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Sustainable stormwater management in Yinchuan New Town

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Abstract

In Yinchuan, China, a new urban area is planned for 160,000 inhabitants, in the vicinity of the Yellow River and close to a valuable natural landscape. To achieve sustainable development, an approach integrating urban planning, transport, energy, solid waste and water resources management is necessary. In order to achieve this, the SimbioCity approach was applied, where resource use and pollutant loads are reduced by creating cycles in which materials and water are recycled to the largest possible extent. In this context, the stormwater system is an important component. The objectives for the planned stormwater system in Yinchuan New City were to reduce flood risk and introduce stormwater purification, to maintain or improve water quality in the existing water bodies. A Sustainable Urban Drainage System approach was proposed and applied, during configuration and design of the new town's infrastructure. This proved both successful and cost effective.

Key words: sustainable cities, sustainable urban drainage systems, urban water and sanitation

Objectives

The configuration and design objectives for water and solid waste management in the Yinchuan New Town project were to:

- Determine a general water balance for the project area
- Develop guidelines and a design for the stormwater drainage in the area
- Design a wastewater system integrated with the solid waste system
- Design a wastewater treatment plant including nutrient reduction
- Prepare a proposal for potable water use reduction by separating black and grey waters

The water balance included an estimate of water need for the area, including evaporation from Mingcui Lake, and predicted water use in Yinchuan New Town, as well as estimates of water availability from different sources like water reuse and abstraction from existing irrigation channels.

The objective of this paper is to present the methodology applied in order to achieve SuDS in the project area and the results obtained.

INTRODUCTION AND BACKGROUND

Yinchuan is the capital of Ningxia Hui Autonomous Region, China (People's Republic of China (PRC)). It has a typical, temperate continental monsoon climate, with little rain and high evaporation rates. Given its proximity to the Yellow River and a developed channel system, the area has relatively good surface- and ground-water conditions. The surrounding region, however, is very short of water.

The main driving forces in Yinchuan's new urban area are housing and tourism. When fully developed, the new town is expected to have approximately 160,000 inhabitants. The aim is to develop it on an artistic and cultural profile, as well as sustainability principles. The Mingcui Lake, a valuable natural landscape, together with a large area of fishponds, channels and ditches, makes up the basic texture of the site. A key requirement was to safeguard the hydrologic and water quality conditions of the lake and wetland in the north of the project area (Sweco 2013). The original site is shown in Figure 1. The wetland is the shallow zone around the lake.

Figure 1 | Existing texture and structure of the project area.

To achieve sustainable urban development, an approach integrating urban planning, transport, energy, and solid waste and water resource management is necessary, with the latter playing a key role. The design of these components was an integral part of the urban planning and design process.

The approach to achieving sustainable urban development was based on the SimbioCity methodology (Ranhagen *et al.* 2007). The principles of SimbioCity incorporate a multi-disciplinary mode of operation that enables combined problems to be solved successfully, taking into account social, institutional, environmental, technical, economic and spatial aspects (Ranhagen *et al.* 2012). A basic tool in the methodology is the eco-cycle model, where reduced resource use and pollutant loads are sought by creating cycles where materials and water are recycled to the largest possible extent, or used in energy generation. Resource use is reduced by introducing efficient techniques, and taking advantage of the synergies created by integrating the water, waste and energy cycles. An example of this is the generation of biogas (energy cycle) from organic waste (waste cycle) and wastewater sludge (water cycle). Similar approaches have been proposed by others (Novotny 2011).

The relevant standards for urban drainage in China are GB 50318-2012 Code of Urban Drainage Engineering Planning, GB 50318-2000 Code of Urban Wastewater Engineering Planning, and GB 50014-2006 Code for the Design of Outdoor Wastewater Engineering.

Average precipitation around Yinchuan is 189 mm/year, with average water surface (potential) evaporation of 1,197 mm/year. Precipitation occurs from June to August, inclusive, and the twenty first century has seen some flooding in the existing urban areas, such as that in the central areas of the city in July 2012.

The relevant Chinese water quality standard is GB 3838-2002. Water quality in Mingcui Lake is below grade III, where grade I is the best and grade V the worst. Water quality in the lake is moderate, due to agriculture drainage and the discharge of untreated wastewater from rural villages in the area.

The Chinese standard states that stormwater pipes must be designed for a storm with a return period up to 3 years, based on the characteristics of the catchment, and its topography and climate conditions, and from 3 to 5 years for important roads (GB 50014-2006).

METHOD

With respect to stormwater management and flood prevention, alternatives to a conventional stormwater sewer system were needed because flood events have been relatively frequent, even though the project area has low average annual precipitation, because of the very concentrated rainy period. Moreover, the stormwater management system had to avoid polluting existing water bodies during rainfall events. In order to comply with these demands, a new approach was applied based on stormwater detention and treatment.

The method and solution applied had two objectives:

- To avoid flooding important roads, as well as residential and commercial areas, for a 100-year return period flood, although the costs for achieving this must be reasonable.
- To introduce stormwater treatment to maintain or improve water quality in Mingcui Lake.

To achieve these goals, a SuDS approach was applied during configuration and design of Yinchuan New Town's infrastructure.

The approach proposed in the CIRIA SuDS Manual (Woods-Ballard *et al.* 2007) was used as the design basis. According to CIRIA, stormwater should be managed in small, cost-effective landscape features in small sub-catchments, rather than being conveyed to and managed in large systems at the bottom of drainage areas (end of pipe solutions). In addition, solutions used in Malmö, Sweden (Stahre 2006, 2008) as well as Portland, USA (Liptan 2011) were applied, with some adaptation to local conditions in Yinchuan.

Three stormwater management levels were proposed for Yinchuan (Figure 2): plot level, channels leading to a purification pond, and discharge to the existing wetland or lake.

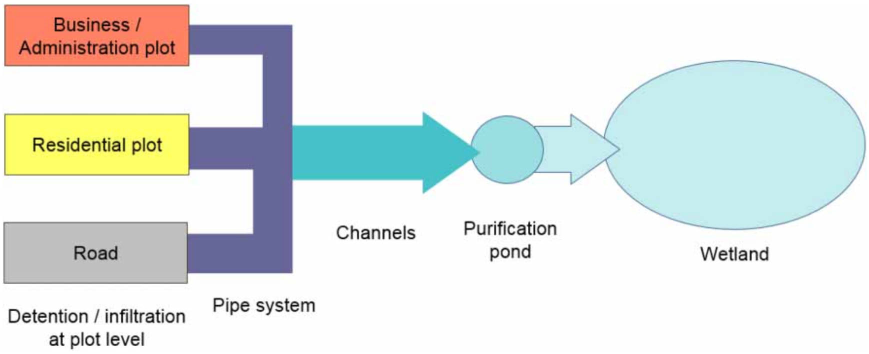

Figure 2 | Basic configuration of the stormwater system in Yinchuan New Town.

The detention volumes required for a catchment area, at plot and channel level, were calculated using the Equation (1) below:

$$V_{detention} = (\mathrm{Q_{in}} - \mathrm{Q_{out}}) * \mathrm{tr} * \frac{60}{1,000} \tag{1}$$

where:

$V_{detention}$: detention volume (m^3)
t_{r}: rain duration (min)
Q_{in}: runoff flow, calculated as

$$Q_{in} = Q_{runoff} = i * \sum_{k=0}^{n} C_k * A_k \left(\frac{l}{s}\right) \tag{2}$$

Δ_{k}: Area k within the plot or channel watershed (ha)
i_{k}: runoff coefficient for Area k (dimensionless)
Q_{out}: given outflow from the channel or detention structure at plot level (l/s)
L rainfall intensity (l/s/ha)

The rain intensity equation recommended for Yinchuan by China's Meteorological Agency is

$$i = 242 * \frac{1 + 0.83 logT}{t_r^{0.477}} \tag{3}$$

where T is the return period (years). The return period for the plot level detention structures was 10 years, that for the channels 100.

Detention volumes were calculated using formulas (1) to (3) above, for different values of rain duration (tr). The maximum of these detention volumes is thus that required for the catchment.

The pollutant loads and treatment requirements were estimated using the StormTac watershed modelling tool (StormTac version 2015-1, StormTac Storm Water Solutions). The structure of Storm Tac is presented in Figure 3.

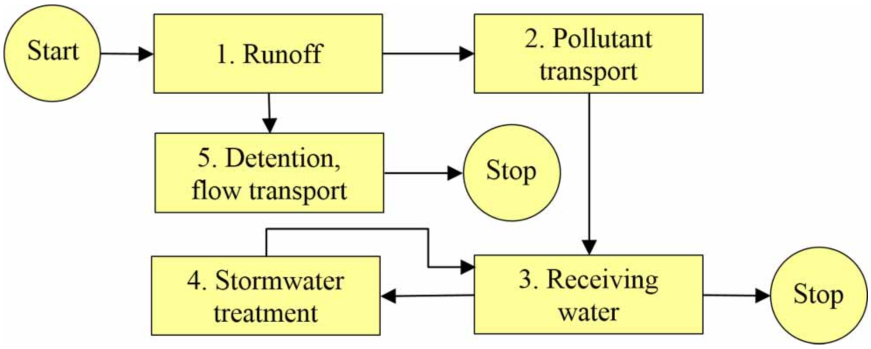

Figure 3 | Simplified flowchart for the watershed management model StormTac.

Stormwater discharge was identified as one of the major polluting emissions in urban areas in Sweden (Alm *et al.* 2010). StormTac is used to estimate the mean pollutant concentration based on the specific land use(s) in the catchments. It uses 'standard concentrations' per land use type, to calculate pollution loads at the catchment discharge point.

In Yinchuan New Town, the treatment facilities considered will comprise the channels or ditches, and the treatment ponds upstream of the discharge point. There is also some treatment at plot level; however, since there will be some stormwater detention facilities at this level, so it is not possible to establish which load reduction is applicable. Because of this, the treatment at plot level was excluded from the load reduction estimates – i.e., no load reduction is considered in the estimates at plot level – yielding a conservative approach.

For wet ponds and constructed wetlands, reduction efficiency is calculated using Equation (3) (Larm 2014)

$$\mathrm{Reduction}\ (\%) = \left[k_1 * \ln\left(\frac{A_p}{A_{red}}\right) + k_2\right] * f_{Cin} * f_{veg} * f_{bypass} * f_{vd} * f_{Cirr} * f_{temp} * f_{shape} \tag{4}$$

where:

A_p: Pond or constructed wetland area (m^2)
A_{red}: Reduced catchment area, calculated as $A_{red} = \sum_{k=0}^{n} C_k * A_k$, that is the area multiplied by its runoff coefficient
A_k: Area k within the catchment (ha)
C_k: runoff coefficient for Area k
k_1, k_2: regression coefficients for the individual pollutant
f_{Cin} : inlet concentration factor
f_{veg} : vegetation factor
f_{bypass} : bypass factor
f_{Vd} : detention volume factor
f_{Cirr} : irreducible concentration factor
f_{temp}: temperature factor.
f_{shape} : shape factor.

The runoff and regression coefficients, and all factors above, are dimensionless.

The minimum outlet concentration, the 'irreducible concentration' (C_{irr}), arises from influent content and internal processes in ponds and wetlands (decomposition of plants, seepage of anaerobic liquors from the bottom, exchange with sediment, sediment disturbance by benthic animals, etc.), which limit the extent to which pollutants can be removed. In StormTac, the reduction efficiency is adjusted so that nothing less than minimum concentrations are obtained at the outlet. The irreducible concentrations were estimated from effluent concentration data from facilities in Europe. Some examples of these are C_{irr} (P_{tot}) 20–30 µg/l, C_{irr} (Cu) 6–7 µg/l, C_{irr} (Zn) 14–25 µg/l and C_{irr} (SS) 5–10 mg/l (Larm 2014).

For channels, swales and ditches, the reduction efficiency is calculated using Equation (5) below:

$$\mathrm{Reduction}(\%) = \left[k_1 * \ln\left(\frac{A_{ditch}}{A_{red}}\right) + k_2\right] \tag{5}$$

where:

A_{ditch}: channel or ditch area (m^2)
A_{red}: reduced catchment area (ha)
k_1, k_2: Regression coefficients for the individual pollutants, dimensionless.

The regression coefficients and factors used in the equations above have been obtained from existing ponds, swales and other stormwater detention and treatment facilities, mainly in Europe and North America (Larm 2000; Larm & Hallberg 2008). The annual precipitation at these overseas sites is higher than that at Yinchuan but, as precipitation in Yinchuan occurs mainly between June and August, rainfall intensity is similar to that at the sites used as a base for StormTac. Other factors which may influence removal efficiency, apart from pond size and form, are the vegetation and soil types used in the treatment ponds, which are basically the same or very similar in Yinchuan and the sites where the factors and coefficients were deduced.

The recommended surface area for a channel or ditch to achieve a satisfactory pollutant removal rate is at least 2% of the reduced catchment area (Larm & Banach 2011).

RESULTS

The project area was divided into sub-catchments on the basis of topographic levels, and road and green areas, as well as stormwater infrastructure planned for Yinchuan New Town. The topographic levels, and the proposed infrastructure and landscape, were all based on the site's existing natural characteristics. The main roads usually established the watershed limits, while the green corridors and channels constituted the flooding areas. This required an iterative process involving different professionals – e.g., hydrologists, road engineers, landscape architects and city planners.

The catchment area for Channel B, is shown in Figure 4. The sub-catchment characteristics are presented in Table 1.

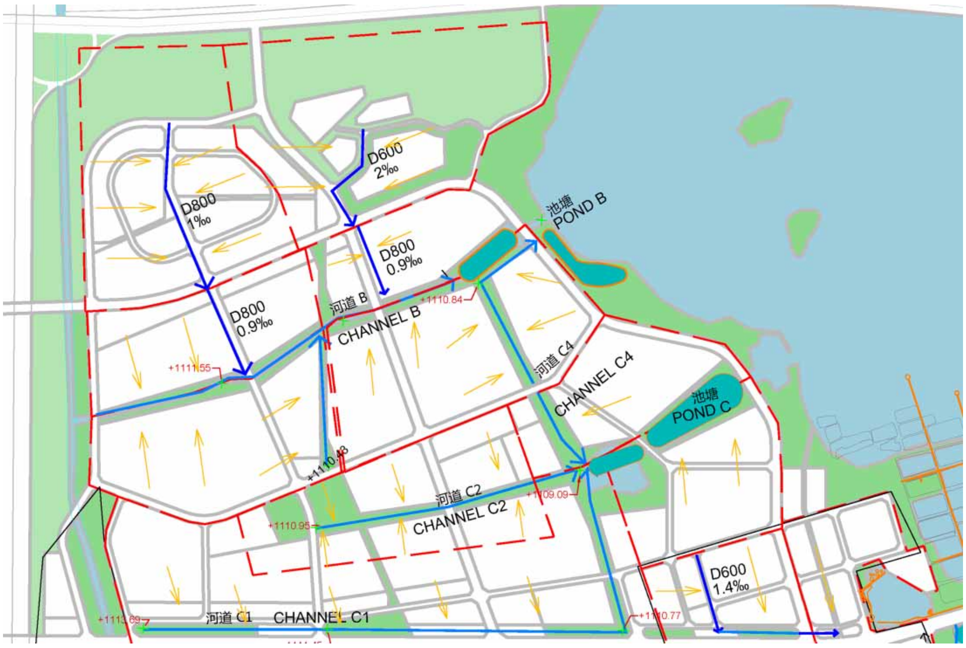

Figure 4 | Catchment area for Channel B.

Table 1 | Main data sub-catchments in Yinchuan New Town

Sub-catchment	A + B	C	D	E	H + I
Area (ha)	232	167	249	207	164
Average runoff coefficient	50%	49%	53%	53%	54%
Reduced area (ha)	116	82	132	110	89

The required detention volumes at plot level for a 10-year return period and channel level for a 100-year period for the sub-catchments in Yinchuan New Town are presented in Table 2.

Stormwater detention structures, such as road planters (Figures 5 and 6) and detention ponds, were proposed as means of detaining the plot level volumes reported above.

Table 2 | Required detention volumes

	Required detention volumes (1,000 m^3)	
Sub-catchment	plot level	channel
A + B	67	78
C	47	51
D	81	90
E	26	30
H + I	55	61

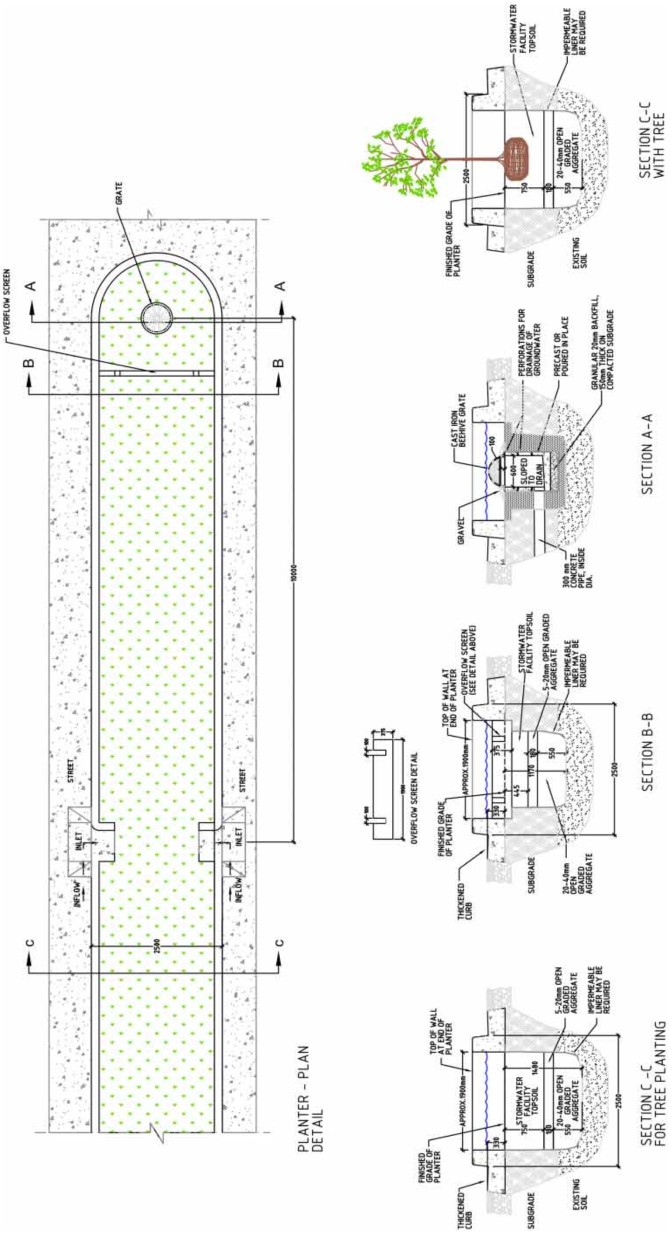

Figure 5 | Type drawing for road planters.

Figure 6 | Road planters, Yinchuan New Town.

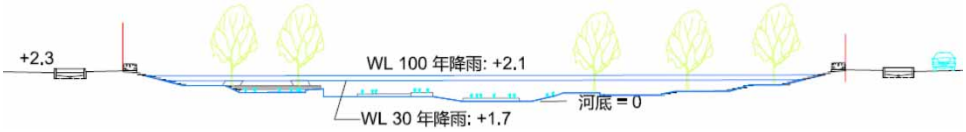

Figure 7 | Floodwater retention area, Channel B (WL 100 = 100-year return period water level).

Figure 8 | One of the detention/treatment ponds in Yinchuan New Town.

Table 3 | Detention ponds areas and volumes

Sub-catchment	A + B	C	D	E	H + I
Pond area (m^2)	12,000	28,000	7,000	7,000	34,000
Pond volume (m^3)	71,200	85,500	153,200	150,200	142,700

Multi-functional areas have been used in Yinchuan to obtain the necessary detention volumes at channel level. The landscape channels and adjacent parks have been designed to function as floodwater holding areas during rainfall events. Landscape levels have been designed to secure the necessary volumes, maintaining flood levels below road and building thresholds. As an example, see Figure 7.

The detention pond surface areas and volumes, and calculated pollutant loads before and after treatment in channels and ponds are shown in Tables 3 and 4. One of the detention ponds in Yinchuan New Town is shown in Figure 8.

The length to width ratio of a detention pond should be 3:1 or greater, and vegetation in the shallow zones should cover 25 to 45% of the pond's area (Larm & Banach 2011). The anticipated pollutant concentrations in stormwater runoff were calculated on the basis of the proposed land use(s), see Table 4:

Table 4 | Anticipated pollutant concentrations

		Concentrations prior to treatment, calculated using StormTac, μg/l				
	Grade III limit concentrations, μg/l (Chinese standard GB 3838-2002)	A + B	C	D	E	H + I
Tot P	50	197	195	195	185	172
Tot N	1,000	1,773	1,547	1,775	1,838	1,858
Tot Pb	50	11	11	11	10	8
Tot Cu	1,000	20	19	21	21	21
Tot Zn	1,000	86	82	85	79	71
Tot Cd	5	0.6	0.5	0.5	0.5	0.4
Tot Cr	50	5.0	4.2	5.1	5.4	5.6
Tot Hg	0.1	0.0	0.0	0.0	0.0	0.0
oil index	50	821	627	762	733	628
COD	20,000	56,437	62,482	54,245	46,057	36,583
BOD	4,000	6,887	7,960	6,733	5,731	4,780

Table 5 | Proportional pollutant load reduction arising from treatment in channels and ponds

	Proportional pollutant load reduction (%)				
	A + B	C	D	E	H + I
Tot P	79	79	79	78	76
Tot N	51	50	52	52	49
Tot Pb	87	86	86	84	81
Tot Cu	61	60	61	62	62
Tot Zn	83	82	82	81	79
Tot Cd	83	83	84	84	79
Tot Cr	68	68	69	70	71
Tot Hg	80	80	82	82	78
oil index	98	98	98	98	98
COD	96	96	97	97	94
BOD	96	96	97	97	95

As shown in Table 4, the anticipated – i.e., calculated – concentrations of Tot P, Tot N, oil index, Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), in the untreated run-off waters all exceed the permissible Grade III water quality levels. The values given in Table 4 were used to determine the pollutant load reduction required from the stormwater detention and treatment facilities. The proportional pollutant load reduction given by channel areas of between 2 and 6% of the reduced sub-catchment and pond areas – Table 3 – are shown in Table 5:

These pollutant load reductions, from those anticipated in the storm run-off waters, would lead to the post-treatment pollutant concentrations shown in Table 6. All of the latter now meet the Grade III water quality requirements.

Table 6 | Proportional pollutant concentrations after treatment, μg/l

		Concentrations after treatment, μg/l				
	Grade III limit concentrations, μg/l	**A + B**	**C**	**D**	**E**	**H + I**
Tot P	50	41	41	41	41	41
Tot N	1,000	875	768	851	881	948
Tot Pb	50	2	2	2	2	2
Tot Cu	1,000	8	8	8	8	8
Tot Zn	1,000	15	15	15	15	15
Tot Cd	5	0.1	0.1	0.1	0.1	0.1
Tot Cr	50	1.6	1.3	1.6	1.6	1.6
Tot Hg	0.1	0.0	0.0	0.0	0.0	0.0
oil index	50	18.5	14.1	17.1	16.5	14.1
COD	20,000	2,295	2,541	1,646	1,397	2,056
BOD	4,000	249	288	178	151	244

CONCLUSIONS

Stormwater detention – i.e., flood control – was achieved for residential and commercial areas, and roads using a combination of detention at plot and building level, and planned green corridors and spaces. Between them, these provide detention volumes sufficient to maintain the water level below building thresholds for a 100-year return period flood event.

Stormwater treatment is achieved initially at plot level, then at channel level and finally at pond level, before discharge to the natural wetland.

An important factor in the introduction of SuDS in Yinchuan New Town has been its cost-effectiveness, due to the use of multifunctional areas. The green structure was used in an effective way to enable both flood management and stormwater run-off treatment.

High levels of cooperation between different professions – e.g., hydrologists, road engineers, landscape architects and city planners – were fundamental to achieving the necessary agreement on subjects such as topographic planning settings and land use. This, among other factors, helped make a successful stormwater detention and treatment strategy and application possible.

It is recommended that monitoring points are set up to obtain real water quality values. Since the pollutant load calculations are based on development and stormwater detention facilities in Europe and North America, measurements of the actual loads and load reductions should be made. They will form the basis of a follow-up strategy, allowing adaptive measures to be taken to ensure a successful outcome, when the new development and proposed stormwater facilities are complete and functioning.

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