Development and evaluation of ArcGIS based watershed-scale L-THIA ACN-WQ system for watershed management

Jichul Ryu, Won Seok Jang, Jonggun Kim, Gwanjae Lee, Kwangsik Yoon, Yong Seok Kim and Kyoung Jae Lim

ABSTRACT

The Long-term Hydrologic Impact Assessment Model with Asymptotic Curve Number Regression Equation and Water Quality model (L-THIA ACN-WQ) has been developed to simulate streamflow as well as instream water quality using fewer parameters, compared to other watershed models. However, since model input parameters (i.e. hydraulic response unit (HRU) map, stream network, database (DB), etc.) should be built by user manually, it is difficult to use the model for a nonprofessional or environmental policy decision-maker. In addition, it is difficult to analyze model outputs in time and space because the model does not provide geographic information system (GIS) information for the simulation results. To overcome the limitations, an advanced version of L-THIA ACN-WQ system which is based on ArcGIS interface was developed in this study. To evaluate the applicability of the developed system, it was applied to the Banbyeon A watershed in which total maximum daily load (TMDL) has been implemented. The required model input datasets were automatically collected in the system, and stream flow, T-N and T-P pollutant loads were simulated for the watershed. Furthermore, flow duration curve (FDC) and load duration curve (LDC) were generated to analyze hot spot areas in the system through automatic processes included in the system. The system can establish the model input data easily, automatically provide the graphs of FDC and LDC, and provide hot spot areas which indicate high pollutant loads. Therefore, this system can be useful in establishing various watershed management plans.

Key words | ArcGIS, FDC, hotspot area, L-THIA ACN-WQ system, LDC, pollutant loads

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INTRODUCTION

Estimations of runoff and pollutant loads in a watershed have played pivotal roles for efficient watershed management (USEPA 2003). Various computer models such as Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 2012), Hydrologic Simulation Program-Fortran (HSPF) (Bicknell *et al.* 2001), Storm Water Management Tool

(SWMM) (Gironas *et al.* 2010; USEPA 2010), L-THIA Long Term Hydrologic Impact Assessment (L-THIA) (Harbor 1994; Bhaduri *et al.* 1997; Engel 1997; Lim *et al.* 2006), Pollutant Loading Application (PLOAD) (USEPA 2013), Spreadsheet Tool for Estimating Pollutant Load (STEPL) (Tetra 2011; Park & Engel 2014), etc. have been developed and used for various objectives at spatial and temporal scales worldwide.

The watershed-scale Long-term Hydrologic Impact Assessment Model with Asymptotic Curve Number

Regression Equation and Water Quality (L-THIA ACN-WQ) (Ryu *et al.* 2016a) is an efficient model with baseflow/routing components and instream water quality capability. The model has been demonstrated as an accurate tool for stream-flow estimation and instream water quality as shown in the previous studies (Ryu *et al.* 2016b). It has been proven that the model could solve underestimation issues in the original L-THIA model (Harbor 1994) with asymptotic curve number (CN) approaches (Ryu *et al.* 2016c), lack of baseflow component and flow routing for watershed application, and dynamic simulation of instream water quality at a watershed.

Although only 10 additional input parameters for streamflow simulation, eight additional input parameters for pollutant load estimation from hydraulic response units (HRUs), and 33 additional input parameters (default values of 33 parameters recommended by the United States Environmental Protection Agency (US EPA) could be used, which were not sensitive factors in watershed applications as found in previous sections) for instream water quality simulation are needed for instream water quality simulation, the watershed-scale L-THIA ACN-WQ model is relatively simple with easy-to-prepare input dataset, compared with various complex watershed scale models.

However, to configure stream networks manually for flow routing and instream water quality simulation could be time-consuming and tedious jobs in the watershed-scale L-THIA ACN-WQ model, which could result in errors in building input parameters for a watershed. In addition, since the model was developed as a screening level model, users expect that less effort is needed in operating this model.

Flow duration curve (FDC) and load duration curve (LDC), as well as time series analysis, are often used to evaluate watershed conditions in various TMDLs (total maximum daily loads) studies (Hwang *et al.* 2011; Kang *et al.* 2011; Kim *et al.* 2012; Kim *et al.* 2016). However, the watershed-scale L-THIA ACN-WQ model (Ryu *et al.* 2016b) does not provide these functionalities.

Thus, the objectives of study are: (1) to develop the ArcGIS-based watershed-scale L-THIA ACN-WQ model for spatial and temporal analysis of simulated results with hot spot mapping and FDC/LDC analysis capability; and (2) to apply the ArcGIS-based watershed-scale L-THIA

ACN-WQ system from the perspectives of FDC/LDC analysis and hot spot mapping for evaluation of model applicability in practical watershed management plans.

METHODOLOGY

Overview of L-THIA ACN-WQ model

The L-THIA model has been widely used in calculating direct runoff and nonpoint source pollution in small watersheds. However, the model cannot consider the hydrologic transport processes and baseflow and cannot simulate the variation of instream water quality, which causes difficulty in simulating the stream flow and pollutant loads successfully for large watersheds. To overcome the limitation, the L-THIA ACN-WQ model was developed by adding several new modules for direct runoff, baseflow, and channel routing and linking the QUAL2E model to the original L-THIA model (Ryu *et al.* 2016b; Figure 1).

Modules for direct runoff, baseflow and channel routing

In the direct runoff module of the L-THIA ACN-WQ model, direct runoff is calculated for each hydrologic response unit (HRU) using 52 asymptotic curve number equations by land covers and hydrologic soil groups (Equation (1)), and the direct runoff reached to a stream is then estimated using Equation (2).

$$Q^1_{DR,HRU} = \frac{(P - 0.2S)^2}{(P + 0.8S)}, P \geq 0.2S,$$
$$S = \frac{25400}{Adj\_CN_{HRU,ACN}} - 254 \quad (1)$$

where $Q^1_{DR,HRU}$ is the amount of direct runoff generated by an HRU for each day (mm), P is the rainfall (mm), S is the potential maximum retention (mm) and $Adj\_CN_{HRU,ACN}$ is adjusted CN value determined from asymptotic CN regression equations.

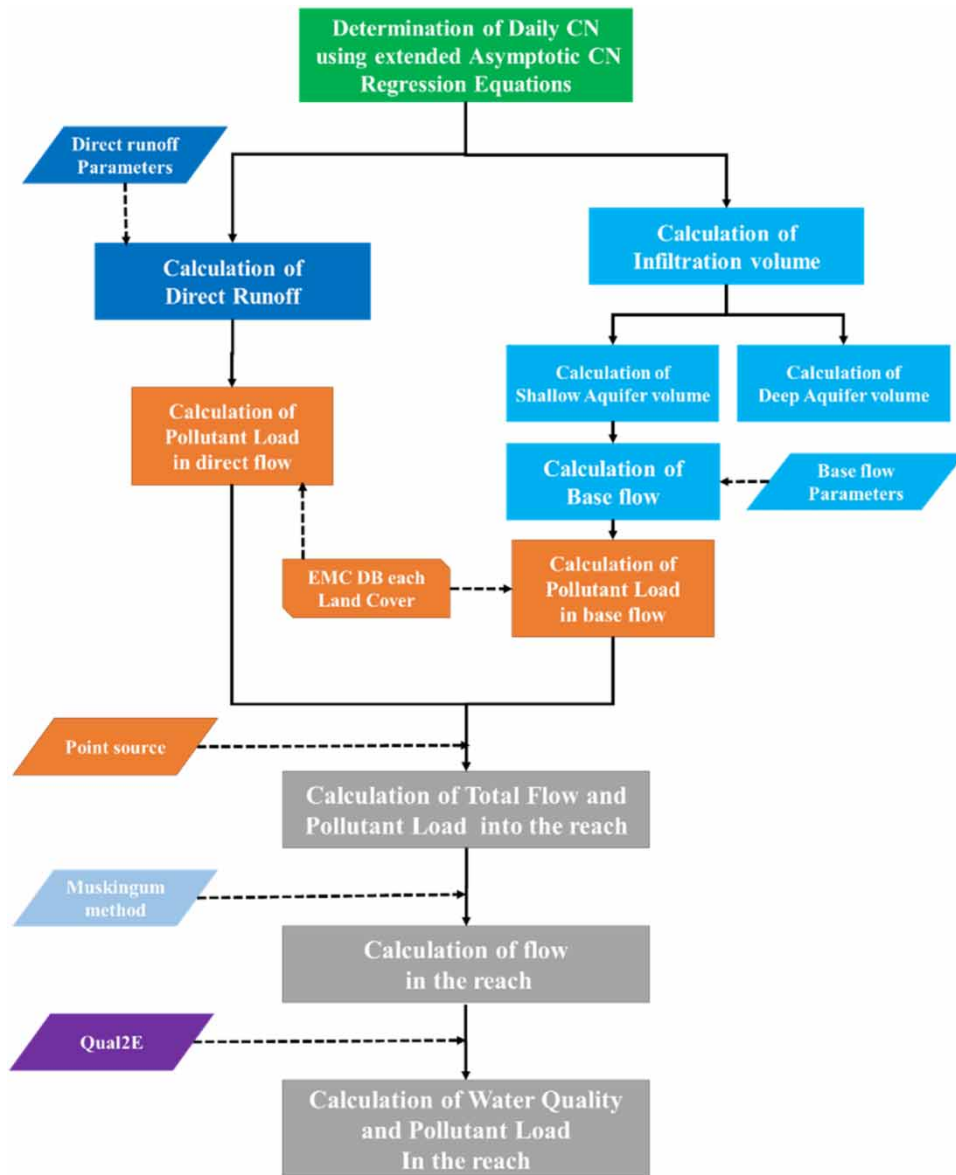$$Q_{DR,HRU} = (Q^1_{DR,HRU} + Q_{stor,i-1}) \times \left(1 - \exp\left[\frac{-DR_{lag}}{TC}\right]\right) \quad (2)$$

Figure 1 │ Flow diagram for L-THIA ACN-WQ model (Ryu *et al.* 2016b).

where $Q_{DR,HRU}$ is the amount of direct runoff discharged to the main channel on a given day (mm), $Q^1_{DR,HRU}$ is amount of direct runoff generated by the HRU on a given day (mm), Q_{stor} is the direct runoff lagged from the previous day, DR_{lag} is the direct runoff lag coefficient and TC is the time of concentration (h).

In the baseflow module, infiltration is calculated by Equation (3) transformed from the NRCS-CN method, and then the recharged water into aquifer and baseflow flowed into stream are estimated by Equations (4) and (5). Lastly,

streamflow is calculated using the MUSKINGUM method that is widely used in hydrology for stream routing.

$$F_{hru,i} = \frac{S(P - I_a)}{P - I_a + S}, \ I_a = 0.2S, \ S = \frac{25400}{Adj\_CN_{HRU,ACN}} - 254$$

(3)

where $F_{HRU,i}$ is the amount of infiltration on a given day (mm), S is the is the potential maximum retention (mm), P is the rainfall (mm), $Adj\_CN_{HRU, ACN}$ is the adjusted CN value determined from asymptotic CN regression equations

and I_a is the initial abstraction (mm).

$$\omega_{rchrg,HRU,i} = \left[1 - \exp\left(\frac{-1}{BF_{delay}}\right)\right] \times F_{HRU,i} + \exp\left(\frac{-1}{BF_{delay}}\right) \times \omega_{rchrg,HRU,i-1} \tag{4}$$

where $\omega_{rcharg,HRU,i}$ is the amount of recharge entering both aquifers on a given day (mm), BF_{delay} is the delay time in aquifer recharge once the water infiltrates from the surface (days), $F_{HRU,i}$ is the amount of infiltration on the given day (mm) and $\omega_{rcharg,HRU,i-1}$ is the amount of recharge that enters the aquifers on the

previous day (mm).

$$Q_{BF,HRU,i} = Q_{BF,HRU,i-1} \times \exp\left[-\alpha_{BF} \times \Delta t\right] + \omega_{unconf,HRU} \times (1 - \exp\left[-\alpha_{BF} \times \Delta t\right]), \text{ if } aq f > aq f_{thr}$$
$$Q_{BF,HRU,i} = 0, \text{ if } aq f < aqf_{thr} \tag{5}$$

where $Q_{BF,HRU,i}$ is the baseflow into the main channel on a given day (mm), $Q_{BF,HRU,i-1}$ is the baseflow into the main channel on the previous day, α_{BF} is the baseflow recession constant, $\omega_{unconf,HRU}$ is the amount of recharge entering the unconfined aquifer on the given day (mm), Δt is the time step (1 day), aqf is the amount of water

Table 1 | Description of direct runoff, baseflow, and channel routing parameters used in the streamflow (Ryu *et al.* 2016a)

Calibration component	Calibration parameter	Description of parameter	Range of parameter
Direct runoff	$Adj\_CN^{(1)}$	Adjusted coefficient for CN	−0.1–0.1
	$DR_{lag}^{(1)}$	Direct runoff lag coefficient	1–12
	$SLSUB^{(2)}$	Adjustment for slope length	−10–10
Baseflow	$\alpha_{BF}^{(1)}$	Baseflow recession constant	0.1–1.0
	$Fr_{conf}^{(1)}$	Fraction of water flowing into confined aquifer	0.0–0.9
	$aqf_{thr}^{(1)}$	Threshold water level in the unconfined aquifer for baseflow contribution (mm)	0.0–5000
	$BF_{delay}^{(1)}$	Delay time for aquifer recharge after water infiltration from surface (day)	1–10
Channel routing	$MK1^{(1)}$	Weighting factor for influence of normal flow on storage time constant value	0.1–0.9
	$Mk2^{(1)}$	Weighting factor for influence of low flow on storage time constant value	0.1–0.9
	$Mkx^{(1)}$	Weighting factor for Muskingum method	0.1–0.9

(1) constant value; (2) multiplied value.

Table 2 | Description of event mean concentration (EMC), nitrogen, and phosphorus parameters used in the calculation of pollutant loads module (Ryu *et al.* 2016b)

Parameter name	Description	Range	Default value
$Adj\_EMC_{DR,N}$	Constant value for adjustment of nitrogen in surface	−0.9–0.9	1.0
$Adj\_EMC_{BF,N}$	Constant value for adjustment of nitrogen in aquifer	−0.9–0.9	1.0
$Adj\_EMC_{DR,P}$	Constant value for adjustment of phosphorus in surface	−0.9–0.9	1.0
$Adj\_EMC_{BF,P}$	Constant value for adjustment of phosphorus in aquifer	−0.9–0.9	1.0
TN_ratio1[a]	Ratio of organic-N in total nitrogen	0.0–0.9	0.05
TN_ratio2[a]	Ratio of NO_3-N in total nitrogen	0.0–0.9	0.8
TN_ratio3[a]	Ratio of NH_3-N in total nitrogen	0.0–0.9	0.1
TP_ratio1[b]	Ratio of organic-P in total phosphorus	0.0–0.9	0.5

[a]Ratio of NO_2-N = 1 − (Sum of TN_ratio1, TN_ratio2 and TN_ratio3).
[b]Ratio of dissolved P = 1 − TP_ratio1.

stored in the unconfined aquifer on the given day (mm) and aqf_{thr} is the threshold water level in the unconfined aquifer for baseflow contribution to the main channel to occur (mm).

Modules for pollutant loads and water quality

The water quality module calculates pollutant loads for direct runoff and baseflow reached to stream using the improved

Table 3 │ Description of QUAL2E parameters (Ryu *et al.* 2016b)

Parameter name	Description	Recommended range in QUAL2E	Default value
RS1	Local algal settling rate in the reach at 20 °C	0.15–1.82	0.3408
RS2	Benthic source rate for dissolved phosphorus in the reach at 20 °C	0.001–0.1	0.1
RS3	Benthic source rate for NH_4-N in the reach at 20 °C	0.0–1.0	0.0
RS4	Rate coefficient for organic nitrogen settling in the reach at 20 °C	0.001–0.1	0.001
RS5	Organic phosphorus settling rate in the reach at 20 °C	0.001–0.1	0.08
RK1	Carbonaceous biological oxygen demand (*CBOD*) deoxygenation rate coefficient in the reach at 20 °C	0.02–3.4	0.3
RK2	Oxygen reaeration rate in accordance with Fickian diffusion in the reach at 20 °C	0.0–100.0	1.0
RK3	Rate of loss of *CBOD* due to settling in the reach at 20 °C	−0.36–0.36	−0.36
RK4	Benthic oxygen demand rate in the reach at 20 °C	0.0–100.0	0.0
BC1	Rate constant for biological oxidation of NH_4 to NO_2 in the reach at 20 °C	0.1–1	0.1
BC2	Rate constant for biological oxidation of NO_2 to NO_3 in the reach at 20 °C	0.2–2	0.2
BC3	Rate constant for hydrolysis of organic N to NH_4 in the reach at 20 °C	0.2–0.4	0.03
BC4	Rate constant for mineralization of organic P to dissolved P in the reach at 20 °C	0.01–0.7	0.1
RTH	Algal respiration rate at 20 °C	0.05–5.0	0.05
TFAC	Fraction of photosynthetically active solar radiation	0.0–1.0	0
MMX	Maximum specific algal growth rate at 20 °C	1.0–3.0	1.0
IG	QUAL2E algae growth limiting option (1: multiplicative, 2: limiting nutrient, 3: harmonic mean)	1, 2, 3	1
A0	Ratio of chlorophyll-*a* to algal biomass	10.0–100.0	10
A1	Fraction of nitrogen algal biomass	0.07–0.09	0.071
A2	Fraction of phosphorus algal biomass	0.01–0.02	0.003
A3	Rate of oxygen production per unit of algal photosynthesis	1.4–2.3	1.4
A4	Rate of oxygen uptake per unit of algal respiration	1.6–2.3	1.6
A5	Rate of oxygen uptake per unit NH_3-N oxidation	3.0–4.0	3.0
A6	Rate of oxygen uptake per unit NO_2-N oxidation	1.0–1.14	1.0
Lam0	Non-algal portion of the light extinction coefficient	0–10	0
Lam1	Linear algal self-shading coefficient	0.006–0.065	0.006
Lam2	Nonlinear algal self-shading coefficient	0–1	0
KN	Michaelis-Menten nitrogen half-saturation constant	0.01–0.3	0.01
KP	Michaelis-Menten phosphorus half-saturation constant	0.001–0.05	0.001
KL	Light half-saturation coefficient	0.223–1.135	0.223
Knb	Nitrification rate coefficient in $CBOD_5$	–	0.5
Kdb	Deoxidation rate coefficient in $CBOD_5$	–	0.5
PN	Preference factor for ammonium nitrogen	0.0–1.0	0.0

event mean concentration (EMC) DB by 13 land covers that are based on the long-term monitoring data provided by Korea Environment of Ministry. In turn, the calculated pollutant loads are used as the input data for QUAL2E, and instream water quality is then estimated by the simplified equations of QUAL2E. The QUAL2E model integrated into the L-THIA ACN-WQ model can consider the variation of instream water quality. The model parameters consist of 10 parameters for streamflow, eight parameters for EMC calculation and 33 parameters for the QUAL2E model (Tables 1–3).
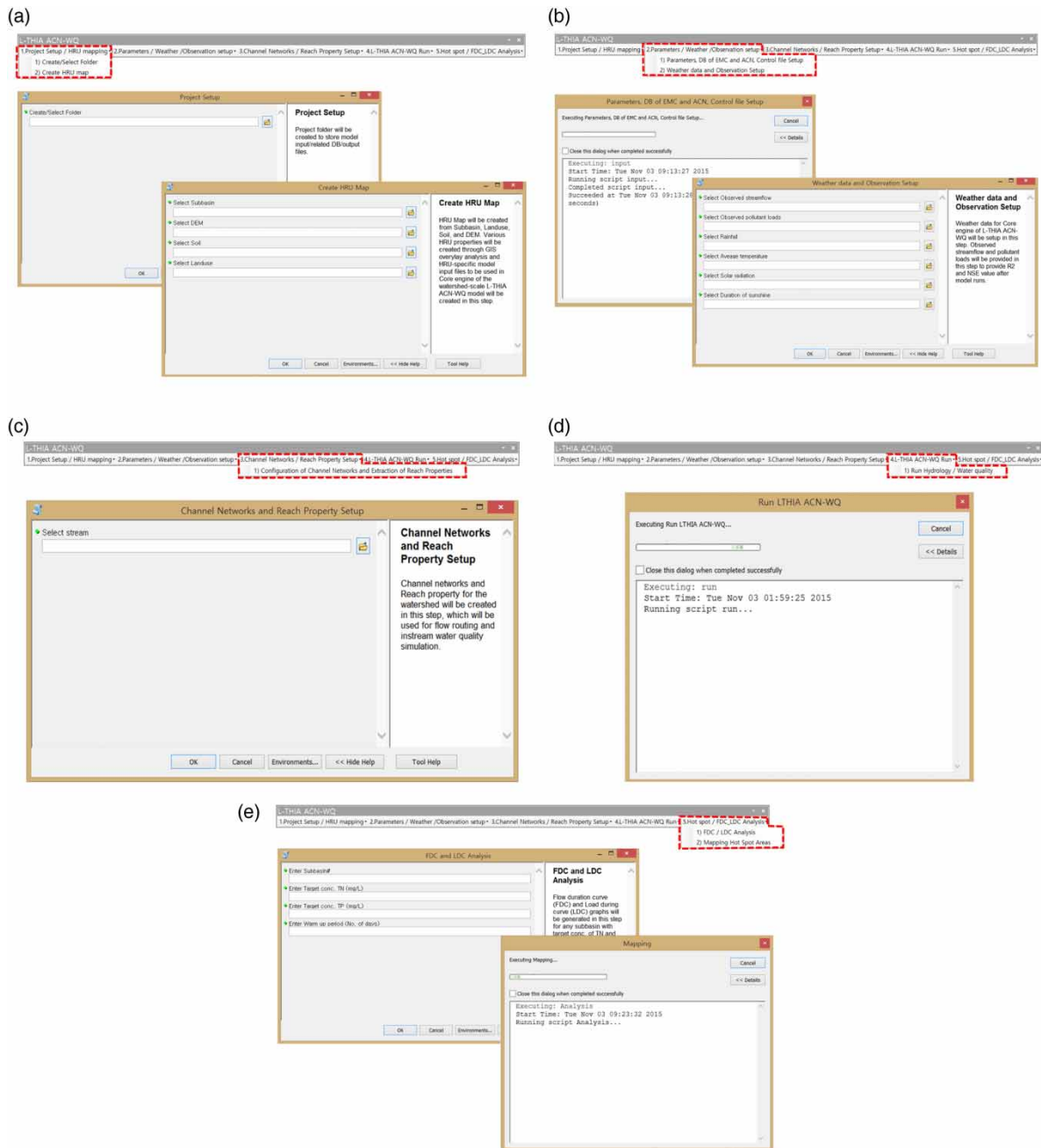
Figure 2 │ ArcGIS interface for L-THIA ACN-WQ system. (a) Setup of project folder and creation of HRU map. (b) Setup for parameters, related DB, and weather data. (c) Creation of channel routing files. (d) Operation model. (e) Post-process for analysis of FDC/LDC and mapping of hot spot areas.

Figure 3 │ Study watershed for evaluation of watershed-scale L-THIA ACN-WQ system in perspective of efficient watershed management tool. (a) Location of Banbyeon A watershed. (b) Land cover map of study watershed. (c) Soil map of study watershed.

Development of ArcGIS interface of watershed scale L-THIA ACN-WQ model

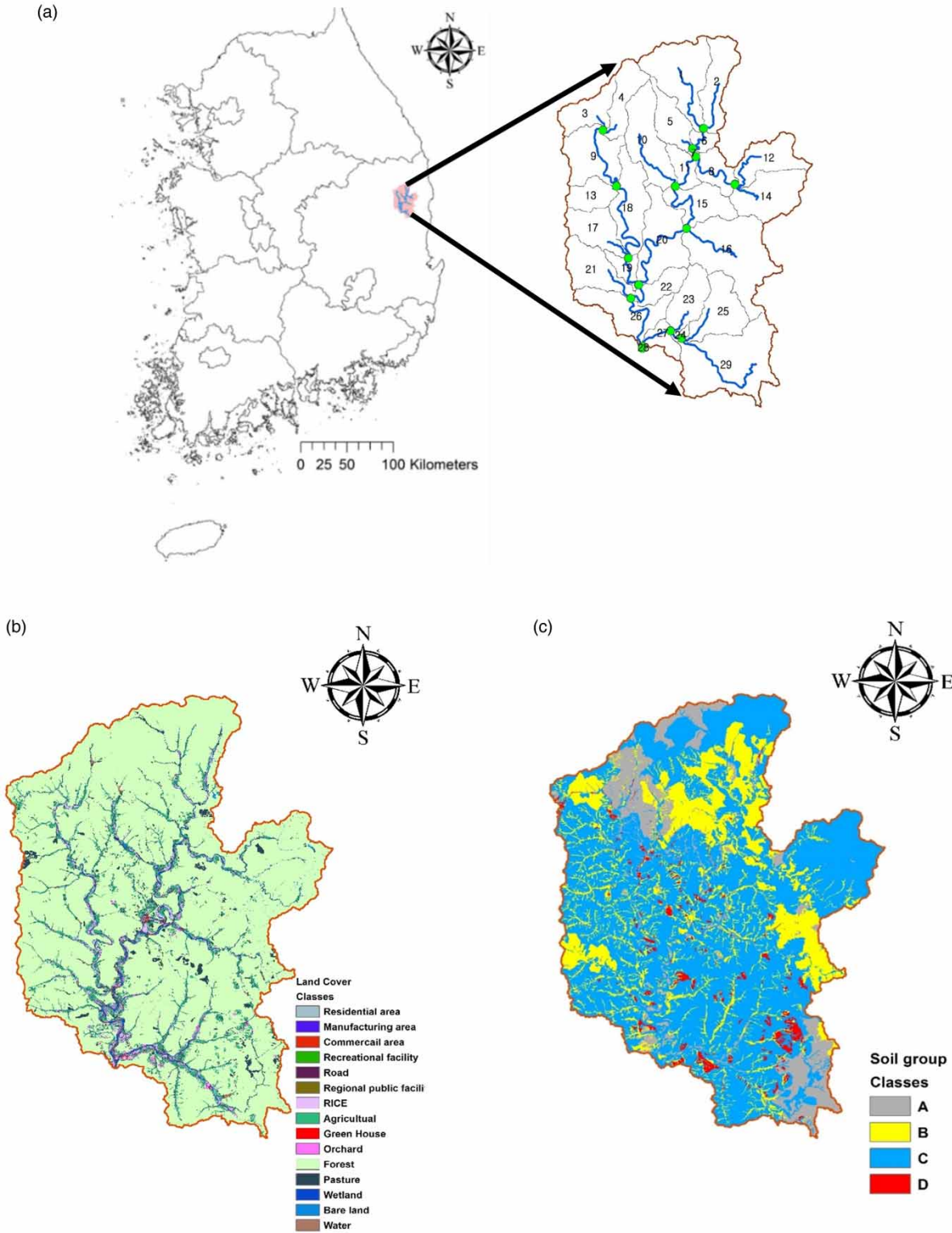In this study, the ArcGIS (version 10.1) interface was developed using the ArcPy GIS programming language, which is a Python site-package to provide useful and productive ways in various GIS applications (Dutta *et al.* 2014). Python programming language is used to automate computing task through programs. The language was created in the early 1990s by Guido van Rossum at Stichting Mathematisch Centrum (CWI, see http://www.cwi.nl/) in the Netherlands. All Python releases are Open Source (see http://www.opensource.org/ for the detail). The programming language has been widely used for general purpose as a high-level programming language. Recently, it was chosen for the ArcGIS platform as a scripting language.

ArcPy is a site-package of Python that helps to build successful ArcGIS scripting modules. Its goal is to create the script tools for performing geographic data analysis, data conversion, data management, and map automation using Python. ArcPy provides access to geoprocessing tools, additional functions, classes, and modules that allow the user to create simple or complex processes conveniently and easily (Dutta *et al.* 2014).

ArcPy, which is a very efficient programming language in GIS interface, has been used in various GIS applications. It has been used (Alam 2014) to extract sub-catchment, outfall, function, and conduit information in urban drainage modeling. Dahal and Chow used ArcPy to develop a module for automated partitioning urban lands in urban growth modeling (Dahal & Chow 2014). Jones *et al.* used ArcPy to develop the cloud-based MODFLOW model (Jones *et al.* 2015). As shown in these examples, ArcPy has been widely used to develop GIS interface in various hydrology and environmental modeling (Santos *et al.* 2014; Quan *et al.* 2015; Walsh *et al.* 2015).

The ArcGIS interface of the watershed-scale L-THIA ACN-WQ model consists of five parts in toolbar built with the ArcPy programming. The ArcGIS script developed using ArcPy can handle various special features with GIS input data (e.g. digital elevation map (DEM), soil, land cover, and stream). In addition, the parameters related to model DB files (e.g. parameters, asymptotic CN regression equations, control of system, EMC data) are generated through the ArcGIS script. The detailed processes are as following.

In the first part ('Project Setup / HRU Mapping' option in the toolbar), the L-THIA ACN-WQ project folder is created, and the basic computation unit of the model is prepared in this part (Figure 2(a)). Using the ArcGIS script, the HRU map is created based on subbasin boundary, land use, and hydrologic soil group map with DEM provided by model users. HRU information (e.g. area, slope, land cover, soil, stream length, Manning's n value and etc.) for each subbasin map is created from the HRU map in this step.

In the second part, the databases of model input parameters, asymptotic CN for each land use and hydrologic soil group, and EMC databases are built for the L-THIA ACN-WQ model run. In addition, system control file and weather data such as daily rainfall, mean temperature, and solar radiation for the duration of it are set up for the project run. When model users want to check the R^2 and NSE for the comparison of model estimates with observed data, this option could be set up in this step with changes of flag in the control file (Figure 2(b)).

In the third part, basic information of stream networks and reach properties (e.g. length, width, depth, slope, and Manning's n value of reach segment) for flow routing are automatically generated from GIS-based stream networks and watershed information in the project folder in this step (Figure 2(c)).

In the fourth step, the core engine of L-THIA ACN-WQ is run with input data sets for hydrology and water quality simulation at a watershed (Figure 2(d)).

Lastly, two options are provided in this part. To generate FDC and LDC for a watershed of interest, the FDC/LDC options were developed in this option, and model users can find hot spot areas easily with the second option provided in this step (Figure 2(e)).

Table 4 │ Water quality standard in the stream (MOE 2012)

Level	pH	BOD (mg/L)	COD (mg/L)	TOC (mg/L)	SS (mg/L)	DO (mg/L)	TP (mg/L)
I	6.5–8.5	1.0	2.0	2.0	25	7.5	0.02
Ia	6.5–8.5	2.0	4.0	3.0	25	5.0	0.04
II	6.5–8.5	3.0	5.0	4.0	25	5.0	0.1
III	6.5–8.5	5.0	7.0	5.0	25	5.0	0.2
IV	6.0–8.0	8.0	8.0	6.0	100	2.0	0.3
V	6.0–8.0	<10.0	<11.0	<8.0	–	>2.0	>0.5
VI	–	>10.0	>11.0	>8.0	–	<2.0	<0.5

(a)

(b)

HRUMAP.csv

```
FID_SUBS1,OID_,SUBBASIN_,LUCODE,SOLCODE,ARSLP,TOT_WATER,SUB_FR,HRU_FR,HRU_SLP,OV_N,SCH,C_S_L
0,1,1,11,3,14224600.0,660.4875,0.0635598705502,0.0215365165881,0.44055300951,0.1,14.7829664403,0.152392563243
1,2,2,11,3,9876800.0,660.4875,0.0380623403168,0.0149538030621,0.374303996563,0.1,12.3016460967,0.152392563243
2,3,3,11,3,2853700.0,660.4875,0.0285034917391,0.00432059652908,0.376752018929,0.1,8.35050865276,0.152392563243
3,4,4,11,3,5199200.0,660.4875,0.0285539090445,0.00787176138837,0.46164599061,0.1,10.3208387387,0.152392563243
4,5,5,11,3,2469200.0,660.4875,0.0275809913132,0.00373845076553,0.415587991476,0.1,10.2916460967,0.152392563243
5,6,6,11,3,614599.999999,660.4875,0.00853006302163,0.000930524801755,0.361995011568,0.1,5.30646752982,0.152392563243
6,7,7,11,3,33199.9999998,660.4875,0.00106693919264,5.02659020796e-05,0.138494998217,0.1,1.45474134086,0.152392563243
7,8,8,11,3,1807200.0,660.4875,0.0217189575881,0.00273616079033,0.346259981394,0.1,9.34690475583,0.152392563243
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9,10,10,11,3,5237200.0,660.4875,0.0531493783001,0.00792929464979,0.379952013493,0.1,15.1750984746,0.152392563243
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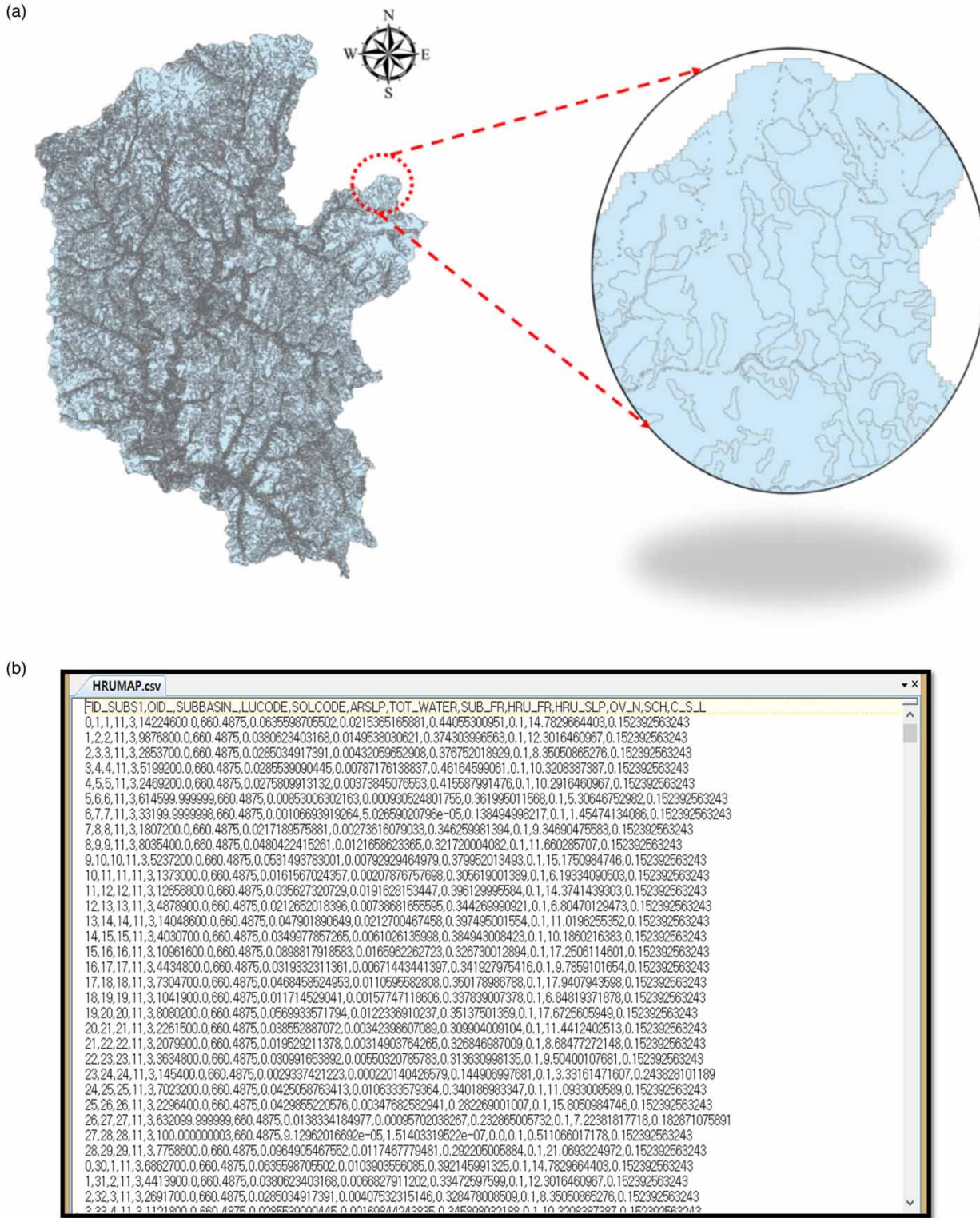
Figure 4 | HRU map and text file for HRU information. (a) HRU map created with ArcGIS-based interface. (b) HRU information to be used as input to the model.

Application of the ArcGIS based watershed-scale L-THIA ACN-WQ system

The ArcGIS based watershed-scale L-THIA ACN-WQ system was applied to the Banbyeon A watershed to evaluate its applicability in perspective of watershed environment management. The study watershed is located in Imha basin and designated as the primary non-point source (NPS) pollution hot spot area from 2007 to 2014 by the Ministry of Environment (MOE) in South Korea (Figure 3(a)). The TMDL target pollutant is sediment with the aim of sediment reduction by less than 50 NTU (Nepthelometric Turbidity Unit). Streamflow and water quality samples were also monitored every 8 days by the MOE.

Area of the Banbyeon A watershed is 660.5 km2. The dominant land uses are forest (83.8%) and agricultural (8.5%) with additional land uses of pasture (4.0%), water (1.7%), urban (1.3%), and bare land (0.6%) as shown in Figure 3(b). Agricultural areas are located at downstream areas in the Banbyeon A watershed. The average slope is 21.0%, and the HSG is composed of A (10.9%), B (21.1%), C (65.8%) and D (2.2%) (Figure 3(c)).

In this study, the streamflow and pollutant loads (total nitrogen (TN) and total phosphorus (TP)) were calibrated using the ArcGIS based watershed-scale L-THIA ACN-WQ system for the simulation period (from 2010 to 2014 including 1-year warming-up). In order to evaluate the excess rates of pollutant loads to water quality standard decided by the MOE under various flow regime, the long-term simulation of streamflow and pollutant loads estimation with calibrated parameters were analyzed using FDC and LDC module developed in this study. The FDC/LDC analysis revealed that how much/often the pollutant loadings at the watershed exceeded target pollutant load, which is calculated by multiplying the FDC and target concentration of pollutant. The LDC results could be used to determine best management practices (BMPs) with
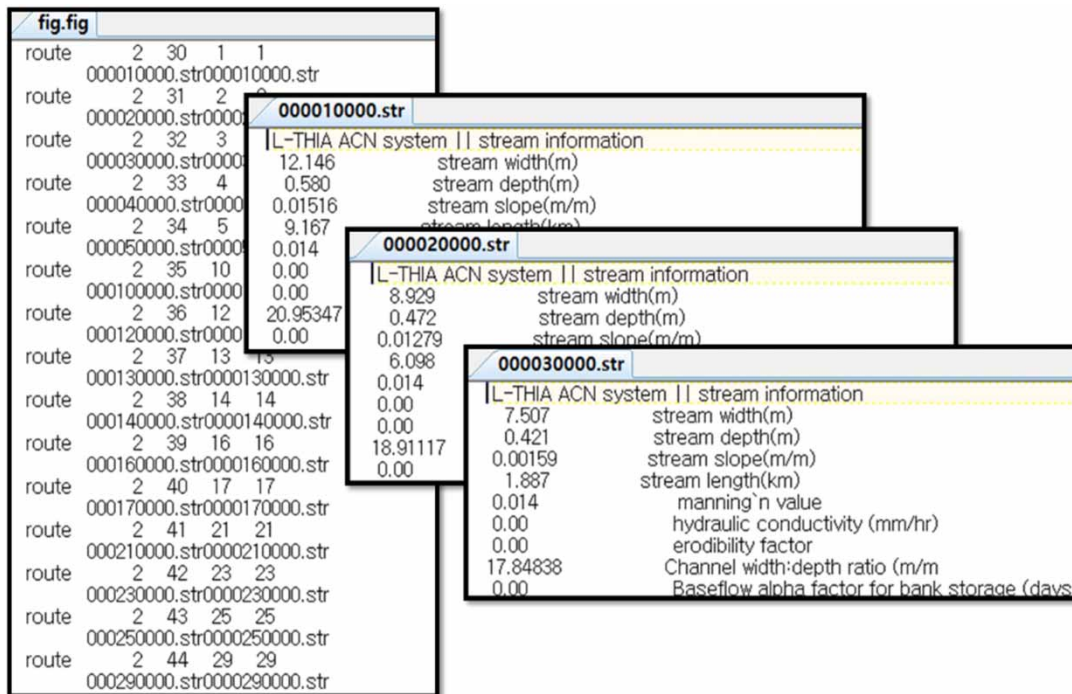
Figure 5 | Text files of figuration and specific attribute for stream.

Table 5 | Calibrated parameters for streamflow

Adj_CN	SLSUB	DR_{lag}	α_{BF}	aqf_{thr}	Fr_{conf}	BF_{delay}	Mk1	Mk2	Mkx[1]
0.0	1.0	9	0.7	100.0	0.4	1	0.05	0.95	0.1

Table 6 │ Calibrated parameters for water quality

Parameters	Value	Parameters	Value
$Adj\_EMC_{DR,N}$	0.55	BC4	0.35
$Adj\_EMC_{BF,N}$	0.75	KdN	0.03
$Adj\_EMC_{DR,P}$	0.90	KdD	0.045
$Adj\_EMC_{BF,P}$	0.70	TFAC	0.30
TN_ratio1	0.05	MMX	1
TN_ratio2	0.84	IG	1
TN_ratio3	0.01	A0	90
TP_ratio1	0.38	A1	0.09
RS1	1.00	A2	0.001
RS2	0.05	A3	1.60
RS3	0.50	A4	2
RS4	0.05	A5	3.50
RS5	0.05	A6	1.07
RS6	2.50	Lam0	1
RK1	1.71	Lam1	0.03
RK2	50	Lam2	0.054
RK3	0.36	KN	0.02
RK4	2.00	KP	0.025
.0RK5	2.00	KL	0.75
RK6	1.71	Knb	0.5
BC1	0.55	Kdb	0.5
BC2	1.10	PN	0.50
BC3	0.21		

visual analysis of exceedance of pollutant loads over target values over a range of flow regime. The FDC/LDC module was applied with estimated flow and pollutant loads from the study watershed.

The target water quality standard for the Banbyeon A watershed was designated based on 'drinking water (Ia)' standard by the MOE, Korea (Table 4; MOE 2012). The target water quality of TN was assumed as that of biological oxygen demand (BOD) (MOE 2012) since the water quality standard of TN has not been established for this watershed. The target water quality of TN and TP were determined as 2.0 mg/L and 0.04 mg/L, respectively. The flow conditions were categorized into the low-flow (95%), dry-condition (75%), mid-range flow (50%) and high flow (15%).

In addition, subbasins were ranked based on the amount of pollutant loads per unit area and visualized based on pollutant ranking at subbasins.

RESULTS AND DISCUSSION

Development of ArcGIS based watershed-scale L-THIA ACN-WQ system

The ArcGIS based watershed-scale L-THIA ACN-WQ system was developed using ArcPy programming language
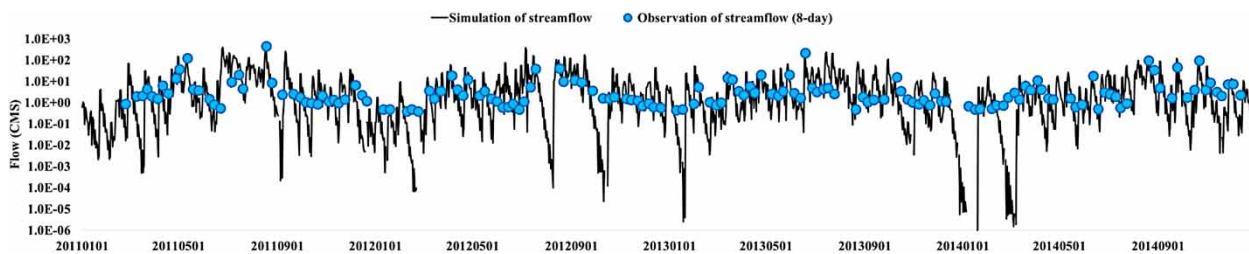
Figure 6 │ Comparison of simulated and 8-day interval observed streamflow (2011–2014).
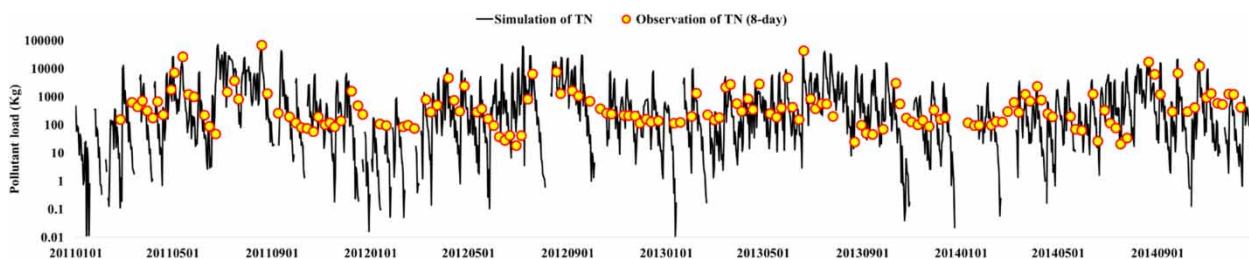
Figure 7 │ Comparison of simulated and 8-day interval observed TN (2011–2014).

to provide user-friendly interface of watershed-scale L-THIA ACN-WQ model, which does not provide any kind of user interface to construct input data and pre-process the data. Using the automated GIS-based system, users can easily create HRU maps using GIS input data (e.g. DEM, soil, land cover, and stream) (Figure 4), and the required parameters and related model DB files (Parameters, asymptotic CN regression equations, control of system, EMC data) are generated automatically from this ArcGIS-based interface/system.

Furthermore, configuration and specific attribute of streams can be extracted from GIS data collected by users and converted into text files to be used in the watershed-scale L-THIA ACN-WQ model automatically (Figure 5). User can install the ArcGIS based watershed-scale L-THIA ACN-WQ system easily in the ArcGIS 10.1 software by adding the 'ESRIaddin' file.

Calibrating parameters and estimating streamflow and pollutant loads

Prior to evaluation of the ArcGIS based watershed-scale L-THIA ACN-WQ system for FDC/LDC analysis at ungauged watershed and hot spot mapping, the streamflow and water quality components in the system were manually calibrated with observed 8-day interval flow and water quality data collected in the Banbyeon A watershed. The results of calibrated parameters for streamflow and water quality components are shown in Tables 5 and 6.

The simulated 4-year averaged streamflow in the watershed was 12.5 m^3/s indicating -14.4% difference compared to the observation (R^2 and NSE values of 0.8 for both) (Figure 6). For pollutant loads, 4-year average TN load was

1,878.0 kg/day. The simulated TN load were lower than observed TN by -0.9% with R^2 and NSE values were 0.76 and 0.75, respectively (Figure 7). In the case of TP, the estimated average loads were 84.5 kg/day with -0.3% difference with R^2 and NSE values were 0.65 and 0.56, respectively (Figure 8). These comparisons indicated that the ArcGIS based watershed-scale L-THIA ACN-WQ system predicts streamflow and pollutant loads successfully with higher accuracies although very limited input data are needed to operate the system (33 instream water quality parameters are not sensitive to the water quality prediction at the watershed outlet).

FDC and LDC analysis

The streamflow and pollutant loads simulated with the calibrated parameters (Tables 5 and 6) are used to derive the FDC/LDC curves. The LDC analysis showed how much/ how often pollutant loads exceeded the target pollutant loads under various flow regimes. These results could be used to determine site-specific BMPs under various flow conditions (i.e., low-flow, dry-condition, mid-range flow, and high-flow).

As shown in the FDC (Figure 9(a)), average streamflow for the four flow conditions (Low-flow, dry-condition, mid-range flow, and high-flow) were 0.01 m^3/s, 0.08 m^3/s, 4.61 m^3/s and 69.70 m^3/s, respectively. The LDC graph of TN generated by multiplying the FDC by target TN water quality standard showed that the estimated pollutant loads were lower than the target pollutant loads in the low flow and dry-condition, while these exceeded the target pollutant loads in the mid-range flow (8%) and high flow (45%). In the case of TP, the estimated pollutant loads exceeded the target pollutant loads in the low
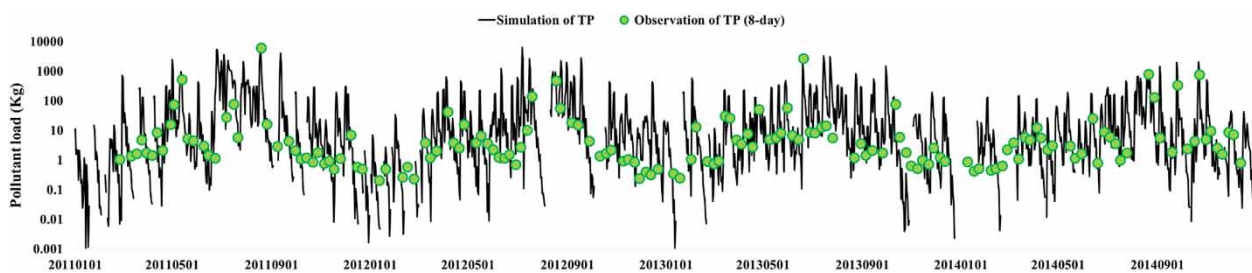

Figure 8 │ Comparison of simulated and 8-day interval observed TP (2011–2014).
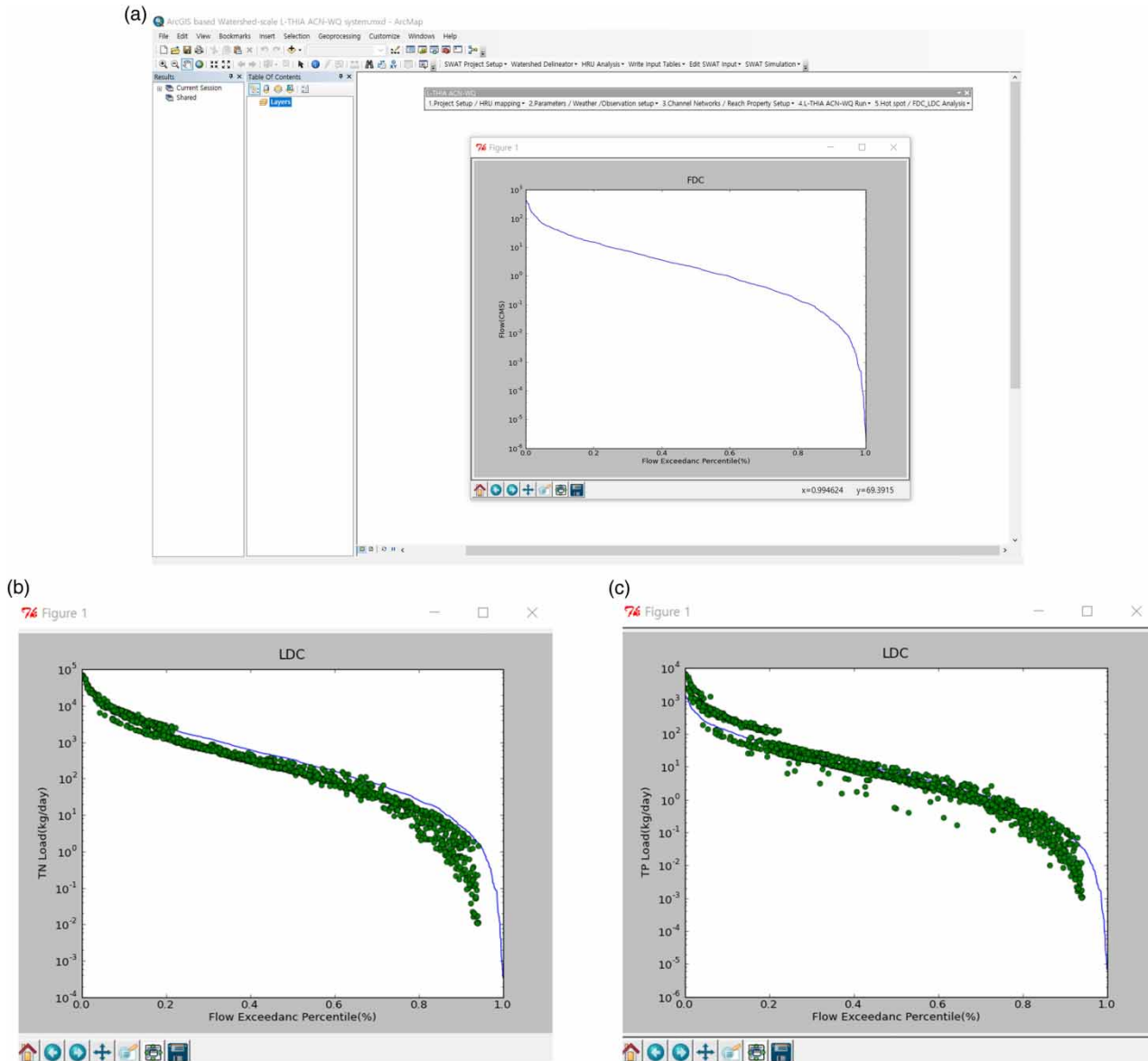
Figure 9 │ FDC and LDC generated using ArcGIS interface at the outlet of study watershed. (a) Flow duration curve. (b) Load duration curve (TN). (c) Load duration curve (TP).

flow (8%), mid-range flow (24%) and high flow (88%) (Figure 9(b) and 9(c)).

Based on this finding, it can be inferred that managements of nutrients through establishing appropriate NPS pollution reduction strategy targeting high flow condition are needed in the Banbyeon A watershed, because TN and TP exceeded significantly the water quality standard of drinking water in the high-flow season (45–88%).

Ranking subbasins based on pollutant load per unit area

The system ranked subbasins based on the pollutant loads per unit area. In this study, the pollutant loads (BOD, TN, and TP) were ranked in the ArcGIS interface (fifth option in the watershed-scale L-THIA ACN-WQ system toolbar), and the pollutant load ranking map was generated to provide the hot spot subbasin to decision makers. Subbasins which are discharging more nutrients were ranked (Figure 10), and
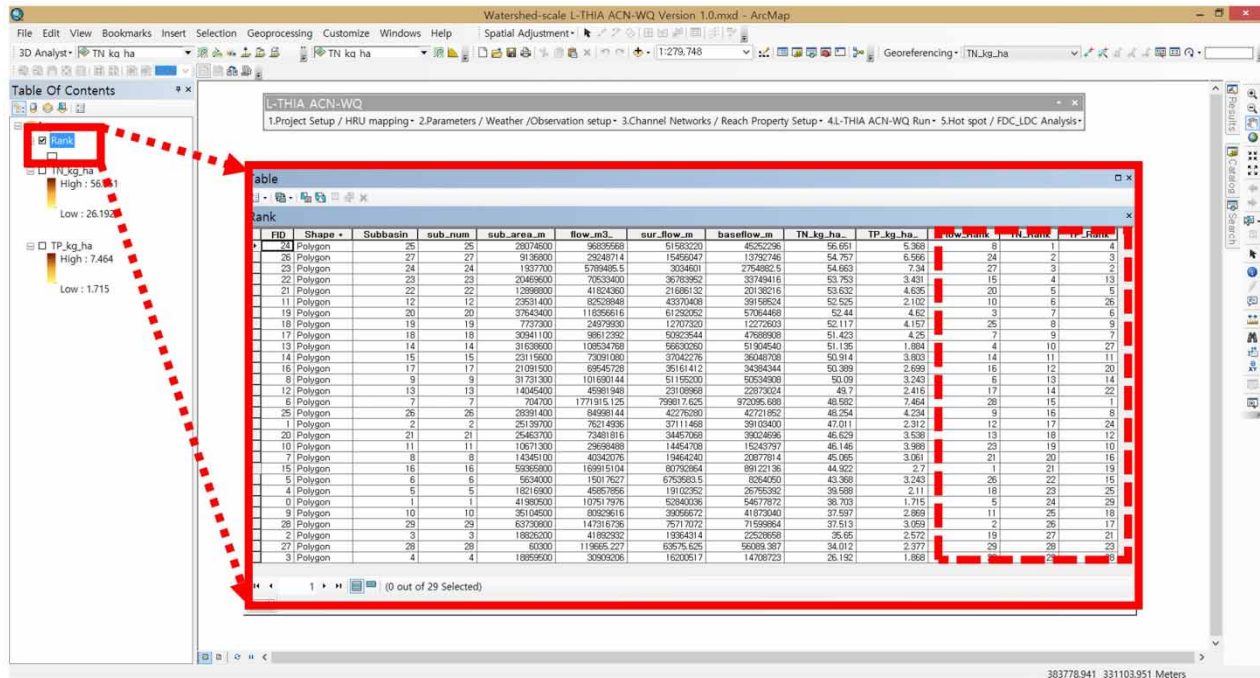
Figure 10 | List of subbasins in order of degree of nutrient discharge per unit area.

the five subbasins (#25, #27, #24, #23, and #22 for TN, and in #7, #24, #27, #25, and #22 for TP) were selected as the hot spot subbasins for nutrient in the Banbyeon A watershed.

It was found that paddy, upland, and orchard occupy the majority of land uses in subbasins #24, #25, and #27. For these subbasins, nutrients discharged from agricultural areas need to be reduced by establishing appropriate agricultural related BMPs.

With the post-processing module (Mapping of Hot Spot Are option in fifth menu) of the watershed-scale L-THIA ACN-WQ system, the TN and TP loading per unit area maps were generated (Figure 11) with the ranking information. Figure 11 showed that pollutant loads were greater in agriculture dominant subbasins located in downstream areas.

CONCLUSIONS

In this study, the ArcGIS based interface of the watershed-scale L-THIA ACN-WQ model was developed using the ArcPy programming language. This interface was designed to construct HRU maps efficiently and to build various

model parameters, channel routing information, and database used in the ArcGIS based watershed-scale L-THIA ACN-WQ system. The ArcGIS based system was applied for streamflow and water quality simulation in the Banbyeon A watershed, and it was further evaluated by analyzing FDC/LDC and pollutant hot spot areas using the post-processing module of the L-THIA ACN-WQ system. These analyses showed that the ArcGIS-based system could be used in various TMDL studies, as well as streamflow and pollutant loadings estimation spatially.

Additional input parameters are needed for the ArcGIS-based watershed-scale L-THIA ACN-WQ system, compared with the original L-THIA system (Harbor 1994; Bhaduri *et al.* 1997; Engel 1997; Lim *et al.* 2006). However, it provides good estimations in streamflow and pollutant loadings with less input data required, compared with the complex SWAT and HSPF models.

The ArcGIS interface of the L-THIA ACN-WQ model developed in this study provides ease-of-use interface to build HRU information used in direct runoff and baseflow estimation, various parameters, databases of EMC and asymptotic CN regression equations, control file, and weather data with observation data, if needed. The ArcGIS
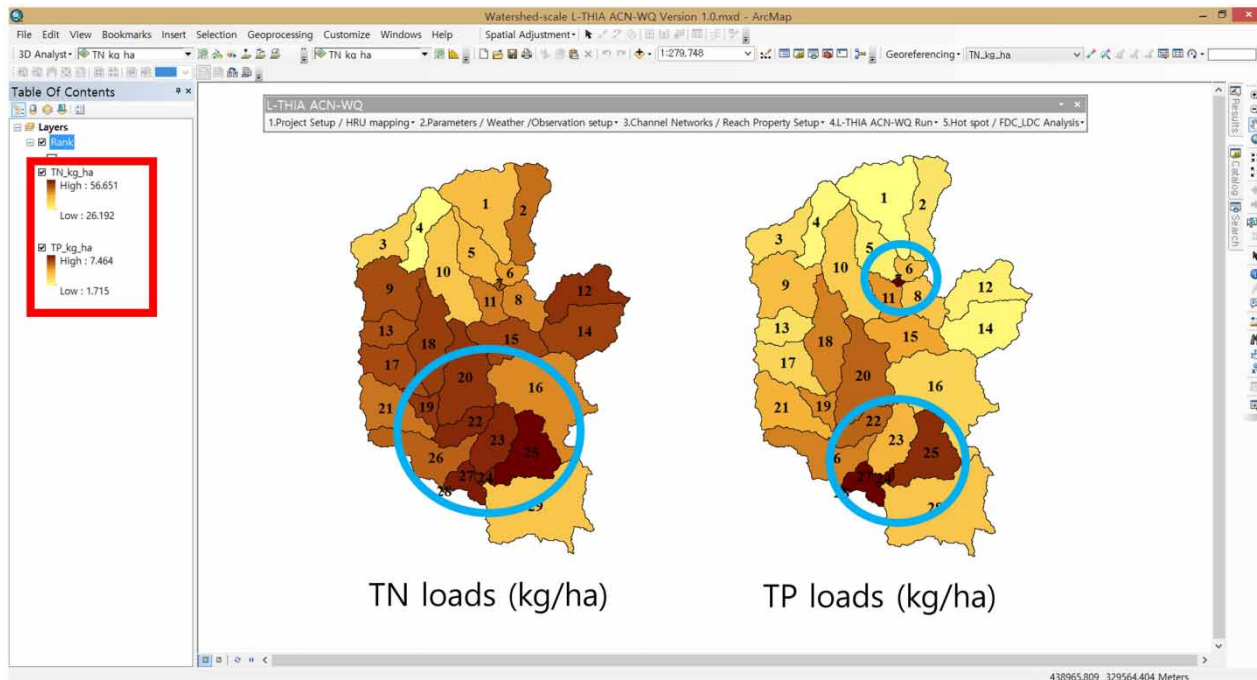
Figure 11 │ TN and TP pollutant loading maps generated with ArcGIS-based interface.

interface also provides an option to automatically configure stream networks for flow and water quality routing with a couple of post-processors for further analysis of model simulated results. The watershed-scale L-THIA ACN-WQ model provides these functionalities to environment-related decision makers with ease-of-use interface. Thus, the L-THIA ACN-WQ system could be used in various TMDL or other NPS management studies.

Currently, the watershed delineation tool is not provided in the ArcGIS interface of watershed-scale L-THIA ACN-WQ system. The tool will be included in the system in the near future.

ACKNOWLEDGEMENTS

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