.0851	-0.0390

Discussion:

Relationship between landscape metrics and watershed responses

- The shape indices (i.e., ED, GYRATE_AM and SHAPE_AM) of cultivated lands had negative relationship with water yield and sediment yield, while those indices of landslide had positive relationship with water yield and sediment yield.
- The edge characteristics may partially determine the erosion characteristics and sediment export.

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Conclusions

- Due to accumulated impact of natural disturbances (e.g., typhoons and heavy rainfall events), the landscape patches were more fragmented.
- Annual precipitation brought from typhoons was found to be dominant influence to the amount of water yield, while the difference in water yield between constant land use and updated land use was led by the change in land cover area (landscape composition).
- The contributions of different hydrological components to water yield can be useful to understand how changes in land cover and landscape configuration affected the ecohydrological processes.

Thanks for your attention!

Questions?