Development of load duration curve system in data-scarce watersheds based on a distributed hydrological model

Jia Wang, Xin-hua Zhang, Chong-Yu Xu, Hao Wang, Xiao-hui Lei, Xu Wang and Si-yu Li

ABSTRACT

Many developing countries and regions are currently facing serious water environmental problems, especially the lack of monitoring systems for medium- to small-sized watersheds. The load duration curve (LDC) is an effective method to identify polluted waterbodies and clarify the point sources or non-point sources of pollutants. However, it is a large challenge to establish the LDC in small river basins due to the lack of available observed runoff data. In addition, the LDC cannot yet spatially trace the specific sources of the pollutants. To overcome the limitations of LDC, this study develops a LDC based on a distributed hydrological model of the Soil and Water Assessment Tool (SWAT). First, the SWAT model is used to generate the runoff data. Then, for the control and management of over-loaded polluted water, the spatial distribution and transportation of original sources of point and non-point pollutants are ascertained with the aid of the SWAT model. The development procedures of LDC proposed in this study are applied to the Jian-jiang River basin, a tributary of the Yangtze River, in Duyun city of Guizhou province. The results indicate the effectiveness of the method, which is applicable for water environmental management in data-scarce river basins.

Key words | best management practices (BMPs), data-scarce watersheds, load duration curve (LDC), Soil and Water Assessment Tool (SWAT), total maximum daily load (TMDL)

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INTRODUCTION

Total maximum daily load (TMDL) of pollutants is employed to quantify total assimilative loads, to identify impaired waterbodies, to build the regulatory benchmarks for water quality control, and to improve the water environment by formulating best management practices (BMPs) (Bonta 2002). After the official approval of TMDL by the Clean Water Act in the United States in 1972, this method has rapidly developed and is widely used throughout the world. Allowable loads of pollutants based on the relevance of pollution source and water quality are an important aspect of the TMDL planning process (US EPA 1991). It is necessary to consider the seasonal variations of water quality for specific pollutants. The load duration curve (LDC) is an effective visualized analytical tool for TMDL to present water quality data, which can describe the water environmental situation and patterns of impairment. It is also a simple, straightforward, and useful way to address assimilative capacity, which is significantly affected by flow (Shen & Zhao 2010). Cleland (2002, 2003) expounded the significance and relative theory of LDC. Cheng (2008) and Johnson *et al.* (2010) applied this method in the Erhai and Texas basins, respectively, to estimate pollutant capacity and identify impaired waterbodies. Chen *et al.* (2011) proposed an approach of the combination of inverse modeling and LDC to express TMDL by temporal variation. Kim *et al.* (2012) developed a system that can visualize real-time LDC.

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However, applications and studies of LDC are quite limited in developing countries and regions, where monitoring systems are not perfect or there is even a lack of monitoring. Usually, developing regions are relatively backward in economic development, or their remote geographical location is not conducive to development. With economic development, these areas inevitably suffer from water environmental sacrifice. In order to develop both the environment and economy, it is necessary to undertake serious monitoring of water quality to facilitate water environmental management. The challenges faced are technical difficulties, hard monitoring conditions, economic constraints, and so on, which lead to the lack of monitoring sites to provide observed data. Water quality monitoring equipment is expensive, and conventional water quality monitoring needs to monitor multiple sections twice a month, which results in economic burdens to the developing regions for this time-consuming, laborious, and costly task. For rivers located in plateaus, alpine areas, and remote mountainous areas with sparse populations and inconvenient transport, data monitoring is so difficult that monitoring frequency is low or there is no monitoring. Also, for special water bodies, such as those with large sediment content, ice, and other harsh water conditions, water quality monitoring technology is inadequate, which increases the difficulty of data monitoring.

First, using LDCs to estimate the water quality situation relating to the magnitude of flows, the present situation of water quality and water quality standards involves flow data and pollutant concentration. For developing regions, flows and water quality data are difficult to obtain, which impedes the establishment of LDC. For datasets with small sizes, Parrish (1990) and Dielman *et al.* (1994) compared various robust statistical methods to improve the efficiencies of estimating existing load. Morrison & Bonta (2008) and Babbarsebens & Karthikeyan (2009) tried to calculate minimum sample sizes required for estimating water quality of LDC. However, research on data-scarce watersheds is rather limited. Saunders & Grippo (2005) used flow information from neighboring gauges, drainage area ratios, and relative composite SCS curve to find the LDC of an ungauged site. Patil *et al.* (2013) extrapolated near real-time flow and water quality data by regression equations to complement data. Unthank *et al.* (2012) used TOPMODEL to obtain the necessary runoff data in ungauged sites.

Second, LDCs do not consider specific fate and transport mechanisms including sediment decreasing, nutrient up-take by plants, and chemical transformations, which may depend on watershed or pollutant characteristics (Shen & Zhao 2010; Luo & Zhang 2017). Thus, LDCs cannot be applied directly to judge the origins of the pollutants, i.e., agricultural practices or other human activities. These curves can only be used as a guide for the efforts of pollutant load reduction in a watershed, while they are not suitable to conduct BMPs. LDCs only consider the process of dilution water, using just hydrological data, and ignore hydraulic data such as velocity, section channel shape, slope, roughness, and discrete coefficient, etc. (Alexander *et al.* 2000). The capacity distribution characteristics of a river reach can be investigated directly from LDCs, since flow plays a significant role in determining the contaminant load.

Lastly, the assimilative capacity is calculated by LDCs at specific sections corresponding to the flow. The flow of the section is influenced by inflowing water in the upstream of the watershed, and the assimilative capacity at the section is an accumulative value, which is the sum of the whole river reach/control units of the upstream section. If the river crosses different administrative areas, the problem of ecological compensation may be involved. Thus, the governments of relative regions need to be clear about the assimilative capacity of the river reach/control units, and the inflow and outflow loading of their jurisdiction. Therefore, the contradiction between the whole and part reach/control units assimilative capacity arises.

Due to the above challenges, practitioners should consider supplementing LDCs with other tools, i.e., water quality models or hydrological models based on physical processes (Park & Roesner 2012). The introduced tool should be employed to assess allocation scenarios, track pollutant sources or source categories, and evaluate the effectiveness of restoration. Currently, there is wide utilization of watershed models, for example, the Soil and Water Assessment Tool (SWAT). The model has been successfully applied in many watersheds globally, including North Bosque watershed (Saleh *et al.* 2000), Rwer basin (Santhi *et al.* 2001), Vantaanjoki watershed (Grizzetti *et al.* 2003), Huron and Raisin watersheds (Bosch 2008), and so on. It is often used in data-scarce areas to obtain more streamflow and water quality data for analysis of modeling impacts of climate change (Candela *et al.* 2012; Liang *et al.* 2018; Da Silva *et al.* 2018; Li *et al.* 2019), sediment yields' simulation (Bieger *et al.* 2012), dynamic analysis of pollution fluxes (Woodward *et al.* 2013), and critical erosion watersheds (Kumar *et al.* 2015). Also, it can effectively identify critical source areas and simulate complex processes including flow, sediment, and pollutants, because it includes land cover, topography, soil characteristics, and land use (White *et al.* 2009), with the aid of meteorological data (Gitau *et al.* 2008; Lamba *et al.* 2016). Furthermore, it is often applied to assess the impact of BMPs in order to obtain intended water quality requirements (Arabi *et al.* 2008; Ullrich & Volk 2009) according to water environmental assimilative capacity, which can be calculated by the developed LDCs.

Limited work has been done to develop LDCs with the aid of hydrological models for studying the pollutant source impairment of BMPs for data-scarce watersheds. Therefore, the purpose of this study is to propose an appropriate approach, which applies the developed LDCs to estimate and analyze the pollutant load exceedance. At the same time, by calculating water environmental assimilative capacity, administrators can control pollution discharge and strengthen the management of the water environment.

METHODOLOGY

Development of LDCs

The LDC method has been widely used in total pollution control in the United States (Singh *et al.* 2004). LDC represents pollutant loading capacity, which is the greatest amount of loading that an upstream water at a specific site or a cross section of the river can receive without violating water quality standards at different flow regimes (Lacy 2000). Using LDCs to realize dynamic management is an important tool in the TMDL plan. The LDC approach is a visual tool that delineates the assimilative capacity and water quality data at different flow zones. By using the developed LDC framework, the maximum allowable loading, the frequency and magnitude of water quality standard exceedances, and the decrement of contaminant load become more obvious and better understood. There are some advantages of LDCs that consider the hydrologic condition of watersheds, enhance assessments of pollutant sources, and provide a meaningful relation between allocations and management targets.

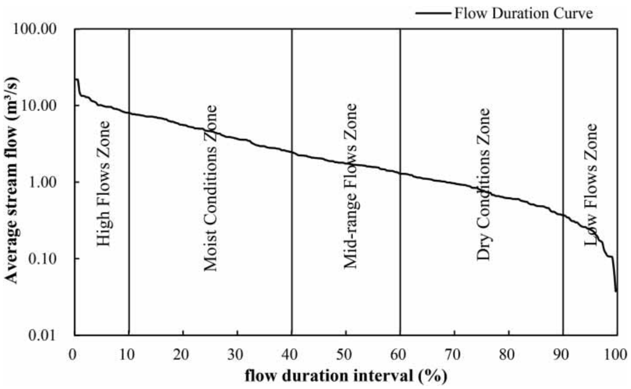

Figure 1 | Flow duration curve and flow duration intervals.

The key step of the method is to establish the flow duration curves (FDCs). The changes in flow regime may affect both point and non-point source loads of contaminant in a stream. The US Environmental Protection Agency divides FDCs into different flow duration intervals (FDI) based on seasonal variation of flows. Generally, FDCs are divided into five zones, as illustrated in Figure 1, which are high flows (0–10%), moist conditions (10–40%), mid-range flows (40–60%), dry conditions (60–90%), and low flows (90–100%). These hydrologic classes facilitate diagnosis and analyze the sources of pollutants in rivers.

The steps to establish LDC are as follows, and a schematic figure of LDCs is shown in Figure 2.

Step 1. Create the FDC of the control section in a river basin. The FDC can be built by ranking the flow discharge

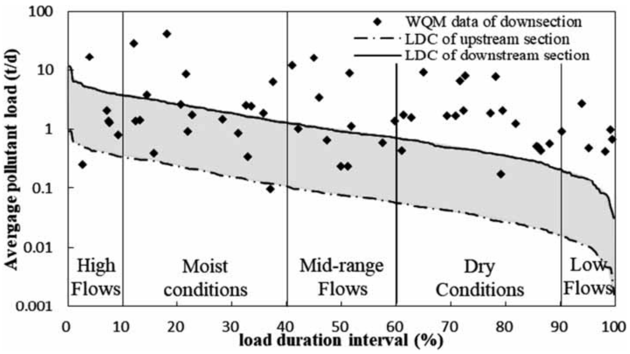

Figure 2 | Schematic figure of LDCs.

Q from the highest to the lowest according to the flow data. In the data-scarce area, Q can be generated by a hydrological model such as the SWAT model.

Step 2. Change FDC into LDC. In lieu of flow in FDC, the ordinate of the vertical axis is expressed in terms of contaminant load (t/month). The allowable load equals the permitted pollutant concentration of the corresponding control section, multiplying by each ordinate of FDC. Use allowable load and the corresponding guarantee rate of one-to-one relation to create the allowable load frequency curve and then get a LDC curve.

Step 3. Add the upstream LDC into the current LDC of the control section to get the assimilative load capacity. There is a shaded part between LDCs of the upstream and current control section, which is the assimilative capacity of the river reach/control unit.

Step 4. Control and allocation of total pollutant amount. Plot the monitored contaminant load on the graph of LDCs. By comparing the location between the measured load and the allowed load in the current LDC, we can judge current water quality status in the specific site of a river. If the current pollutant load is located above the LDC, which means current load exceeds the allowed load according to the water quality criterion, the control of the load is necessary and the exceeded load should be allocated.

SWAT model

The SWAT model, developed by USDA-ARS (Knisel 1980), is a semi-distributed, physically based hydrological and water quality model (Arnold *et al.* 2012). The model can be used to predict runoff, soil erosion, and water quality under various soil, land use, climate conditions, and human activities (Arnold *et al.* 1995). The advantages of this model are that it has strong physical mechanism, high computational efficiency and high accuracy, and it can be applied to data-scarce watersheds. The SWAT model divides the study basin into sub-basins by spatial differentiation. They are composed of a number of hydrological response units (HRUs), which are the smallest units with homogenous land use, soil, and slope in hydrological simulation. Digital elevation model (DEM), land use, soil, weather, point source, etc. should be provided as primary inputs in the model.

The model is driven by water balance. The hydrological processes of the SWAT model include land and channel phases. Consistency between the hydrological cycle and the actual situation of the basin is the basic guarantee for accurately simulating the movement process of pesticide, sediment, or pollution load. The water balance in each HRU is calculated using the Soil Conservation Service's Curve Number (SCS-CN) (Mockus 1969) or the Green & Ampt (1911) infiltration equation (Parajuli *et al.* 2010). The process is based on precipitation, evapotranspiration, infiltration, surface runoff, subsurface flow, ground water returns, and river transport loss.

Soil erosion and sediment in HRUs are calculated using Modified Universal Soil Loss Equation (MUSLE). The nutrient migration in water, especially for non-point source pollution, is closely related to soil erosion. After the erosion of rainfall, the pollutants in soil, which adhere to the surface of sediment particles, flow into the river with runoff.

There are various ways in which the pollutants flow into the river: transportation with sediment by rainfall erosion, existence in the water or reservoir, transformation from different forms, the biochemical effect of organisms, and so on. The model can also simulate nutrient migration/transformation by GLEAMS.

The SWAT model can recognize decay and mineralization of two organic phosphorus substances (fresh residue and humus substance) and three mineral phosphorus substances (labile in solution, labile on the soil surface, and fixed in soil). Mineralization and decomposition of organic phosphorus pools occur when soil temperature is higher than 0 °C. The concentration of soluble phosphorus decreases after soluble phosphorus fertilizer reacts with soil, so that it reaches the fast balanced state between soluble phosphorus pools and labile phosphorus pools, and then a slow balanced state between labile phosphorus pools and fixed phosphorus pools. The eluviation of soluble labile phosphorus is also a method of moving phosphorus.

Using SWAT model to develop LDCs in data-scarce watersheds

There are some obstacles in constructing LDCs when dealing with data-scarce or ungauged watersheds, as less available data are recorded on such watersheds. We use the SWAT model to help establish LDCs when there is a lack of data. The surface runoff following rain events is a significant factor for LDCs and a vital transport mechanism of sediment and non-point source. The SWAT model is an effective assessment tool for simulating runoff and point/non-point source pollution, and it is often applied for simulation, thus providing a detailed estimate of the timing and magnitude of flows and pollutant sources.

Development of flow duration curves

Not all water quality monitoring (WQM) sections have available direct flow measurements in the study, due to the lack of discharge gauging stations. Unfortunately, the information is vital to demonstrate the relation between discharges and water qualities. Therefore, in such cases, to characterize flow, the US Environmental Protection Agency proposes to use water quality models to develop streamflow estimates for each relevant watershed (US EPA 2007).

Global meteorological data, soil map, land use map and other relative data are relatively complete and available, even if there is no observed flow and water quality data in data scarce regions. Therefore, if no equivalent flow data are available for a WQM section, but flow gauges are often operated at upstream or downstream, flows at this section can be estimated by the calibrated SWAT model based on the gauged data at upstream or downstream of the river basin.

Schemes of allocation

Schemes of allocation mean to distribute or apportion those portions of a water's loading capacity or the exceedance of permitted pollutant load among the point sources, non-point sources, and natural background based on their contribution to the pollution. They are also basic criteria for water quality standards to be guaranteed by LDCs. The loading capacity or assimilative capacity closely relates to flow condition in different seasons, so it is easy to diagnose the dominant contributing sources of pollutants.

To maintain the water quality in a river, it is necessary to find out where the pollutants come from. However, to trace the origins or the transportations of pollutants into the river is still a challenge by LDC alone. The physically based and distributed hydrological model of SWAT can not only simulate a variety of processes such as snowmelt, storm water, groundwater infiltration, sediment reduction, plant uptake of nutrients, chemical transformations, or bioaccumulation, but also carry out a scheme or alternatives of pollutant load allocations among different sources of pollutants to see the effectiveness of the scheme or alternatives to reduce the pollution sources. On the basis of results simulated by the SWAT model, BMPs for controlling water quality under the framework of TMDL can be obtained.

Quantify and identify current specific source

LDCs can characterize water impairments by different pollutant sources: the influence of point sources will be the dominant sources in the dry season or during the time of low flow season. Non-point sources will be added to the pollutant load in the rainy seasons. LDCs can provide information about the total exceeding quantities of point sources and non-point sources, but they do not have the ability to quantify or identify the components or contributions of different pollutant sources such as crop and livestock production, wastewater treatment plants, urbanization, natural background, and so on. Therefore, we proposed in this study to identify and quantify a specific source of contaminant by the SWAT model, which can aid in tracking the origins and categories of the pollutants' sources, and then guide the formulation of the BMPs. Typical procedures to develop LDCs are shown in Figure 3.

APPLICATION OF THE PROPOSED METHOD

Study area

Jian-jiang River is a tributary of Yangtze River, located in Duyun city, Guizhou province, whose watershed area is 1,152.6 km^2. The watershed is located between 26°3′ and 26°28′ N, 107°16′ and 107°47′E with altitude ranging from 642 to 1,936 m above mean sea level. The headwaters of the river mainly originate from Doupeng Mountain and flow 91.2 km through Duyun city.

The area receives an average annual precipitation of 1,431 mm, with pronounced seasonality. The climate is

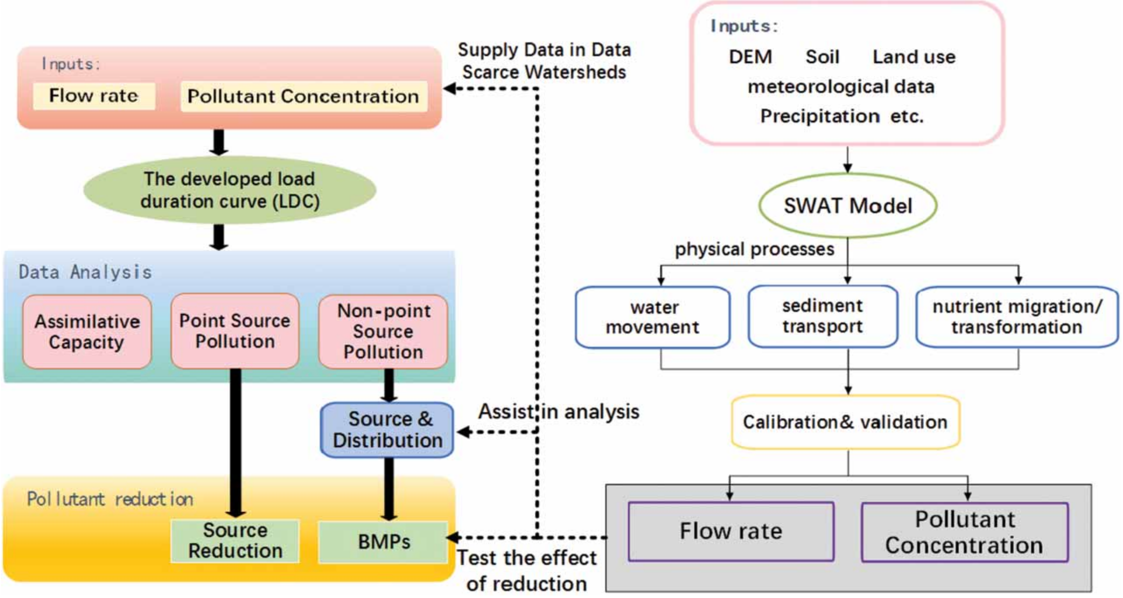

Figure 3 | Schematic for the development of LDCs with the aid of SWAT.

temperate with an annual average temperature around 16.1 °C, the warmest in July is 24.8 °C and the coldest in January is 5.6 °C. The watershed is dominated by paddy soils, yellow earths, and limestone soils with an average slope of 17.8‰. The land use in the area is predominantly forest (62.6%) and cropland (24.8%). Only a small fraction is covered by orchard (6.2%), range-grasses (4.8%), and urban areas (1.3%). The dominant cropland includes tea, rice-canola, and corn-wheat rotations. Details of the catchment information are as indicated in Figure 4.

The available streamflow and meteorological information of Jian-jiang River basin is limited (details are shown in Figure 5). As there is no hydrological gauge station in our study region, the watershed model should be calibrated in a larger watershed or on its neighborhood watersheds. Currently, there is only one hydrological station, Xiasi, which is located about 4 km downstream of Jiadeng outlet and has observed runoff data from 1985 to 2014. The available climate data from Duyun meteorological station including daily values of maximum and minimum air temperature, solar radiation, relative humidity, and wind speed were obtained from the National Science and Technology Infrastructure of China Meteorological Administration (http://data.cma.cn/), and are used as meteorological input variables to the model. The precipitation can be directly obtained from six rainfall stations operated by the Hydrology Bureau of Duyun from 1985 to 2014.

Based on the data of the 2011 Water Conservancy Census, sewage discharge of 39 industrial enterprises and five centralized livestock and poultry farms in the basin are collected. Their sewage is concentrated and discharged from fixed sewage outlets.

The main sources of non-point source pollution of Duyun city are rural domestic wastewater, livestock and poultry excrement, and fertilizer pollution sources. The mostly rural domestic waste and the excrement of free-range livestock and poultry are directly returned to the field or discharged through ditches to the river. According to a field survey, the annual discharge of each person and each individual livestock is TP 0.29 kg and 0.73 kg, respectively. In the Statistical Yearbook of 2011, the population of rural residents in Duyun city was 128,985 and the numbers of free-range livestock and poultry were 97,157 and 7,050, respectively. In order to simplify the simulation of non-point source pollution, the daily excrement of the rural population, free-range livestock and poultry were converted into fertilizer by continuous fertilization operation as an input of the SWAT model. When considering the source of chemical fertilizer pollution, different chemical fertilizers

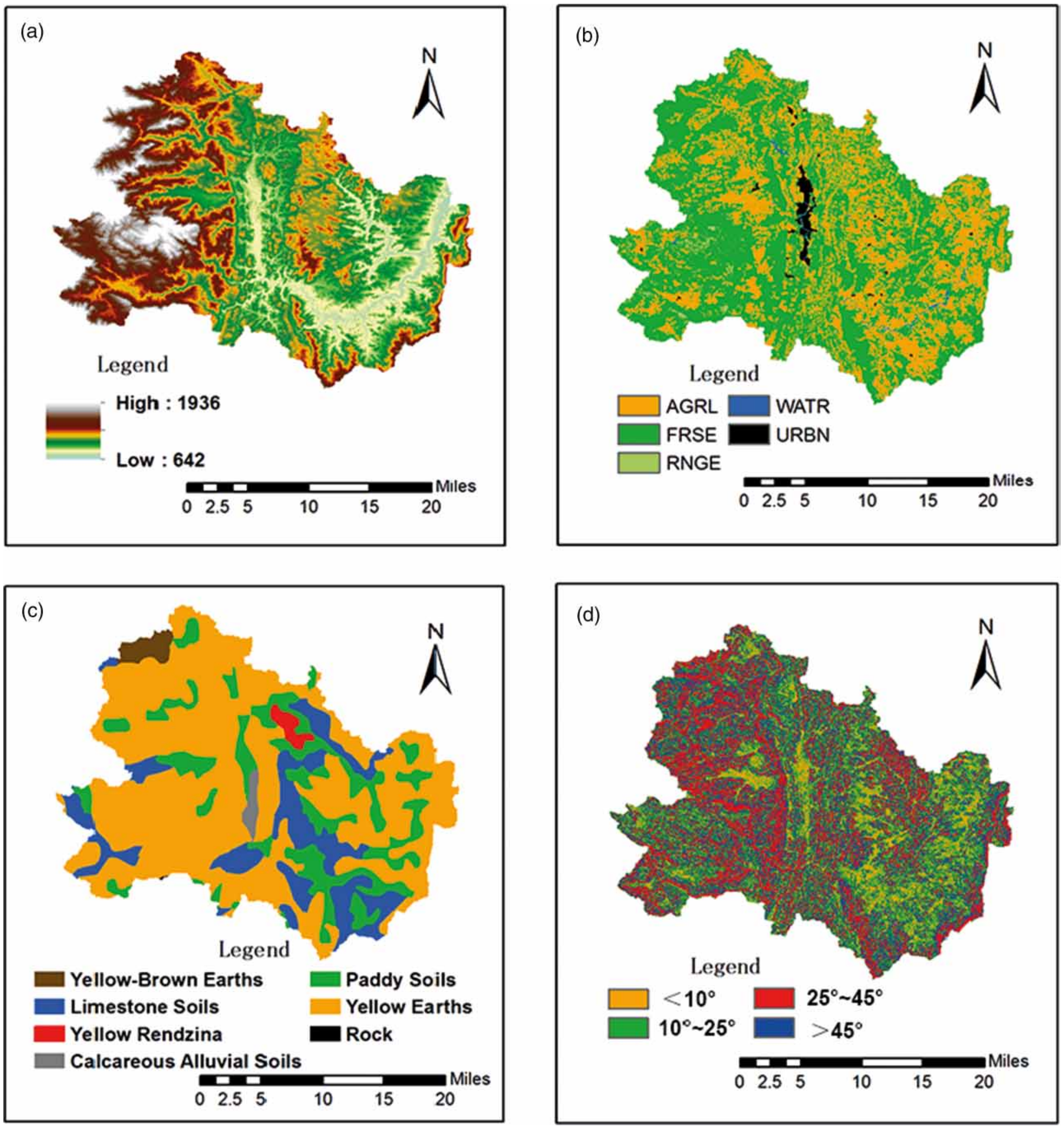

Figure 4 | Jian-jiang River basin in Guizhou province: (a) digital elevation data, (b) land use, (c) soil type, and (d) the slope of the study region.

are added to the model to simulate the crop growth according to the growth law of the crop in the form of fertilization operation, as shown in Table 1.

The major contaminants of the area are total phosphorus (TP). Water quality data of six WQM sections (Chayuan, Duchuanbao, Xiaoweizhai, Youhang, Yingpan, Jiadeng) were obtained from the Environmental Protection Bureau of Duyun, as shown in Figure 5. The WQM data are not synchronous for these sections. Some sections just have three water period values every year, which means the water quality for July, November, and March represents the high water period, the flat water period, and the low water period (details of data are shown in Table 2). Due to Duchuanbao and Xiaoweizhai sections having no data corresponding to flow data, the two sections are not involved in the establishment of the SWAT model. Due to this limitation of available data, the accuracy of established LDCs will be constrained.

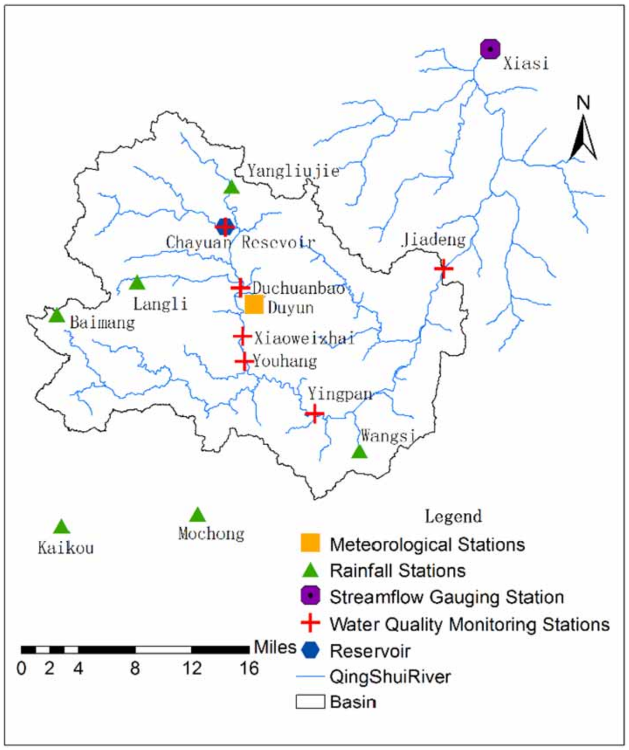

Figure 5 | Locations of meteorological gauges, precipitation gauges, discharge gauges, and WQM sections.

Division of control unit

In order to address spatial variations in pollutant loading capacity or assimilative capacity and make a more purposeful protection scheme for the water environment, the watershed is first divided into smaller units, and then the total loads' allocation is carried out. The principle of division is mainly based on the different characteristics of the water environment and ecological system of the basin. Division can be combined with a comprehensive consideration of the catchment range in terms of hydrological process, administrative division, and the division of water function zones, which reflect the hydrological characteristics, catchment characteristics, and water conservation function.

Table 1 | The investigated data of mineral phosphorus fertilizer for Duyun crops

Crop	Fertilizer (kg/ha)	Fertilizer date	Planted date	Harvest date
Rice	9	May-25	May-1	Oct-25
	45	Jun-5		
	18	Jun-15		
	9	Jun-25		
	9	Jul-15		
Canola	5	Nov-25	Nov-1	Apr-25
	5	Mar-5		
Corn	30	Jun-10	Jun-5	Sep-20
Winter wheat	20	Sep-30	Sep-25	May-25

Table 2 | Summary of the data in each WQM section of Jian-jiang River

	WQM data	
WQM section	July/November/March	Monthly
Chayuan	2010–2012	2013–2014
Duchuanbao		2015
Xiaoweizhai		2015
Youhang		2010–2014
Yingpan	2010–2014	
Jiadeng	2013–2014	

Jian-jiang River basin is divided into six control units, which are water source protection unit, drinking water and industrial utilization unit, landscapes and industrial utilization unit, pollution control unit, downstream transition unit and reservation control unit from upstream to downstream, respectively, as shown in Figure 6. According to the natural situation and research needs of the study area, in the study, the watershed of Jian-jiang River is subdivided into 34 sub-basins.

Calibration and validation of SWAT model

Calibration and validation of the SWAT model are carried out based on the monthly data. In order to ensure the established model of SWAT and its parameters give a good representativeness of the studied catchment characteristics, runoff data of January 1993 to December 2012 were used as the calibration period and January 1988 to December 1992 as the validation period. For the sake of reducing the error and making the parameters more suitable for the study area, a three-year warm-up period was set in order to get rid of the influence of the initial values of some parameters (e.g., soil moisture, ground water) (Lamba *et al.* 2016). For TP, data were calibrated for three years (2010–2012) at monthly time-step and validated for another two years (2013–2014) at the Youhang WQM section. However, water quality data of Chayuan, Yingpan, and Jiadeng WQM sections only encompass three water periods

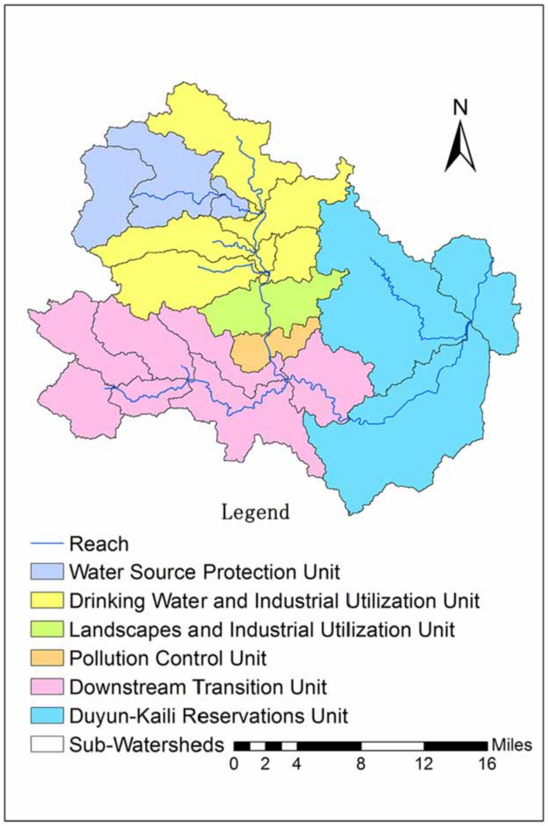

Figure 6 | Division of watersheds and control units.

(March, July, and November) per year, so these data are used for model validation only.

The SWAT model uses a large number of parameters and mathematical equations for simulating the process of output, transport, and transformation of runoff and pollutants in the watershed. In order to improve computational efficiency and reduce the blindness of parameter calibration and verification, parameter sensitivity analysis is needed. The parameters for calibration are selected by their sensitivity ranking, and finally the top six parameters with high sensitivity are determined, as shown in Table 3.

RESULTS AND DISCUSSION

Results of SWAT model calibration and validation

Two objective functions are used to analyze goodness of fit results, which are the Nash–Sutcliffe model efficiency (NSE) (Nash & Sutcliffe 1970) and the coefficient of determination (R^2) (Legates & McCabe 1999). When NSE ≥ 0.5 and $R^2 \geq 0.6$, the model performance can be assumed as satisfactory, by Santhi *et al.* (2001). Table 4 shows the statistical summaries of comparing observed and simulated values of streamflow and contaminant loads, respectively.

Table 3 | Sorting of selected parameters by sensitivity

Sort of sensitivity	Runoff	Sediment	TP
1	CN2	USLE_P	BIOMIX
2	ALPHA_BF	SPCON	CN2
3	CH_K2	USLE_C	ALPHA_BF
4	GWQMN	SPEXP	USLE_P
5	GW_REVAP	CH_COV	PHOSKD
6	EPCO	CH_EROD	ERORGP

The result of total loads' allocation

Every control unit of the basin is equipped with a WQM section. The target concentrations of TP at Chayuan, Duchuanbao, Xiaoweizhai, Youhang, Yingpan, and Jiadeng section are 0.1 mg/L, 0.2 mg/L, 0.2 mg/L, 0.3 mg/L, 0.2 mg/L, and 0.2 mg/L, respectively. The corresponding flow rate sequence from 1988 to 2014 and supplemental water quality data from 2007 to 2014 of the sections are obtained by SWAT model simulation, and thus, the LDCs can be established. The existing (dark plots) and supplemental (light plots) water quality samples of six different sections are plotted on the LDCs, as shown in Figure 7. The LDCs of TP presented in this study are designed to be protective of

Table 4 | Goodness of fit regarding the results of flow and pollutant calibration and validation

		Flow		TP	
Station/section	Data series	R^2	E_{ns}	R^2	E_{ns}
Chayuan	Verification period	/	/	0.89	0.85
Youhang	Calibration period	/	/	0.72	0.61
	Verification period	/	/	0.89	0.60
Yingpan	Verification period	/	/	0.81	0.73
Jiadeng	Verification period	/	/	0.93	0.80
Xiasi	Calibration period	0.85	0.90	/	/
	Verification period	0.90	0.90	/	/

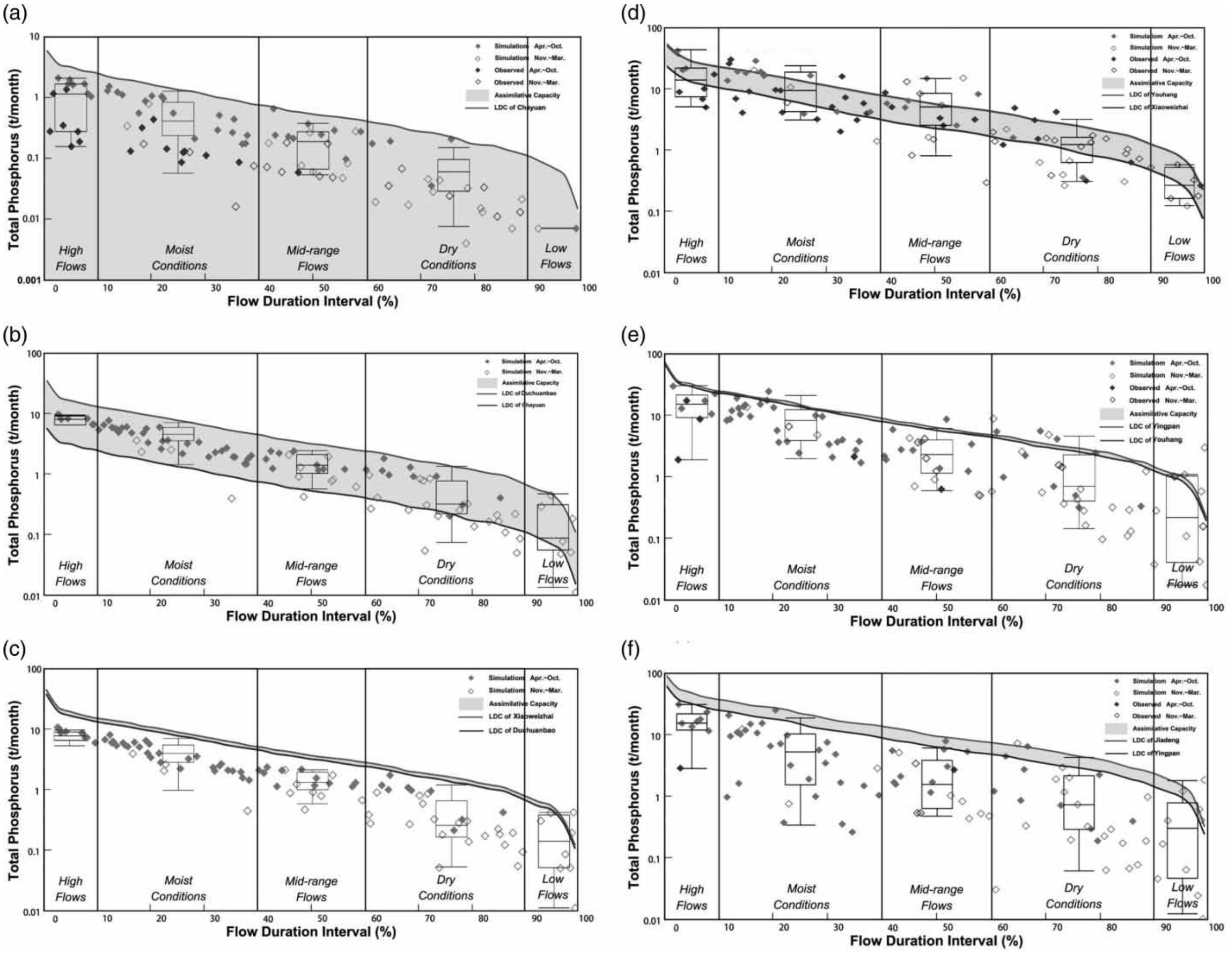

Figure 7 | Developed LDCs, monitored and simulation loads, and box and whisker plots for monthly TP at Chayuan (a), Duchuanbao (b), Xiaoweizhai (c), Youhang (d), Yingpan (e), Jiadeng (f) sections, respectively. The shaded part represents assimilative capacity of the protection unit, drinking water and industrial utilization unit, landscapes and industrial utilization unit, pollution control unit, downstream transition unit, and reservation control unit.

typical flow conditions. The water quality data are separated into five flow zones, and they are marked as flood season from April to October (filled diamond) or non-flood season from November to March (unfilled diamond). As a result, the assimilative capacity of control units can be presented as the shaded part between its upstream and downstream sections.

For Chayuan section, in Figure 7(a), the water quality is good and meets the standard. At the same time, the model complements water data in the low flow regime where there is a lack of monitoring data. Due to the protection unit being the source of the watershed and Chayuan section being the first WQM section of Jian-jiang River, the assimilative capacity of the unit is just the carrying load capacity of the section. All the water quality data of Duchuanbao and Xiaoweizhai sections are simulating data obtained by the calibrated model. In Figure 7(b) and 7(c), water quality of the two sections remains healthy in 2007–2014, except for individual points during the low flow period slightly exceeding the standard. This means point source impairment occasionally occurs in the area where some industrial factories are located. The protection unit and the drinking water and industrial utilization unit play essential roles in water supply for drinking and living. The realization of water security requires strict control of water quality management. The landscapes and industrial utilization unit has less assimilative capacity, mainly because the upstream and downstream sections of the unit with almost the same water quality standards are close to each other, and the difference of flow is small. From the LDCs of the pollution control unit, the pattern of dominant impairment is examined and occurs across dry conditions to high flows. Figure 7(d) shows that some water quality points of the unit break the standard under dry conditions, which is only affected by point sources. From the calculated LDC diagram, it can be seen that most of the exceeding standard water quality data points take place from April to October, and are concentrated in mid-range flow and moist condition. This also shows that the waterbody of this control unit is impaired by both point and non-point sources under the wet period when rainfall is the major driving factor of the pollutant load. Mostly the water quality data of Yingpan section are produced by the model. The pollution of this section is similar to that of Youhang, as shown in Figure 7(e), with the water impaired more seriously in the low flow regime. Thanks to the ability of the model to simulate flow and water quality data, it is possible to discover the water quality status of many years. Most of the data in Jiadeng section are generated by simulation, and few monthly water quality data failed to meet the standard in dry conditions and low flow zones. The assimilative capacity of the reservation control unit is determined by the LDCs of Yingpan and Jiadeng sections.

To meet the LDCs' water quality target, loading reduction needs to be calculated under different flow conditions. No more than 10% of samples should exceed its standard. Thus, it is appropriate to evaluate the 90th percentile of existing TP concentrations under each hydrologic condition class multiplied by the flow at the middle of the flow exceedance percentile (Cho & Lee 2015). Under the low and dry flow seasons, there is only point source discharged into the river. The amount of point source pollution discharge is relatively stable and is often considered as a constant throughout a year. Therefore, in order to meet the requirements of the water quality standard, the overloaded pollutants in these two flow regimes are the quantities needed to be deducted by the point sources, and in other flow regimes, the overloaded quantities of pollutants minus the deducted quantity of the point source reflected within the low and dry flow season is the reduction of non-point sources. As a result, just the load of Youhang and Yingpan sections needs to be reduced. The amount of load reduction of the two sections under the hydrologic condition is shown in Table 5. For Youhang section, under the wet condition, more than 90% reduction is achieved by cutting non-point source pollutant and only part of the point source needs to be reduced for Yingpan.

Analysis of pollutant sources and characteristics of spatial distribution

The LDCs identify the assimilative capacity of water environment based on different flow conditions. According to the shaded part between curves of upstream and downstream, the assimilative capacity of the units is dynamic under different flow duration intervals. With the above calculation method, the capacity of each control unit can be obtained. Details are as shown in Table 6.

The contribution of non-point source pollution to the waterbody increases during the flood season. Mainly due

Table 5 | Load reduction for different flow regimes of Youhang and Yingpan sections

	Hydrologic conditions	Reduction quantity (t/month)	Percentage reduction (%)	Point source reduction (t/month)	Non-point source reduction (t/month)
Youhang section	High flows	11.66	28	0.67	10.99
	Moist conditions	10.38	43	0.67	9.71
	Mid-range flows	8.89	61	0.67	8.22
	Dry conditions	0.67	21	0.67	0
	Low flows	−0.29	−51	0	0
Yingpan section	High flows	−2.75	0	2.43	0
	Moist conditions	2.24	0	2.43	0
	Mid-range flows	−0.62	0	2.43	0
	Dry conditions	2.43	0	2.43	0
	Low flows	1.73	0	1.73	0

Table 6 | Assimilative capacity of different control units

Flow duration interval	Water source protection unit (t/month)	Drinking water and industrial utilization unit (t/month)	Landscapes and industrial utilization unit (t/month)	Pollution control unit (t/month)	Downstream transition unit (t/month)	Reservation control unit (t/month)
5%	0.66	14.95	3.21	10.79	2.77	16.99
25%	0.30	7.15	1.28	5.30	0.84	6.56
50%	0.12	3.02	0.45	2.11	0.60	3.11
75%	0.05	1.36	0.21	0.97	0.36	1.59
95%	0.02	0.45	0.08	0.32	0.18	0.49

to the spring farming and fertilization, increasing living standards, livestock wastewater, and abundant rainfall, most of the impairment occurs within this period. Regarding the values of pollutants, we only know the non-point source pollution is dominant; however, the specific type and the origin or where the non-point source pollutants come from spatially cannot be analyzed by LDCs alone. Therefore, the SWAT model is used to analyze the migration path, spatial distribution, and classification ratio of non-point source pollutants. After the simulation and analysis of the pollution situation of all control units of Duyun, the detailed results are as follows.

In this study, we mainly analyze the spatial distribution of surface source pollution, namely, the non-point sources of pollutants because point sources of pollutants can be easily controlled. The spatial distribution of point source pollution is consistent with the distribution of point source discharge outlets, so the distribution of the non-point source is mainly related to the distribution of rainfall and the land-surface (mainly including land use, soil cover, and slope) of the basin. According to the SWAT model, we simulate the annual average (1988–2014) TP load of each control unit in the basin, in order to facilitate the planning and management of Jian-jiang River basin and the regulation of the water environmental carrying capacity of Duyun. Details of the TP spatial distribution are as shown in Figure 8.

From Figure 8 we can see that the reservation unit encounters the most serious threat of TP pollution. According to the survey, the agricultural acreage of the control unit is relatively large, so the human activities bring about the greater pollution. In contrast, the production of TP in the water source protection unit is the lowest, because the control unit is mainly the Doupeng mountain scenic area, which is largely covered with forest, and where the population is scarce and the pollution source is small.

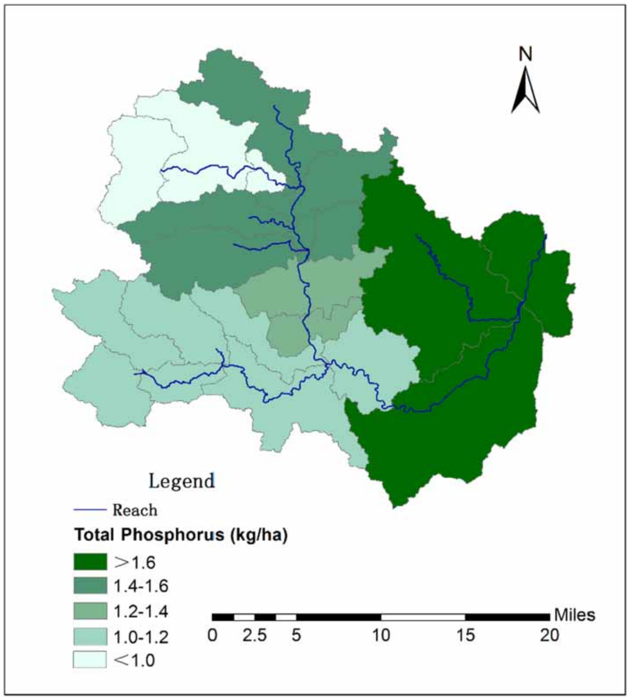

Figure 8 | TP output distribution map of the control units.

The non-point source mainly comes from natural background loss (topography, soil, land use, and other factors) and man-made pollution (fertilizer loss, livestock and poultry breeding, and domestic sewage). The SWAT model has been calibrated and simulated with different representative years (wet year, mean year, and dry year) and various scenarios including rural life pollution, livestock rearing, fertilizer, and natural background. The effects on water environment in the Jian-jiang River basin of Duyun city, and the different representative-year pollution contribution rates are shown in Figure 9.

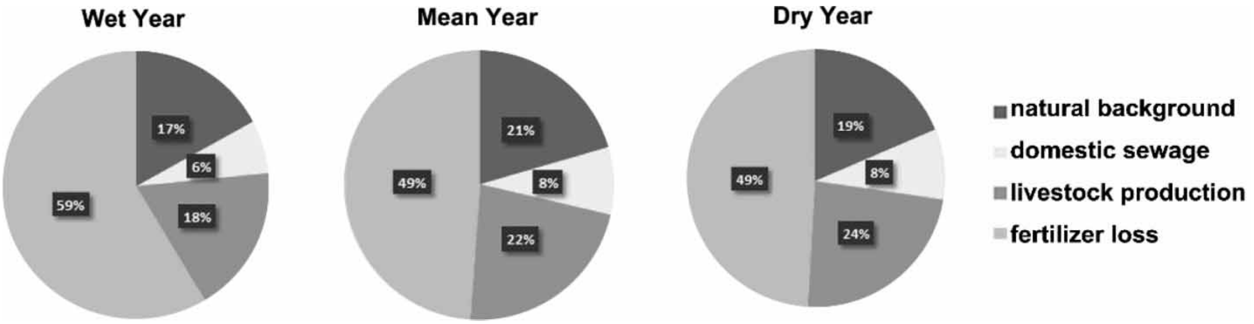

Figure 9 | TP contribution rate of non-point source pollution in different typical years.

From Figure 9 we can see that the largest source of non-point source pollutants in Jian-jiang River basin of Duyun is the loss of fertilizer, which accounts for about 50%, followed by rural domestic sewage and livestock and poultry breeding, accounting for about 30%, with only about 20% coming from natural background. It can be concluded that the main factor of TP pollution load is man-made, and the life and production of mankind is a great burden on the ecological environment. At the same time, the pollution caused by human activities can be controlled by means of management and technology development.

The largest source of non-point pollution is the loss of fertilizer in the basin. The largest proportion of TP in the wet season is 59%, and the lowest proportion is 49% in the dry season. It can be concluded that the amount of pollutant load of fertilizer loss increases with the increase of rainfall, and the main driving force of the fertilizer loss is rainfall. The pollution load of chemical fertilizer loss can be lowered by reducing the amount of fertilizer application and optimizing farming measures.

In addition to the loss of chemical fertilizer, the bulk of livestock and poultry and rural domestic sewage also account for a larger proportion, whose total ratio of phosphorus contributes 30% of the total. The ranking condition of the proportion of the representative year is opposite to the fertilizer loss; the proportion in the wet year is the smallest, and the largest in the dry year. The contribution rate of livestock and poultry of TP is greater than that of domestic sewage. This part of the non-point source can be controlled to improve the water environment by changing the method of discharge and increasing awareness of energy saving and emission reduction.

CONCLUSIONS

This study proposed a way to develop LDC with the aid of a distributed hydrological model of SWAT for a data-scarce small watershed, which is lacking hydrological stations and WQMs. The procedure of developing LDCs involves using an additional tool of the SWAT model for data collection, pollution analysis, and BMP implementation. Through a case study conducted in Jian-jiang River basin, Duyun city of Guizhou province, the following conclusions can be drawn:

(1) Development of the LDC system in data-scarce watersheds based on a distributed hydrological model can negate the limitation of insufficient data, and can also subdivide the pollutant sources and provide the basis for the planning and management of water environment in a data-scarce region.
(2) According to the results of the model output, we can trace back to the sources and find the source of pollutants, which is conducive to reducing pollutants and defining corresponding BMPs from the source.
(3) The modified method can not only analyze the dynamic pollution capacity of each control unit or area, but also be beneficial for the management of water resources for local administrative departments and provide a basis for the work of ecological compensation.

In fact, the SWAT model combined with GIS can visualize the effect of BMPs such as conservation tillage, contour strips, grassed waterways, etc. to assist in the planning and decision-making for the local management department or authorities.

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