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Confronting limitations: New solutions required for urban water management in Kunming City

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Abstract

Despite continuous investment and various efforts to control pollution, urban water environments are worsening in large parts of the developing world. In order to reveal potential constraints and limitations of current practices of urban water management and to stimulate proactive intervention, we conducted a material flow analysis of the urban water system in Kunming City. The results demonstrate that the current efficiency of wastewater treatment is only around 25% and the emission of total phosphorous from the city into its receiving water, Dianchi Lake, is more than 25 times higher than its estimated tolerance. With regard to the crisis of water quantity and quality, the goal of a sustainable urban water environment cannot be attained with the current problem-solving approach in the region due to the technical limitations of the conventional urban drainage and treatment systems. A set of strategies is therefore proposed. The urban drainage system in Zurich is used as a reference for a potential best-available technology for conventional urban water management (BAT) scenario in terms of its low combined frequency of sewer overflow.

Keywords: Eutrophication; Material flow analysis; Scenario planning; Urban water management

1. Introduction

Worldwide research activities are undertaken in the field of urban sanitation to find and test alternative solutions such as source control or ecological sanitation (Larsen and Gujer, 1996; Otterpohl et al., 1999; Langergraber and Muellegger, 2005). However, these alternatives are rarely applied in urban areas at present. The construction of water infrastructures using the prevailing end-of-pipe technology is still the first choice in practice.

As an example, Kunming City (the capital of Yunnan Province in southwest China), has been trying to improve its urban water environment since the late 1980s. Eutrophication caused by rapid urbanisation and an inadequate urban water infrastructure is currently one of the most intractable water problems in Kunming. It is questionable whether this problem can be solved by the prevailing end-of-pipe technology. In other words, what are the technical and economic limits of these practices? How can these limits be overcome? Decision makers and planners require this type of knowledge to avoid pitfalls and to help them make better decisions and plans (Clark et al., 2001).

Kunming is adjacent to the sixth largest body of fresh water in China, namely Dianchi Lake. Due to the severity of its pollution and its important role in water supply, local climate, flood control and tourism in the region, it has been listed in the "Three Important Lakes Restoration Act in China" (KIES, 2003). The city currently faces a difficult dilemma: whereas on the one hand many efforts have been undertaken to improve the local water environment, the pollution problem is still overwhelming. And on the other hand, the city is growing and its dependence on the lake, though already severely problematic, is also growing.

Despite this dilemma, solutions need to be found to avoid the destruction of Dianchi Lake, especially as similar problems are faced by most of the large lakes in China,

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such as Taihu, Chaohu and Dongtinghu (SEPA, 2001). There is a strongly held local belief that freshwater lakes, including their ecological and hydrological functions, should not be diminished by the careless interference of human beings (Li, 2005). It is evident from the regular updated planning efforts, institutional reorganisation and the large investment already made that both political planners and the public want to return Dianchi Lake to its historical pristine state.

Gray and Li (1999) reported that if Dianchi Lake is to have the high water quality it had in the 1960s, the annual total phosphorous (TP) inflow through surface water should be less than 60 tons per year. (Although this critical value may depend on the amount of water flowing through the lake, it is reasonable to take this value as a critical requirement for preventing eutrophication of the lake.) This report drew a pessimistic conclusion: "The TP load reduction envisaged as realistic would only stabilises the lake water quality by about the year 2008; unfortunately, interventions could not return the lake to its former pristine condition."

If we take the current ratio of the TP load into Dianchi Lake from the urban drainage system to that from agriculture, namely 55:45 (KIES, 2003) as our reference value for the future, then 27 tons/year of TP load can be budgeted for agricultural sources while the maximum TP input from the city to Dianchi Lake should not exceed 33 tons per year.

Wastewater discharge from urban drainage systems currently accounts for the main nutrient load to Dianchi Lake (KIES, 2003; Liu et al., 2004). Reliable quantifications of the flows of total nitrogen (TN) and TP in urban drainage systems are currently of major concern. The objective of this paper is consequently to answer the following questions:

- What are the current conditions of the urban drainage system in Kunming?
- What is the best condition attainable by conventional urban drainage and wastewater treatment? What does it imply for the future?

2. Study area description

Kunming City is situated upstream of Dianchi Lake (Fig. 1). The boundary of the study area is the urban settlement of Kunming City within the catchment area of Dianchi Lake. It is being enlarged as the city develops. Its population has grown eightfold since 1950 and is currently approximately 2.4 million. Large population transfers from rural to urban areas are to be expected for two reasons: (1) the limited arable land and jobs in agriculture; (2) the large economic income gap between urban and rural citizens; the current ratio is 3:1 in Kunming (KMSB, 2003; KPB, 2004). According to KPB (2004), the population within the Dianchi catchment area is expected to reach between 4.5 and 5.6 million.

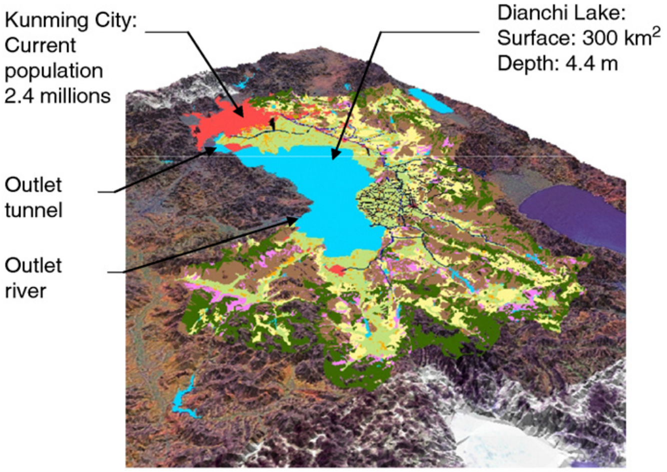


Fig. 1. Kunming and Dianchi Lake, geographical position (satellite picture source: ORL/ETHZ, 2002).

Dianchi Lake has a surface area of 300 km^2 and an average depth of only 4.4 m. The water surface is at 1886.5 m above sea level. The inflow to the lake is mainly from upstream reservoirs and from rain runoff in the greater Kunming catchment area. Its outflow is ultimately discharged into the Yangtze River. Urbanisation and lifestyle changes have on the one hand supplied citizens with convenient water and sanitation, but have on the other hand caused severe eutrophication of the lake since the 1980s (Liu et al., 2004).

The reference study area is the catchment of the wastewater treatment plant (WWTP) of Werdhölzli in Zurich, Switzerland. This area is not a focus of this paper but merely serves as a guide for the best-available technology for a conventional urban water management (BAT) scenario with regard to conventional urban drainage systems. The basic comparison information is listed in Table 1. The population of Zurich city has remained at the same level since 1950. Its reliable urban water management system has contributed to its clean water environment and the quality of life in the city.

3. Method

The method used is a mathematically extended material flow analysis. It describes, quantifies and models the material flows of the system considered (Baccini and Bader, 1996). The method consists of four steps: (1) system analysis, (2) model approach, (3) data acquisition and calibration and (4) simulations including a sensitivity and uncertainty analysis. Studies of material flow analyses in urban water management and related problems can be found in Herrmann and Klaus (1997); Gray and Becker (2002); Jeppsson and Hellstrom (2002); Jönsson (2002); Tangsubkul et al. (2005) and Schmid et al. (2004).

3.1. System analysis

The object of the study is defined as the urban drainage system of Kunming City. Its components and flows are described in Fig. 2. The system consists of seven balance volumes (boxes in Fig. 2) and 23 flows (arrows in Fig. 2). The water, TN and TP flows (in a stationary state, with time resolution of 1 year) of the system described are studied.

3.1.1. Balance volumes

1. *Household wastewater* (*HH*): all households connected to the sewage system.
2. *Runoff collection* (*Runoff*): all places with rain runoff from a pool of impervious areas.
3. *Combined sewers* (*Comb.sewer*): containing wastewater from household, industry and service, urban runoff and sewer infiltration flow (for definition, refer Section 3.3.4). In many cases, this volume comprises a mixture of pipes, open canals and covered ditches.
4. *Separate storm sewer system* (*Storm sewer*): storm water runoff collected separately from sanitary sewers. Wrong connections can occur in the case of careless construction and management. This leads to sewage in storm water pipes and vice versa.
5. *WWTPs* of the city.
6. *Combined sewer overflow tank* (*CSO*): This is widely implemented as a component of urban drainage systems in Switzerland. In heavy rain events, the CSO acts as temporary storage. The stored overflow of wastewater is later pumped into the WWTP for

Table 1
Basic information on case study areas

	Urban population (millions)	Urban area (hectares)	Impervious area percentage	Connection to water supply (%)	Status of urban drainage system
Kunming	2.4	18,000	68	100	Incomplete[a]
WHZH[b]	0.45[c]	5770	43	100	Complete

[a] The quantitative value of the wastewater collecting rate is to be identified in this study.

[b] WHZH here denotes the catchment area of the Werdhölzli wastewater treatment plant (WWTP) in Zurich.

[c] Including residents, commuters and travellers. Commuters are assumed to stay in the city for an average of 9 h each working day (data source on commuters: Statistisches Jahrbuch der Stadt Zürich, 2004).

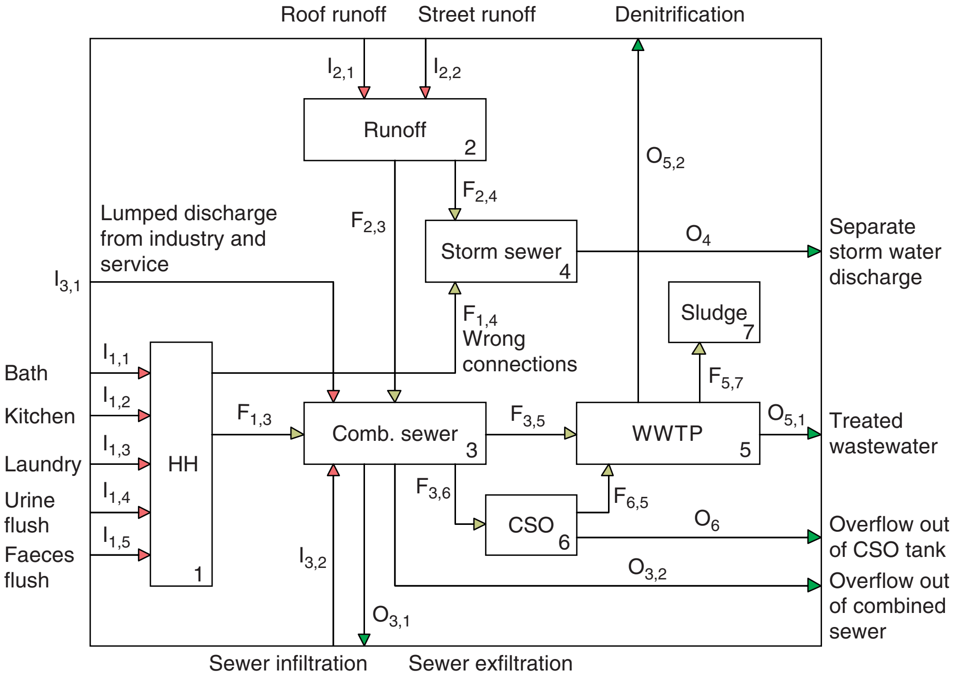


Fig. 2. System description of the urban drainage system. "HH"—household, "StormSewer"—separated storm sewer, "CombSewer"—combined sewer. In the case of Kunming, this is a conceptualisation of the mixed sewers—open canals that are used for conveying wastewater. The CSO detention tank is included in the system for scenario analysis. However, it is currently not a component of the urban drainage system in Kunming. Since separate storm sewers exist only in one residential area of Kunming, only wrong connections from households to storm sewers are considered.

treatment, and this overflows when the runoff exceeds its operational volume. This is currently not a component in Kunming.

(7) *Sludge production from WWTP* (*Sludge*): This is an important sink for pollutants. Whether it goes for incineration, landfill, agricultural reuse or any other disposal is not considered in this paper.

3.1.2. Flows

There are three types of flows described in the defined system, i.e., input flows, internal flows and output flows. Input flows $I_{1,1}$ = "bath", $I_{1,2}$ = "kitchen", $I_{1,3}$ = "laundry", $I_{1,4}$ = "urine flush", $I_{1,5}$ = "faeces flush" are household wastewater flows. Separating household wastewater flows into these five categories allows source control strategies to be considered (Henze, 1997; Larsen and Gujer, 2001). Input $I_{2,1}$ = "roof runoff" and $I_{2,2}$ = "street runoff" are the roof and street runoffs, respectively. $I_{3,1}$ = "lumped discharge from industry and service" is the industrial wastewater and $I_{3,2}$ = "sewer infiltration" is the sewer infiltration water.

$F_{i,j}$ denotes the various internal flows, from balance volume i to j.

The following output flows are self-explanatory: $O_{3,1}$ = "Sewer exfiltration" and $O_{3,2}$ = "overflow out of combined sewer". O_4 = "separate storm water discharge", $O_{5,1}$ = "treated wastewater", $O_{5,2}$ = "denitrification"(the emission to air) and O_6 = "overflow out of CSO".

3.2. Model approach

Thirty variables were used to describe the system, namely seven stock change rates (see below) and 23 flows. There are a total of 90 variables for water (30), nitrogen (30) and phosphorous (30). The equations describing the system behaviour in mathematical terms consist of the seven balance equations and 23 model equations for water and the two substances. According to the current state of system knowledge, a modified input–output model was chosen to adequately describe the current conditions and to assess the possible scenarios of the system. The simulation of current conditions, the sensitivity and uncertainty analysis, the BAT and other scenario analyses were performed using the SIMBOX simulation programme.

3.2.1. Modelling approach for water

3.2.1.1. Stock change rates. Since the analysis presented here is based on yearly averaged flows, it can be assumed that the stock change rates are zero except for the "sludge" balance volume, which is a sink especially for nutrients.

3.2.1.2. Conventions. For flow variables, let the superscripts denote materials or substances and subscripts the balance volume in question. Let I_{tot} be the total inflow into a certain balance volume, including all input flows and inter-compartment flows that enter into that balance volume.

3.2.1.3. Input equations.

$$I_{1,j} = Pp_j 365, \quad j = 1, \ldots, 5, \tag{1}$$

$$I_{2,1} = PHArp_6, \tag{2}$$

$$I_{2,2} = PHA(1-r)p_7,$$

$$I_{3,1} = Pp_8 365, \tag{3}$$

where P is the population of households connected to the sewer system, $p_{1,\ldots,5}$ the specific wastewater flows per person and day from bath, kitchen, laundry, urine flush and faeces flush respectively in (l/cap day), H the rainfall in (mm/year) = kg/(m^2 year), A the specific impervious area of roofs and streets per capita in (m^2/cap), r the fraction of roof area in impervious area, p_6 the net runoff coefficient of roofs, p_7 the net runoff coefficient of streets, p_8 the specific wastewater per person and day from industry and services in (l/cap day).

The factor of 365 transforms daily flows to yearly flows.

Eqs. (1)–(3) are called "source oriented" since the parameters $p_1, \ldots, p_8$ represent the intensity of the different sources in households, industry and services and impervious areas.

3.2.1.4. Input–output equations:.

$$F_{1,4} = k_{1,4} I_{tot_1}, \tag{4}$$

$$F_{2,3} = k_{2,3} I_{tot_2}, \tag{5}$$

$$F_{6,5} = k_{6,5} I_{tot_6}, \tag{6}$$

$$O_{3,1} = k_3^{(1)} I_{tot_3}, \tag{7}$$

$$O_{5,1} = k_5^{(1)} I_{tot_5}, \tag{8}$$

$$O_{5,2} = k_5^{(2)} I_{tot_5}, \tag{9}$$

where $k_{i,j}$ is the transfer coefficient from balance volume i to balance volume j, $k_i^{(j)}$ is the transfer coefficient from balance volume V_i to the jth output of V_i, e.g., $k_3^{(1)}$ is the transfer coefficient of water from V_3 (combined sewer) to its first output flow $O_{3,1}$, $k_{1,4} = p_9 p_{10}$, p_9 is the fraction of people living in areas with separated storm sewerage systems, p_{10} the fraction of wrong connections that connect household wastewater to the storm sewer system in separate sewer areas.

$$k_{2,3} = p_{11} + (1 - p_{11})p_{12},$$

p_{11} is the fraction of impervious area which is intentionally connected to combined sewers within the whole area, p_{12} the fraction of wrong connections that connect storm water to sanitary sewer systems in separate sewer areas.

Eqs. (4)–(9) describe the "distribution patterns" of the household, runoff, part of the combined sewer, CSO and WWTP, respectively.

3.2.1.5. Specific equations. Sewer infiltration:

$$I_{3,2} = p_{13}(F_{1,3} + I_{3,1}). \tag{10}$$

Input into WWTP and CSO:

$$F_{3,5} = \begin{cases} F_{Vol} \\ \quad \text{if} \quad I_{tot_3} - F_{2,3} - O_{3,1} \geqslant F_{Vol}, \\ \text{Min}(F_{Vol}, \text{Max}(k_{3,5}(I_{tot_3} - O_{3,1}), I_{tot_3} - F_{2,3} - O_{3,1})) \\ \quad \text{if} \quad I_{tot_3} - F_{2,3} - O_{3,1} < F_{Vol}, \end{cases} \tag{11}$$

$$F_{3,6} = \text{Min}(k_{3,6}(I_{tot_3} - O_{3,1}), I_{tot_3} - F_{2,3} - O_{3,1}), \tag{12}$$

where p_{13} is the ratio of sewer infiltration to sanitary wastewater, F_{Vol} the operating volume of the WWTP per year, equivalent to treated wastewater quantity, in (m^3/year).

Eq. (10) relates the sewer infiltration to the wastewater input to the combined sewerage from households, industry and services.

The first case in Eq. (11) describes the situation where the operating volume of the WWTP is smaller than $I_{tot_3} - F_{2,3} - O_{3,1}$, which is the output of wastewater from combined sewers during dry weather conditions. This is the current condition in Kunming.

The second case of Eq. (11) describes the transfer of wastewater to the WWTP if the operating volume is higher. The min/max functions guarantee that $F_{3,5}$ is continuous as a function of I_{tot_3}, $F_{2,3}$, $O_{3,1}$ and F_{Vol}.

Note that the transfer coefficients $k_{3,5}$ and $k_{3,6}$ refer to the total input into combined sewers reduced by the exfiltration: $I_{tot_3} - O_{3,1}$. The minimum condition in Eq. (12) is responsible for the fact that $F_{3,5} + F_{3,6}$ is not greater than the output of the combined sewers.

3.2.2. Model approach for N and P

The model approach for nitrogen and phosphorous can easily be set out on the basis of the following principles:

The inputs I_1 and $I_{3,1}$ are given, similar to Eqs. (1) and (3). For the inputs $I_{2,1}$, $I_{2,2}$ and $I_{3,2}$ the concentrations are given as parameters.

Ideal mixing is assumed in balance volumes V_1, V_2 and V_4. Therefore, the flows $F_{1,4}$, and $F_{2,3}$ are related to the total input of their original balance volumes and the corresponding water flows.

The transfer coefficients of the WWTP to treated wastewater and to sludge are given for nitrogen, and those to treated wastewater and into air for phosphorous. For the current conditions, ideal mixing in a "combined sewer" is assumed, whereas the transfer coefficients are given for BAT for the flows $F_{3,6}$, $F_{6,5}$, $O_{3,1}$ and $F_{3,5}$.

3.3. Data acquisition and calibration

Due to the scarce data for Kunming, we combined the available data from the city, data from the literature and data from reference cases in Zurich to estimate the values of the various parameters. The idea of plausible reasoning (Collins and Michalski, 1989; Wagman, 2003) proved helpful in this process.

3.3.1. Data for household wastewater flows

According to the Zurich Water Supply Authority (2001), the water consumption pattern in Zurich is approximated as: Bath:Kitchen:Laundry:Urine Flush:Faeces Flush = 7:4:4:4:1. A similar water consumption pattern is assumed for Kunming since no data are available for this or any other Chinese city. To address this vagueness, a large uncertainty factor for the consumption pattern has been assumed.

The total wastewater quantity from households in Kunming is estimated as follows based on (Yang and Zhang, 2005): (1) the total water production is: 2.4×10^8 m^3/year; (2) the industrial production (from groundwater) is: 4.8×10^7 m^3/year; (3) the losses in the distribution systems are estimated at 18% (which seems to be very low compared to many other cities in Asia); (4) industrial water consumption is 9.0×10^7 m^3/year, (5) losses, including evaporation through industrial processes, are approximately 20% of industrial water consumption. Based on these data, household wastewater production in Kunming City is approximately 185 l/cap/day, slightly higher than the Swiss average of 162 l/cap/day (SVGW, 2002). However, the distribution loss in Kunming's system is much higher. The specific wastewater production pattern (parameter $p_1, \ldots, p_5$) listed in Table 2 is derived from the household wastewater and the consumption pattern described above.

3.3.2. Data for roof and street runoff

The yearly rainfall shown in Table 2 is the long-term average over 30 years. The normal yearly variation is ±200 mm (Task group urban water planning Kunming, 1990). The impervious areas of roofs and streets were obtained by multiplying the urban area of Kunming City, namely 18,000 ha (Table 1), with the ratio of the impervious area, i.e., 68% (KMSB, 2003). It can be inferred from Herrmann and Klaus (1997) that the ratio of roof area to street area is 1:1 for European cities. The population and building density in Kunming is obviously higher. It is therefore plausible to assume that the ratio of roof area to street area is also higher for Kunming. We assumed a ratio of 3:2 in consensus with the local planning institute in Kunming (KIES, 2003).

The runoff coefficients of roofs and streets (p_6 and p_7) are assumed to be the same. However, since Kunming is on a high plateau, has more intense sunshine and a dry and windy climate, evaporation is expected to be higher. On the basis of the Zurich runoff coefficient for impervious areas,

Table 2
Data sets for material flow analysis of the urban drainage system in Kunming, current conditions and BAT scenario

Data sets for simulation of current conditions

	Items	Q (l/cap · day)	TN (g/cap · day)	TP (g/cap · day)	Data source
	Grey water	(1)	(2)	(2)	(1) KMWS (2003)[a]
p_1	Bath	65 (±20%)	0.3±10%	0.2±10%	(2)Herrmann and Klaus (1997)
p_2	Kitchen	37 (±20%)	0.2±10%	0.1±10%	
p_3	Laundry	37 (±20%)	0.3±10%	0.2±10%	
	Black water				
p_4	Urine flush	37 (±20%)	9.6±10%	1.1±10%	Jönsson and Vinneras (2003)
p_5	Faeces flush	9 (±20%)	1.4±10%	0.55±10%	
p_8	Industry	80 (±20%)	1.4 (±20%)	0.06(±20%)	KIES (2003)[b]

	Items	TN	TP	Data source
C_{roof}	Average concentration in roof runoff (mg/l)	0.5–2.0	0.1–0.4	Boller (2005)
C_{street}	Average concentration in street runoff (mg/l)	2.3±20%	0.28±40%	Boller (2005)
C_{infil}	Average concentration in infiltration (mg/l)	0–5	0.01±50%	Estimation
η_c	Removal rate	0.56±10%	0.7±10%	KMSC (2003)[c]
$k_{5,7}$	N transfer coeff. WWTP to sludge	0.16±10%		KMSC (2003)
$k_5^{(2)}$	P transfer coeff. WWTP to air		0	Gujer (1999)

	Items	Water	Data source
H	Rain (mm)	1005±20%	KIES (2003)
A	Specific impervious area (m^2/cap)	51±20%	KMSC (2003)
r	Fraction of roof area in impervious area	0.6±10%	KIES (2003)
p_6	Runoff coefficient of roof area	0.75±20%	Estimation
p_7	Runoff coefficient of street area	0.75±20%	Estimation
p_9	Fraction of people living in separated storm sewerage area	0.2±20%	KMSC (2003)
p_{10}	Wrong connection rate in separated storm sewerage area	1/3±30%	KMSC (2003)
p_{11}	Rate of impervious area connected to combined sewerage system	0.8±20%	KMSC (2003)
p_{12}	Wrong connection rate that connects runoff by mistake to combined sewer in designed separated storm sewerage area	1/6±30%	KMSC (2003)
p_{13}	Ratio of infiltration to foul wastewater discharge	0.5–1.7	Parameter estimation
$k_5^{(1)}$	Transfer coefficient of water to treated wastewater	0.9992	Herrmann and Klaus (1997) and Lenz (2004)
$k_5^{(2)}$	Transfer coefficient of water to air	0	Assumption
$k_3^{(1)}$	Transfer coefficient water to exfiltration	0	Assumption
F_{Vol}	Average operating volume[b] (m^3/year)	1.4×10^8(±20%)	KMSC (2003)

Data sets for BAT scenario (based on estimates of Zurich)

p_{10}	Wrong connection rate in separated storm sewerage area	0	Assumption
p_{12}	Wrong connection rate that connects runoff by mistake to combined sewer in designed separated storm sewerage area	0	Assumption
p_{13}	Ratio of infiltration to foul wastewater discharge	0.3	Assumption

	Items	TN	TP	Data source
η_c	Removal rate	0.62	0.98	ERZ (2003) for TN, Siegrist (2005)[d] for TP

	Items	Water	TN	TP	Data source
$k_{3,5}$	Transfer coeff. combined sewer (cs) −>WWTP	0.9	0.965	0.965	ERZ (2003)[e]
$k_{3,6}$	Transfer coeff. (cs)−>CSO	0.095	0.034	0.034	ERZ (2003)
$k_{6,5}$	Transfer coeff. CSO−>WWTP	0.84	0.84	0.84	ERZ (2003)

[a] KMWS—Kunming Water Supply.
[b] KIES—Kunming Institute of Environmental Science.
[c] KMSC—Kunming Municipal Sewerage Co.
[d] Personal communications.
[e] ERZ—Entsorgung und Recycling Zurich.

which is 0.85 (Gujer, 1999), the runoff coefficient for impervious areas in Kunming is estimated to be 0.75 ± 0.05 (log normal distribution).

3.3.3. *Transfer coefficients*

There is currently no CSO tank in Kunming's urban drainage system, hence for simulation of the current conditions: $k_{3,6} = k_{6,5} = 0$. According to KMSC (2003), approximately 20% of the city's population live in an area where a separate storm sewer system is used ($p_9 = 0.2$). In this area, the wrong connection rate p_{10} is approximately 1/3. This leads to a wrong connection transfer coefficient $k_{1,4} = p_9 p_{10} = 0.067$. The fraction of the area connected to the combined sewer system is 80% ($p_{11} = 0.8$); it is worthwhile noting that although in this specific case $p_9 + p_{11} = 1$, it is not always so, because p_9 is a population ratio, while p_{11} is an area ratio. The ratio of wrong connections of runoff to sanitary sewers in the area with separated storm sewerage is 1/6 (p_{12}). Hence, the transfer coefficient from the runoff to the combined sewers $k_{2,3} = p_{11} + (1 - p_{11})p_{12} = 0.83$.

Since the evaporation of water from WWTPs into air can be neglected, $k_5^{(2)}$ (WWTP to air) is 0. Because Kunming applies a mechanical sludge dewatering process, the volume of dewatered sludge is very small. Hence, $k_5^{(1)}$ (WWTP to treated wastewater) is approximately 1.

3.3.4. *Estimating sewer infiltration and sewer exfiltration*

Sewer infiltration is undesired unpolluted water entering the sewer system, which leads to poor performance of the system (Weiss et al., 2002). It includes the flow from groundwater infiltration through cracks or open sewers as well as river water that is connected to sewers. Sewer exfiltration is wastewater that leaks out of sewers into the ground through cracks or unimproved sewer systems. Sewer exfiltration rates are dependent on groundwater levels. If left uncontrolled, sewer exfiltration harms the groundwater quality. These two "hidden" flows are frequently ignored in planning urban drainage systems.

Kunming is a shallow groundwater region. The groundwater table ranges from 0.4 to 2.5 m below the ground surface (Song, 2005), while the depth of constructed sewer pipes ranges from 1 to 8 m (KMSC, 2003). Therefore, a large part of the sewer system is actually below the water table. Since the groundwater level in Kunming is high, sewer exfiltration can be assumed to be insignificant. Therefore, $k_3^{(1)}$ is assumed to be zero.

A direct measurement of infiltration is not practicable. However, an estimation can be made on the basis of the dilution of the inflow to the WWTP. For dry weather conditions, the following holds:

$$F_{1,3}^{(s)} + I_{3,1}^{(s)} + I_{3,2}^{(s)} = C_{3,5}^{(s)}(F_{1,3}^{(w)} + I_{3,1}^{(w)} + I_{3,2}^{(w)}), \tag{13}$$

where $C_{3,5}^{(s)}$ is the dry weather concentration of the substance s in the inflow to the WWTP.

From Eq. (13) for N and P and the model equations of Section 3.2, the concentrations $C_{3,5}^{(\mathrm{N})}$ and $C_{3,5}^{(\mathrm{P})}$ can be calculated as a function of the sewer infiltration parameter p_{13}. The results are shown in Fig. 3. Comparing these values with measured values for $C_{3,5}^{(\mathrm{N})}$ and $C_{3,5}^{(\mathrm{P})}$ allows an estimation of p_{13}. Unfortunately, the sampling scheme for chemical analysis of the WWTP in Kunming is based on grab samples, i.e., an instant wastewater sample for analysing concentrations is usually taken at approximately 9 a.m. However, what is needed is an average concentration of TN and TP weighted to the daily flow. So we need to adjust the value of the 9 a.m. sample to the daily average value according to the hourly variation patterns.

After carefully studying the local measured data and combining expert knowledge with the experience of local engineers, we performed two operations here: First, to obtain the average concentration of TN and TP, we selected WWTP no. 2 in Kunming whose inflow concentration of TN and TP is unaffected by the re-circulation from sludge dewatering processes. It is plausible to take this WWTP as representative of the "average" condition for determining sewer infiltration in Kunming. The details are not discussed in this paper. Secondly, an empirical ratio$C_{9\,\mathrm{a.m.}}/C_{av}$(notes:$C_{9\,\mathrm{a.m.}}$—9 a.m. concentration; C_{av}—average daily concentration) was obtained by comparing the hourly variation of water consumption in Kunming with that of the city of Zurich. Data from both cities showed similar patterns in the morning. Therefore it was assumed that the empirical ratio of $C_{9\,\mathrm{a.m.}}/C_{av}$ for Zurich can be used for Kunming. A reliable measurement would require flow-proportional sampling techniques.

On the basis of this procedure, we estimated a range for the average concentration of TN in wastewater in Kunming as: 20–28 mg/l; and TP as 3.6–4.8 mg/l for dry weather conditions (Table 3). The parameter p_{13} is then

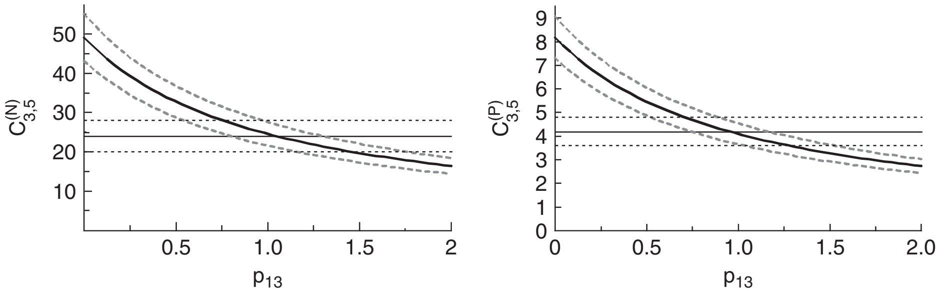


Fig. 3. Calculated concentrations $C_{3,5}^{(\mathrm{N})}$ and $C_{3,5}^{(\mathrm{P})}$ as a function of parameter p_{13}. The dashed line indicates the range of uncertainty.

Table 3
Adjusted 9 a.m. sample concentrations in daily average concentrations, in dry weather conditions (mg/l)

	9 a.m. sample concentration, dry weather	Empirical ratio $C_{9:00\,\text{a.m.}}/C_{av}$	Estimated daily average concentration, dry weather
$C_{3,5}^{\text{N}}$	33 ± 2	1.26–1.54	20–28
$C_{3,5}^{\text{P}}$	3.4 ± 0.2	0.74–0.90	3.6–4.8

estimated as 0.5–1.7 (uniform distribution) on the basis of the above analysis, which means that under dry weather conditions the influent to the WWTP consists of about 50% of relatively unpolluted sewer infiltration water.

3.3.5. Operational volumes of WWTPs

According to KMSC (2003), the operational volume of all the WWTPs in Kunming is measured by ultrasonic water level measurements in a Venturi channel. The current operational volume of all these WWTPs is $1.4\times10^8\,\text{m}^3/\text{year}$ with an uncertainty of ±20%. It is important to note that we are referring to the average operational volume instead of the design capacity of the WWTPs.

3.3.6. Data for specific pollutant emission pattern

Diet plays an important role in the nutrients contained in human waste. Jönsson and Vinneras (2003) studied the relation between food consumption and nutrient emission in human waste. They showed that the Chinese diet produces more phosphorous and potassium than that of India, Africa and other developing countries, but less nitrogen in urine than that of Europe. The fraction of TN and TP originating from human waste in China is taken from Jönsson and Vinneras (2003) (Table 2).

Data on grey water emission are summarised by Herrmann and Klaus (1997). Industrial emissions are measured by local environmental agencies (KIES, 2003).

3.3.7. Data for concentrations in rainwater and sewer infiltration

Where solid waste is well collected and disposed of, urban runoff is not a major source of nitrogen and phosphorous. The data collected in Switzerland by Boller (2005) for TN and TP are used in this study, since no data were available for China and nutrients in urban runoff do not represent sensitive quantities for the problems of interest in the system described here. Heavy metals are of greater concern in urban runoff (Boller, 1997; Zobrist et al., 2000).

An average concentration of TN and TP in sewer infiltration is assumed to be: 0–5 mg/l of TN and 0.01 mg/l of TP with an uncertainty factor of 50% (Table 2). TN is expected to be in the form of nitrate.

3.3.8. Data for transfer coefficients of N and P of WWTP

The current average efficiency of TN and TP removal in the WWTP of Kunming is 56% and 70%, respectively (KMSC, 2003). Since the transfer coefficient of nitrogen from the WWTP to sludge is primarily dependant on the heterotrophic growth of biomass, i.e., less dependent on nitrogen removal processes, it can be assumed to be a constant for WWTPs with different nitrogen removal efficiencies. It is therefore assumed to be similar to general data from the literature $k_{5,7}^{(\text{N})}=0.16$ (Herrmann and Klaus, 1997); for TP the transfer coefficient to air $k_5^{(2)}(P)=0$.

4. Results and discussions

4.1. Current conditions

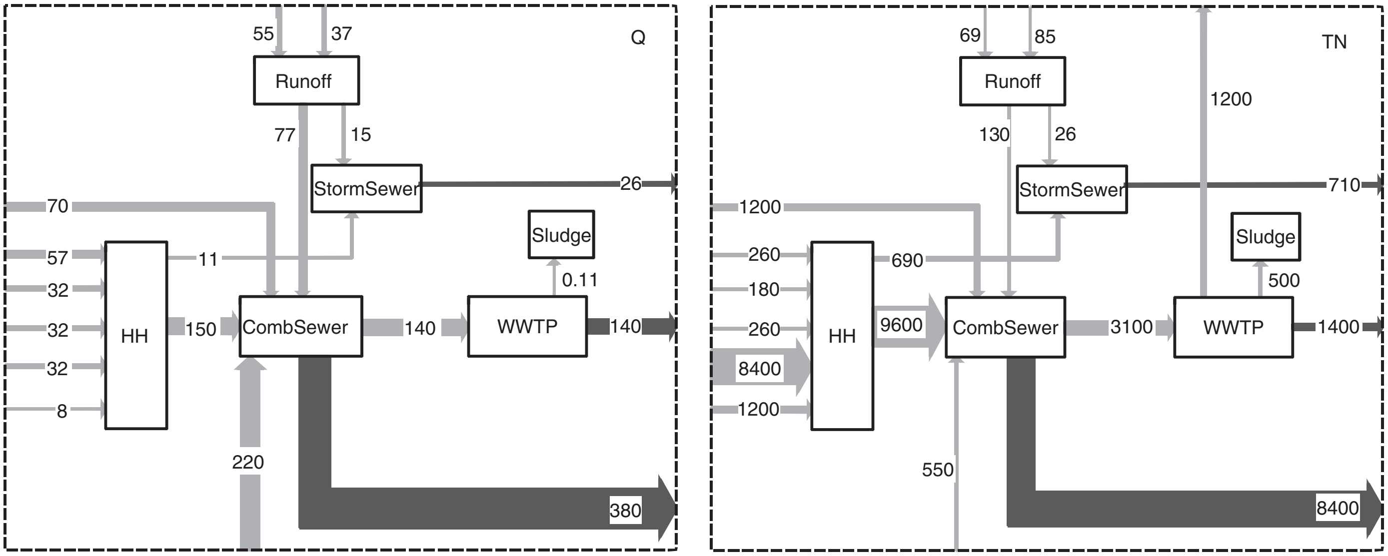
Simulation results for the current conditions of water, TN and TP flows in the urban drainage system of Kunming are illustrated in Fig. 4. The main results for the current status can be summarised as follows:

(1) The efficiency of the current wastewater collecting system (i.e., the ratio of wastewater treated in the WWTPs versus the overall incoming wastewater) in Kunming is less than 30%. As a result, large amounts of wastewater are discharged into receiving waters without treatment.
(2) Sewer infiltration is as high as 100% of the total quantity of sanitary wastewater discharged into the sewer system during dry weather; this is a major problem for the current sewer system in the city.
(3) The emission of TP from the current urban drainage system is more than 20 times higher than the total tolerance level of Dianchi Lake estimated by Gray and Li (1999).
(4) The existing wrong connections alone contribute more than twice the TP tolerance of Dianchi Lake.

Table 4 compares the TP results of Liu et al. (2004); Liu (2005) and of this paper. As can be seen from the table, previous studies greatly underestimated the overflow load because they overlooked the large amount of sewer infiltration, including both groundwater and river water, entering the sewerage system.

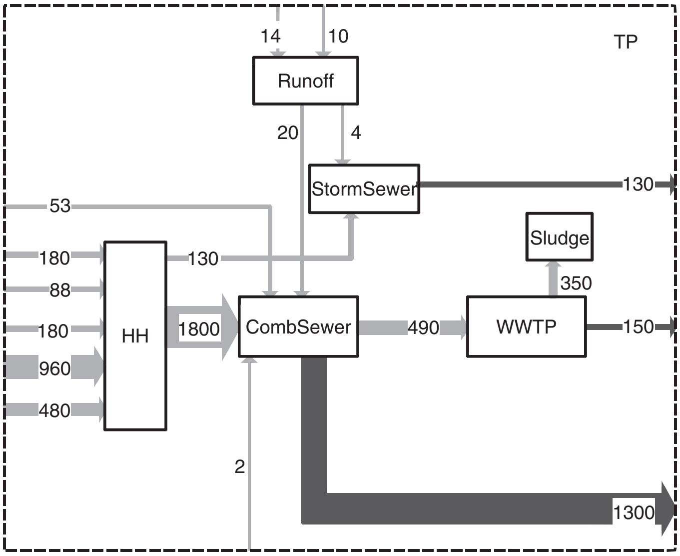
4.1.1. Sensitivity and uncertainty analysis

To identify the most sensitive parameters for the total emission of the whole system, a sensitivity analysis is conducted by altering each of the parameters by 10%. It showed that the most sensitive parameters with respect to the total output to receiving waters are the population in the catchment area, the specific emission per person and



Water flow, Kunming: [10^6 m3 / year]

TN flow, Kunming: [tons / year]



TP flow, Kunming: [tons / year]

Fig. 4. Current conditions—material flow scheme of water, TN, TP in the urban drainage system of Kunming City. For descriptions about flows, refer to Fig. 2.

Table 4
Results comparison with Liu, 2004, 2005

TP flows (tons/year)	Denotation in model	Liu (2004)	Liu (2005)	This paper
Human waste	$I_{1,4}+I_{1,5}$	1601	895	1440 ± 200
Input WWTP	$F_{3,5}$	581	533	490 ± 110
Overflow	$O_{3,2}$	0	233	1300 ± 180
Effluent WWTP	$O_{5,1}$	150	138	150 ± 45
WWTP to sludge	$F_{5,7}$	430	394	350 ± 80

day from urine and faeces, the WWTP capacity and the treatment efficiency. The sewer infiltration flow is currently one of the key reasons for reduced wastewater collection and treatment efficiency. However, it must be pointed out that this is only true for the set of parameters used for the current conditions. Other parameters may be more sensitive for other parameter sets.

Uncertainty analysis is a necessary way of estimating the uncertainty of the simulation results. The uncertainty of the parameters in Table 2 was estimated using comparative

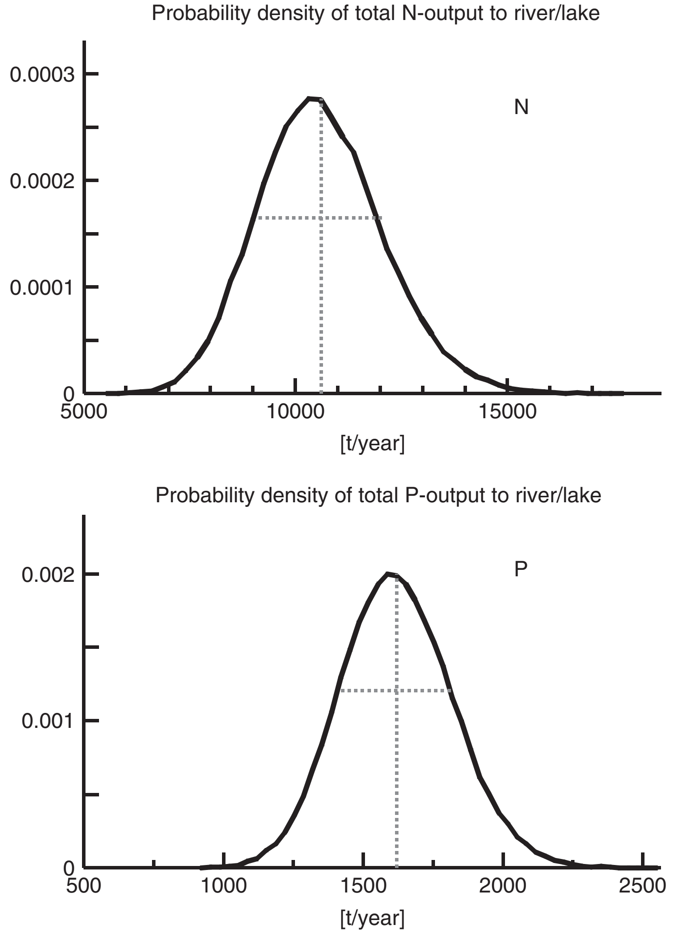


Fig. 5. Uncertainty analysis—probability density of the total output of TN and TP (in tons/year) to receiving water from the current urban drainage system in Kunming in terms of the uncertainties of all parameters involved.

literature data and plausibility arguments. A log-normal probability distribution was assumed for the parameters of Table 2 with given mean and standard deviation in %. A uniform distribution was assumed for the parameters given by ranges.

A Monte Carlo simulation with a sample size of 100,000 was applied to calculate the distribution of the flows and stock change rates. Fig. 5 shows the result for the flows of nitrogen and phosphorous to the receiving water. Thus even taking into account the large uncertainties of the data, the phosphorous flow to the receiving water is far beyond the critical load of Dianchi Lake (33 tons/year of TP from the urban drainage system).

4.2. Technical limitation

In this analysis, we apply the scenario of BAT to the case of Kunming.

It is assumed that Kunming will upgrade its urban drainage system to the standard of Zurich and all WWTPs will use BAT for their wastewater treatment. For the BAT scenario, the operational data of CSO tanks in Zurich are used for calculating the transfer coefficients $k_{3,6}$, $k_{3,5}$, $k_{6,5}$, etc. It is important to note the differences of these transfer coefficients between water and other substances, because the CSO occurs at heavy rain events when wastewater is diluted. The details are listed in Table 2.

In the BAT scenario, wrong connections are eliminated by properly standardised industrially designed pipes and by sewerage construction management. Sewer infiltration is controlled to a range of approximately 30% of water consumption. Simulation results (Fig. 6) show the emissions from the urban drainage system with the BAT to be about 39 tons/year from WWTP effluent and 11 tons/year from CSO tank overflow. Moreover, 2 tons/year from high-water discharge ($O_{3,2}$ in Fig. 2 for the BAT scenario), and 5 tons from separated storm-water discharge (20% of area connected to separated storm sewerage). Altogether the emission into receiving water is approximately 57 tons/year, which is about 1.7 times the estimated critical value for the urban drainage system. Therefore, even with a BAT dimensioned for the current population size, the urban drainage system is incapable of removing sufficient phosphorous to remain below the critical load for Dianchi Lake.

4.3. Discussion on measures

The above discussion of the BAT has made it clear that new strategies have to be taken to avert the ecological deterioration of Dianchi Lake. The present serious conditions and the technical limitations of current methods are certainly a surprise for practitioners who are eager to imitate the past "success" stories of conventional urban water management in developed countries. The functionality of many ecosystems could be restored if appropriate action was taken in time (Lubchenco, 1998). In situations like that of Kunming, both immediate as well as long-term action are necessary. The longer the present situation is allowed to continue, the more difficult it will be to restore the lake.

Several scenarios were selected in order to design or identify strategies for improving the situation. These scenarios are described below:

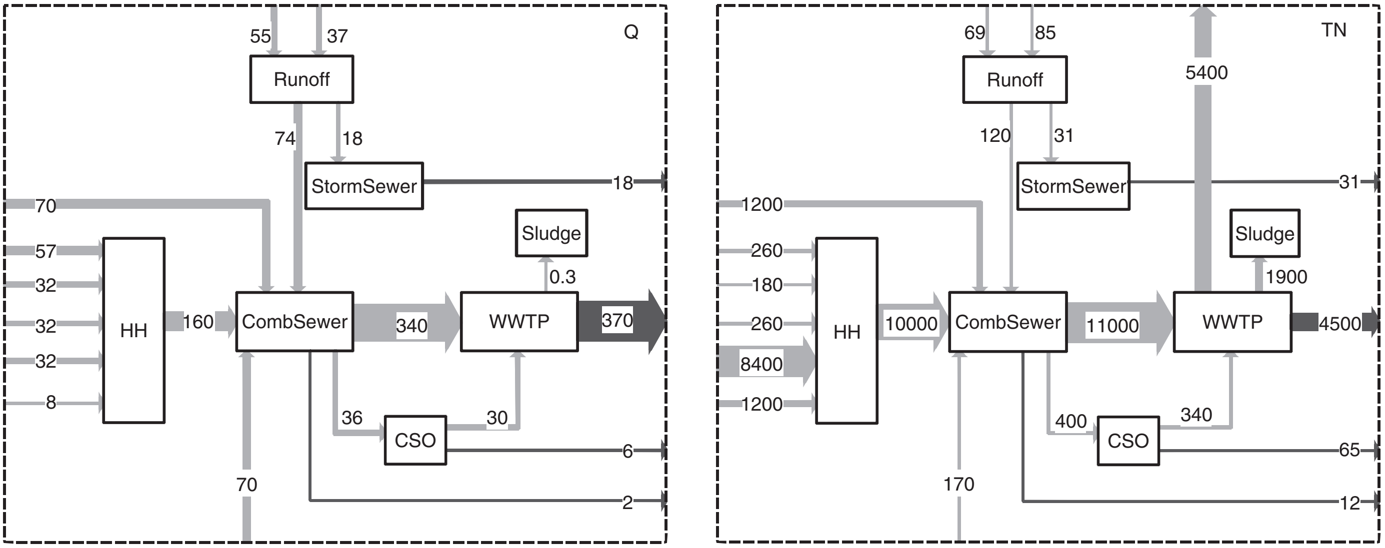
(1) Current conditions with total separation of urine and faeces, (2) BAT with current urban population; (3) BAT with a projected urban population of 4.5 million; (4) 40% of urine separation based on scenario 3; (5) Scenario 4 and 60% of water diverted to rivers downstream of Dianchi Lake.

The crucial flow is the TP output to the receiving waters:

$$O_{tot}^{(\mathrm{P})} = O_{5,1}^{(\mathrm{P})} + O_{6}^{(\mathrm{P})} + O_{3,2}^{(\mathrm{P})} + O_{4}^{(\mathrm{P})}.$$

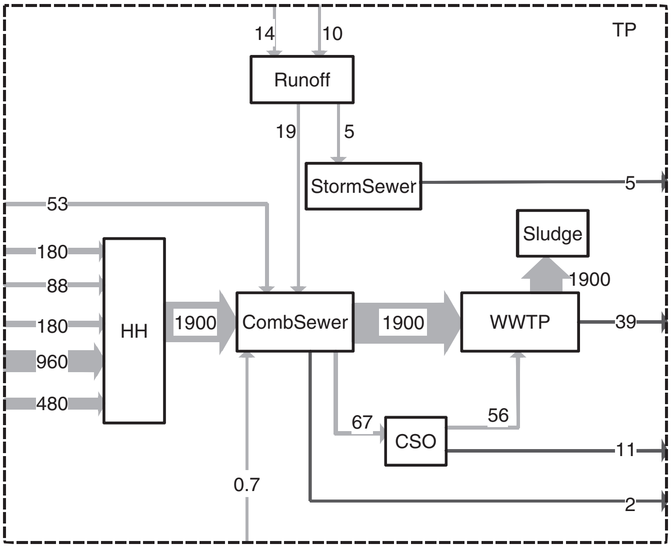
In order to gain insight into the various dependencies of $O_{tot}^{(\mathrm{P})}$, the following formula is useful. Neglecting the phosphorous sewer infiltration flow$I_{3,2}^{(\mathrm{P})}$, it follows in the case of BAT that for$O_{tot}^{(\mathrm{P})}$

$$O_{tot}^{(\mathrm{P})} = P\{1 - \eta_c^{(\mathrm{P})}(k_{3,5}^{(\mathrm{P})} + k_{3,6}^{(\mathrm{P})}k_{6,5}^{(\mathrm{P})})\}(p_1^{(\mathrm{P})} + p_2^{(\mathrm{P})}$$



BAT scenario, water flow, Kunming: [10^6 m^3 / year]

BAT scenario, TN flow,Kunming:[tons / year]



BAT scenario, TP flow, Kunming:[tons / year]

Fig. 6. BAT scenario—material flow scheme of water, TN and TP of the urban drainage system in Kunming for the best-available technology. For descriptions about flows, refer to Fig. 2.

$$+p_3^{(\mathrm{P})}+p_4^{(\mathrm{P})}+p_5^{(\mathrm{P})}+p_8^{(\mathrm{P})})365$$
$$+PHA\{C_{roof}^{(\mathrm{P})}rp_6+C_{street}^{(\mathrm{P})}(1-r)p_7\}$$
$$\times(1-p_{11}\eta_c^{(\mathrm{P})}(k_{3,5}^{(\mathrm{P})}+k_{3,6}^{(\mathrm{P})}k_{6,5}^{(\mathrm{P})})). \qquad (14)$$

The first term in Eq. (14) is the load from households, industry and services. The first bracket describes the technical state of the wastewater treatment system and the second bracket the "source intensity" of households, industry and services. The second term in Eq. (14) represents the load from roof and street runoff, which is normally of minor importance. Eq. (14) allows a simple quantitative discussion of the different reduction strategies such as source control (parameters $p_1^{(\mathrm{P})},\ldots,P_8^{(\mathrm{P})}$) or technical improvements (parameters $k_{3,5}^{(\mathrm{P})}$, $k_{3,6}^{(\mathrm{P})}$, $k_{6,5}^{(\mathrm{P})}$) as well as the scenario with a specified population growth.

Taking into account the Dianchi "tolerance equation":

$$\kappa O_{tot}^{(\mathrm{P})}\leqslant\tau, \qquad (15)$$

where τ is the allowable TP load from the urban drainage system into Dianchi Lake, ton/year; κ the percentage of urban water effluent that discharges into Dianchi Lake, $1-\kappa$ is the percentage of urban water effluent discharged into downstream rivers; it is possible to estimate the carrying capacity of a population P_{crit} which is tolerable for Dianchi Lake under the given conditions of "source intensities" and the technical state of the wastewater treatment system.

Table 5 lists the total output of TP into Dianchi Lake for the five scenarios. The main results are:

- The results of scenario "1" show that going back to the old traditional way of handling urine and faeces would

Table 5
Total emission of TP into Dianchi Lake in various scenarios

Scenario	No of scenario	Total output of TP into Dianchi Lake (tons/year)
Current condition + urine and faeces separation	"1"	410
BAT	"2"	57
BAT + projected future population	"3"	106
"3" + 40% of urine separation	"4"	87
"4" + 60% water diversion	"5"	35

indeed reduce the TP load considerably from about 1600 t/year to about 400 tons/year (Table 5). However, this load is still far from the critical limit. Moreover, it is questionable if such a development would be accepted by society. The handling of this "night soil" remains another question.

- If all effluent is discharged into Dianchi Lake, the current population in Kunming City has already exceeded the lake's carrying capacity, even in the BAT scenario, see Table 5 and Section 4.2. Calculations show that the carrying capacity of the population under current conditions is: $P_{crit} = 91,000$ and for BAT: $P_{crit} = 1.4$ million.
- Urine separation (reduced specific emission $p_4^{(P)}$ in Eq. (14)) and water saving is to be recommended, if implemented in a feasible way (Starkl and Brunner, 2004). Some 40% of urine separation would reduce the total emission into Dianchi Lake considerably and would therefore increase the carrying capacity of the catchment area. It would not just increase the carrying capacity, but the contribution of urine separation would also reduce the required size of the WWTPs by decreasing of nitrogen removal load, which is the main reason for enlarging a WWTP. The separated urine is assumed to be collected and treated appropriately as fertiliser, since this is still traditional agricultural practice in the local rural area.
- In highly populated areas such as Kunming, diverting the discharge of the urban drainage system is almost obligatory to halt the eutrophication problem of the receiving lakes. On the basis of the scenarios for Dianchi Lake mentioned above, a 60% diversion of urban drainage discharge, even with an enlarged population, can meet the critical requirement of TP emission from the city. It must be noted that the prerequisites for this are (1) the water balance of Dianchi Lake is maintained and (2) the diverted discharge should meet the requirements of the downstream rivers.

The water balance of Dianchi Lake must be handled carefully if the water diverting measure is taken. It is nevertheless feasible when (1) a certain amount of clean water is discharged from upstream reservoirs into Dianchi Lake and (2) the lake itself is also used as a source of water supply. This condition could only be enabled when the water quality of the lake had already been improved to meet the standard of water supply resources.

5. Conclusions

Fundamental progress in improving the water environment in developing countries cannot be achieved through incremental advancement with conventional technical approaches. Decision makers and planners face both serious current conditions and the technical limitations of conventional urban drainage and wastewater treatment, as exemplified by the city of Kunming. However, this should neither be taken as a criticism of today's urban drainage concepts nor as an argument for abandoning these concepts. A city without sewerage and a WWTP is difficult to imagine. But to overcome the limitations of these systems and to prevent ecological problems in the future, there is urgent need for measures to improve the performance of today's systems.

With this message, we would argue that the research efforts made to develop household sanitation oriented to source control and its appropriate policy enforcement are still required until an equivalent or better household sanitation service can be supplied than the traditional approach. This should be done despite the fact that a generally accepted alternative system is not yet practical for a city beyond the pilot scale.

We would also argue that solutions must be found in a systematic way. As indicated by the case of Kunming, this will not only involve the improvement of the household sanitation system, sewerage system and wastewater treatment, but also the regional water balance and the water supply system. Such a complexity of solutions requires further studies.

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