

# Sustainability requirements of implementing water-reuse concepts for new industrial park developments in water-stressed regions

S. Bauer , A. Dell, J. Behnisch, H. J. Linke and M. Wagner 

## ABSTRACT

Requirements for wastewater management and water-reuse concepts concerning sustainability are gaining greater importance, especially in times of climate change. Industrial park developments are often hindered due to water scarcity. Thus, nowadays, the reuse of wastewater is becoming more and more important to increase the availability of water and to enable new developments. The sustainable Industrial WasteWater Management Concept with the focus on Reuse ( $IW^2MC \rightarrow R$ ) provides a solution strategy to produce reuse water from industrial wastewater within production plants. To achieve sustainability, certain requirements are essential since the reuse water can be provided directly via an optimized wastewater treatment process for subsequent use. Hence, it is then 'fit for purpose'. This enables a more efficient application of reuse water. Furthermore, due to environmental issues, it is important to construct space-saving water resource recovery facilities for reducing land consumption within industrial parks.

**Key words** | 'fit for purpose', industrial parks, industrial wastewater, water reuse, water scarcity

## HIGHLIGHTS

- The reuse of wastewater is becoming more and more important to increase the availability of water and to enable new developments.
- An optimized treatment process reduces the required area inside the industrial park.
- The IRF can be increased by optimized industrial park management by controlling new production plant settlements.
- The  $IW^2MC \rightarrow R$  has to fulfill diverse sustainability requirements.

**S. Bauer**  (corresponding author)  
Hochschule für Technik Stuttgart,  
Stuttgart,  
Germany  
E-mail: [sonja.bauer@hft-stuttgart.de](mailto:sonja.bauer@hft-stuttgart.de)

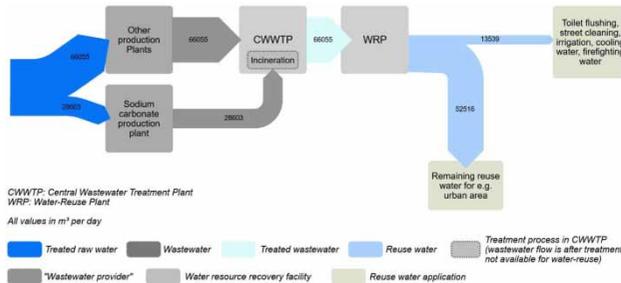
**A. Dell**  
**H. J. Linke**  
Department of Land Management,  
Technische Universität Darmstadt,  
Darmstadt,  
Germany

**J. Behnisch**  
**M. Wagner**   
Department of Wastewater Technology,  
Technische Universität Darmstadt,  
Darmstadt,  
Germany

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## GRAPHICAL ABSTRACT



## INTRODUCTION

In water-scarce regions, for instance, the northwestern parts of China, huge areas have high levels of water stress due to an uneven distribution of natural water resources and high levels of pollution of water bodies (WRI – World Resource Institute 2018). The development of industrial parks is generally related to the availability of water. Due to increasing water shortages, industrial park developments are often hindered; production plants may have high water requirements depending on their production processes. For instance, food production processes require less water than chemical production processes (Bauer *et al.* 2019). However, water is also needed for infrastructural purposes, such as the irrigation of green spaces or street cleaning in the park. Especially in water-stressed regions, the water demand for production plants increasingly competes with other water requirements such as municipal and agricultural water demand. This is resulting in the limitation of industrial expansions (Bauer *et al.* 2020a).

To enable new industrial park locations or their expansion in water-scarce regions, a sustainable water supply has to be ensured and water consumption from natural resources has to be reduced. In this context, and due to worsening climate change, new sustainable water-reuse concepts are achieving greater importance. Another important element is that industrial park developments drive urban developments (Zhao *et al.* 2017), which usually occur in densely populated urban areas. Thus, in industrial parks, the space for wastewater treatment plants is often limited due to the restricted availability of land as it is mostly provided for production plants. Hence, the reduction of

land consumption and a high water-reuse potential is important to implementing water-reuse concepts.

Previous studies in the context of water reuse focus mostly on municipal wastewater treatment and reuse in an urban context. A well-known concept is integrated urban water management (IUWM), which includes all aspects of the water cycle: wastewater, drinking water, stormwater, and evaporation (Sharma *et al.* 2008). IUWM is an approach for urban water utilities to minimize their impact on the environment, to maximize their contribution to social and economic issues, and to generate well-being (Maheepala *et al.* 2010). Another important approach is 'urban metabolism,' which can be holistically understood according to Musango *et al.* (2017) as a 'collection of complex socio-technical and socio-ecological processes by which flows of materials, energy, people, and information shape the city, service the needs of its populace, and impact the surrounding hinterland.' A further approach is the innovative SEMIZENTRAL approach (Tolksdorf *et al.* 2016; Tolksdorf & Cornel 2017). It was developed for a semi-centralized supply and disposal system for fast-growing urban areas. The municipal wastewater is treated in a semi-centralized Resource and Recovery Center (RRC). Instead of only one municipal central wastewater treatment plant in a large urban area, the urban area is divided into smaller units, each of which has an RRC. The RRC provides water 'fit for purpose' via an in-house solution. It integrates the sectors of wastewater treatment, reuse water supply, and waste treatment. The concentration of pollution in industrial wastewater varies greatly and usually depends on the

production process. Therefore, studies dealing with the treatment of industrial wastewater are very different and refer to specific case studies. As an example, a project by [Whyman \*et al.\* \(2019\)](#) dealing with industrial wastewater reuse at San Francisco airport can be mentioned here.

The particular aspect of the  $IW^2MC \rightarrow R$  concept presented here is that wastewater flows are clustered according to certain concentrations and can therefore be specifically treated. The wastewater treated according to the 'fit for purpose' principle is reused for infrastructural purposes. This approach is therefore not purely project-specific or production plant-specific and can therefore be transferred to other projects.

## MATERIAL AND METHODS

To enable sustainable industrial park developments, an innovative Industrial WasteWater Management Concept with the focus on Reuse (brand name:  $IW^2MC \rightarrow R$ ) is developed. The concept includes the efficient treatment of industrial wastewater in a central wastewater treatment plant (CWWTP) and an additional water-reuse plant (WRP) which provides reuse water 'fit for purpose' ([Bauer \*et al.\* 2020a](#)). The treated wastewater can directly be reused for respective applications, for instance, for the irrigation of green spaces. To achieve further aspects of sustainability, the  $IW^2MC \rightarrow R$  aims to reduce land consumption via an area-saving construction type of the CWWTP and the WRP. This aspect is an especially important issue in densely populated areas. To reduce land consumption, the wastewater treatment processes have to be optimized. Furthermore, the concept enables an optimization of water-reuse opportunities by reaching a high industrial park reuse factor (IPRF). The IPRF describes the relation between the wastewater inflow to the CWWTP and all possible reuse water flows. The IPRF includes the infrastructure reuse factor (IRF), which relates to infrastructural reuse applications, e.g., irrigation, street cleaning, and toilet flushing. Additionally, the IPRF includes the production plant reuse factor (PPRF), whereby it is possible to calculate the reuse water requirements for the production plants, such as process water ([Bauer \*et al.\* 2020a](#)). The  $IW^2MC \rightarrow R$  is not focusing on treatment processes for internal water

reuse for production plants within the industrial park. This is due to the fact that water reuse for infrastructural purposes is a further water-reuse opportunity as the internal reused water is discharged into the water resource recovery facilities at the end ([Bauer \*et al.\* 2020b](#)). Furthermore, production processes require a higher quality water than, for example, irrigation does. Consequently, the cost of treatment processes is higher as well. The concept focuses on the outflow of the WRP which is treated 'fit for purpose' for infrastructural purposes. Remaining reuse water can be discharged to the adjacent urban area since the water demand for irrigation and street cleaning cannot be covered by the municipal water resource recovery facility ([Bauer \*et al.\* 2020b](#)). Hence, it is not necessary to implement further cost-intensive treatment tracks for the treatment of the industrial wastewater for an internal production plant water reuse.

To calculate and evaluate area requirements for the CWWTP and WRP and to calculate the IRF, the creation of a model industrial park (MIP) is essential. Therefore, the case study of China was chosen due to its dynamic in developing greenfield areas as new industrial park locations ([Bauer \*et al.\* 2020a](#)). Furthermore, due to the uneven distribution of natural water resources, and the relatively high levels of pollution of water bodies, water shortage is often a challenge ([WRI – World Resource Institute 2018](#)). Another reason for choosing this case study area is that besides the United States, China is the country with the highest worldwide water requirements for industrial purposes ([FAO 2017](#)).

For the first IRF calculation, six exemplary production plants were taken into account. Accordingly, the IRF results in ~25% when including three infrastructural reuse applications: irrigation of green spaces, street cleaning, and toilet flushing ([Bauer \*et al.\* 2020a](#)). To get more viable results, an extended calculation that considered 19 production plants instead of six production plants was conducted. Using a MIP as methodology allows the adjustment parameters concerning wastewater quantity and quality. Even if the IRF varies due to the variety of production plants with different water demands, the MIP shows a methodology which calculates the reuse potential of a specific industrial site. If this is applied on real industrial parks, all parameters can be adjusted. The IRF shows a specific reuse potential for further applications as well as the

volume of remaining treated wastewater flows that can be discharged into the water body or can be applied for further purposes such as for the irrigation of city parks in an adjacent urban area.

Besides the MIP of six production plants, the reuse applications for cooling water and firefighting water were further considered. Concerning the land consumption of the water resource recovery facilities, the needed treatment technology for the MIP is identified and average sizes of CWWTPs and WRPs are analyzed. However, it should be noted in this context that a MBR plant is not necessarily needed for processing reuse water for infrastructural purposes, even if it takes up little space. If the use of reuse water has higher requirements, it would be possible to include the MBR, even if the costs are higher.

## RESULTS AND DISCUSSION

### Characteristics of the MIP with 19 production plants

For the MIP, the 19 production plants included several types of industries, such as chemical, paper, food, and beverage production facilities, as they are statistically the most water-intensive industries and various production types are often localized in industrial parks. Additionally, the wastewater of a canteen and generally sanitary wastewater are considered.

Wastewater flows were divided into categories (A to C) according to their carbon, nitrogen, and phosphorus concentration (see [Table 1](#)). These parameters were chosen because they are common in the characterization of wastewater flows and are often used to determine the qualities to be maintained for the treatment of wastewater. It was assumed that the wastewater would be of constant quality throughout the entire year. This is due to the fact that in industrial CWWTPs, the equalization tank homogenizes the loads, concentrations, and wastewater flow.

The criterion for characterization was a minimum nutrient supply for aerobic biological wastewater treatment with COD:N:P ratio of 100:5:1 ([Sahm \*et al.\* 2013](#)), as it is the central treatment process of each CWWTP ([Bauer \*et al.\* 2020a](#)). Wastewater flows with special characteristics, such as sodium carbonate (see No. 21, [Table 1](#)), which have a very

high salt concentration, have to be considered separately and should not be mixed with others. Incineration could be one solution for those flows. Based on this consideration of the basic parameters for wastewater characterization, a treatment track was defined, which must ensure a cleaning performance to comply with all required limit values. Those limit values are based on two Chinese water reuse standards. The 'Water quality standard for urban miscellaneous water consumption' ([GB/T 18920-2002](#); [MoHURD 2003](#)) contains quality requirements for toilet flushing, street cleaning, firefighting, irrigation, vehicle washing, and construction. The standard addressing industrial usage, in particular, is the 'Water quality standard for industrial water consumption' ([GB/T 19923-2005](#); [MoHURD 2006](#)). In this standard, requirements relating to reuse water qualities for cooling water, washing water, boiler feedwater, and process/product water are prescribed (for extracts see [Table 2](#)).

Due to the many food industries in the MIP, which produce highly loaded organic wastewater ([Ranade & Bhandari 2014](#)), in categories A to C the amount of COD (2,488,010 kg/d) is relatively high compared to the amounts of nitrogen (124,987 kg/d) or phosphorus (10,528 kg/d). It is, therefore, appropriate that the CWWTP provides at least two treatment tracks for wastewater treatment: anaerobic treatment to reduce carbon concentration and aerobic treatment to eliminate nutrients and further reduce COD (see [Figure 1](#)).

The anaerobic treatment makes it possible to obtain biogas and thus achieve the most energy-efficient treatment of wastewater. A detailed consideration of the wastewater flows shows that ethanol (see No. 10, [Table 1](#)) must be pre-treated to reduce high concentrations of solids. In this case, a simple sedimentation stage would be the best solution. The anaerobically pre-treated wastewater has to be discharged further into the aerobic process line to achieve further elimination of COD and nutrients. After the aerobic biological treatment, low concentrations of COD and nutrients are reached. To meet the requirements for the reuse standards, the treated wastewater is discharged to the WRP, filtered, disinfected by means of UV, and mixed with chlorine. It can then be reused for different applications. As the Chinese quality requirements of reuse water for irrigation, toilet flushing, firefighting, street

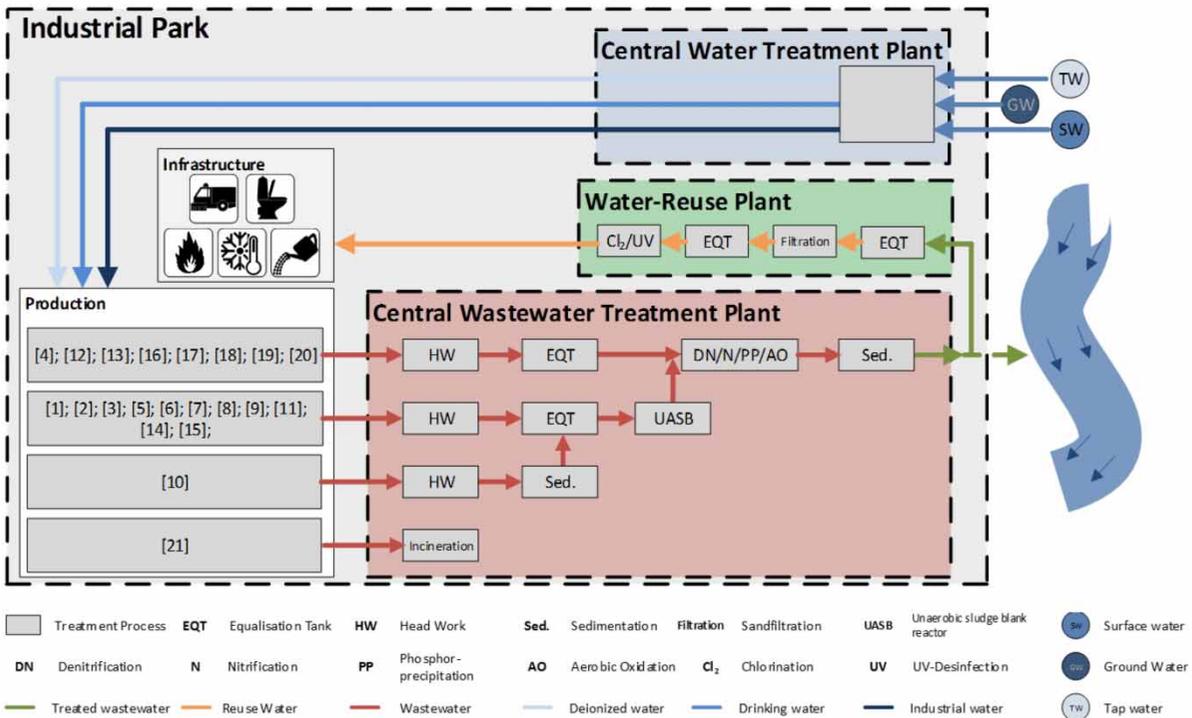
**Table 1** | Production plants in the MIP with the characteristics of the different wastewater flows (Bauer et al. 2019)

No.	Wastewater origin (production process/ other)	Annual output [t/a]	Wastewater characteristics							Reference
			Flow [m <sup>3</sup> /d]	COD [kg/d]	N [kg/d]	P [kg/d]	TSS [kg/d]	TDS [kg/d]	TS [kg/d]	
CATEGORY A: Wastewater with carbon as a main component										
1	H <sub>2</sub> O <sub>2</sub>	230,000	945	1,207	0	0	58	nda	nda	BVT Large Volume Organic Chemical Industry (2017)
2	Polystyrene	300,000	904	33	0	0	8	nda	nda	BVT Production of Polymers (2007)
3	Chlorine	215,000	365	26	0	0	nda	212	nda	BVT Chlor-Alkali Manufacturing Industry (2014)
4	Fruit juice	40,000	147	250	3	1	nda	nda	nda	DWA-M766 and Rosenwinkel et al. (2015)
5	Maize starch	1,100,000	1,658	3,315	10	0	nda	nda	nda	DWA-M 776
6	Wheat starch	182,500	700	19,250	700	140	nda	nda	nda	DWA-M 776
7	Yeast	55,000	1,243	26,541	230	34	nda	7,087	nda	DWA M 778 and Rosenwinkel et al. (2015)
8	Sugar (beets)	1,000,000	2,740	23,973	370	0	nda	nda	nda	DWA-M 713 and Rosenwinkel et al. (2015) and Südzucker Werk-Offenau
9	Silicone	50,000	3,288	1,973	0	0	nda	29,451	nda	BVT Production of Speciality Inorganic Chemicals (2007)
10	Ethanol	800,000	25,001	2,387,624	118,756	8,876	nda	nda	2,250,117	Rosenwinkel et al. (2015)
11	Paper	300,000	10,274	8,527	0	0	nda	nda	nda	DWA-M 731
12	Canteen	–	375	709	4	2	nda	nda	nda	DWA M 775
CATEGORY B: Wastewater with carbon and nitrogen as the main component										
13	Butchery (cattle)	100,000	260	1,822	137	14	nda	nda	nda	DWA-M 767 and Rosenwinkel et al. (2015)
14	Potato	175,200	1,920	6,985	568	48	nda	nda	nda	DWA M 753
15	Animal by-products	15,000	41	339	53	0	52	nda	nda	DWA-M 710
16	Filament glass fibre	500,000	8,904	601	89	0	nda	11,037	nda	BVT Manufacture of Glass (2013)
CATEGORY C: Wastewater with carbon, nitrogen and phosphorus as the main component										
17	Superphosphate	850,000	2,911	1,397	3,959	1,374	nda	nda	nda	BVT Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilizer Industries (2007)
18	Soft drinks	600,000	2,564	1,749	34	18	nda	nda	nda	Rosenwinkel et al. (2015) and DWA M 766 and Nachhaltigkeitsbericht 2015 Coca Cola Deutschland
19	Potato starch	10,000	45	633	57	7	nda	nda	nda	DWA-M 776 and Rosenwinkel et al. (2015)
20	Sanitary wastewater	–	1,769	1,056	18	14	nda	nda	nda	
CATEGORY D: Other										
21	Sodium carbonate	1,200,000	28,603	1,216	1,106	205	nda	4,138,852	nda	BVT Large Volume Inorganic Chemicals – Solids and Others industry (2007)
<b>Sum</b>			<b>94,658</b>							

nda: no data available; COD: chemical oxygen demand; N: total nitrogen; P: total phosphorus; TSS: total suspended solids; TDS: total dissolved solids; TS: total solids.

**Table 2** | Quality parameters for water reuse according to GB/T 18920-2002 and GB/T 19923-2005

Parameter	GB/T 18920-2002			GB/T 19923-2005	
	Toilet flushing	Street cleaning/Firefighting	Irrigation	Parameter	Cooling water (recirculating)
pH	6.0–9.0			pH	6.5–8.5
Color	30			Color	30
Olfactory	No odor			SS [mg/l]	–
NTU	5	10	10	NTU	5
TDS [mg/l]	1,500	1,500	1,000	COD [mg/l]	60
BOD <sub>5</sub> [mg/l]	10	15	20	BOD <sub>5</sub> [mg/l]	10
NH <sub>4</sub> -N [mg N/l]	10	10	20	Chlorid [mg/l]	250
LAS [mg/l]	1.0	1.0	1.0	SiO <sub>2</sub>	50
Fe [mg/l]	0,3	–	–	Fe [mg/l]	0.3
Mn [mg/l]	0.1	–	–	Mn [mg/l]	0.1
DO [mg O <sub>2</sub> /l]	1.0			CaCO <sub>3</sub> [mg/l]	450
Total residual chlorine [mg Cl/l]	Contact 30 min later ≥1.0; endpoint of pipe network ≥0.2				
Total coliforms [1/l]	3				



**Figure 1** | The IW<sup>2</sup>MC→ R with respect to 19 production plants (Bauer et al. 2019).

cleaning, and cooling are very similar, the effluent of the CWWTP/WRP is expected to remain within the limits. Hence, to reach the required water quality, only one WRP treatment technology is necessary.

### Calculation of the (enlarged) infrastructure reuse factor (IRF)

Concerning the dimension of the MIP with 19 production plants, different average values of 12 existing Chinese industrial parks and governmental design regulations served as a basis. To determine the park size, the average site size per company in units/ha was calculated by dividing the park size of the investigated parks through the number of companies, assuming that the park areas are fully occupied by production plants (no free construction areas) and the area is evenly distributed. The achieved data should, therefore, be regarded as a first approximation to be verified via real production plant sizes with their respective capacities. The number of employees in the different parks divided by the respective park size was the second essential average value (employees/ha) to be gathered from the investigated parks. Consequently, the total MIP has a size of 823 ha, the green spaces take up 165 ha (20%), and the area of roads amounts to 74 ha (9%) (see Table 3).

For this enlarged calculation, further applications such as cooling and firefighting water are taken into account. For the implementation of the  $IW^2MC \rightarrow R$ , it is premised that with respect to the water shortage in several regions, the industrial park enables only recirculating cooling instead of once-through cooling systems. The latter needs high water flows which cannot be provided in water-stressed regions. Therefore, the calculation of the IRF only includes the

make-up water for cooling towers. Due to the German directives for cooling water (VGB R455 2000; VGB R135 2001), the make-up water is estimated as 2% of the total cooling water demand. It is assumed that this value can also be transferred to other countries, such as China, due to similar technical conditions. Minor deviations according to Chinese conditions would not have a noticeable effect on the result. For four of the 19 production plants, specific cooling water demand is given (see Table 4). For the first approximation of the others, it is calculated with the average cooling water demand of two existing industrial parks. As in water-stressed regions where the provision of firefighting water could be a challenge, (underground) fire water storage tanks are considered. To maintain the water quality, a partial water exchange in these tanks is expected, which results in permanent water demand of  $60 \text{ m}^3/\text{d}$  (see Table 4) even if there is no fire. This shows the example of the industrial park *InfraServ Gendorf* (2018). For toilet flushing, street cleaning, and irrigation of green spaces, the calculation of the water demand is based on Bauer et al. (2020a) (see Table 4). For the MIP with 19 production plants in China, the result is an IRF of  $\sim 14.3\%$  (wastewater flows:  $94,685 \text{ m}^3/\text{d}$ ; reuse water demand:  $13,539 \text{ m}^3/\text{d}$ ), which is less than the IRF of six production plants. The water flows of the MIP are shown in Figure 2. Since there is remaining reuse water, the water can be discharged to the urban area to meet the water requirements that cannot be covered by municipal treated wastewater (Bauer et al. 2020b).

An essential reason for this lower factor is the considerably higher wastewater effluents of the chosen production plants. It should be noted that the IRF depends on the water requirements of the production type and the quantities produced which can be controlled via industrial park management (Bauer et al. 2019). Furthermore, a low IRF can equally be a potential for the adjacent urban area, as it allows remaining water to be reused for urban purposes such as the irrigation of city parks or street cleaning (Bauer et al. 2020b).

### Reaching sustainability by an area saving construction type of the water reuse plant

Due to the restricted availability of land, as it is mostly provided for production plants, the size of the CWWTP and

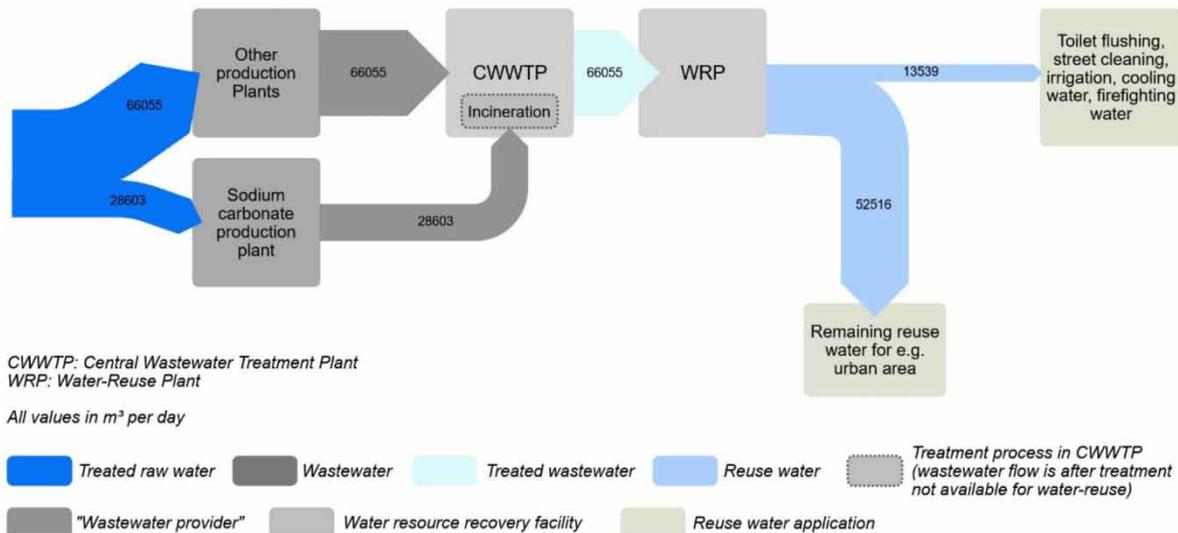
**Table 3** | Dimensioning principles of the MIP (own table)

	Average values for China	Calculated dimension of the MIP
Number of production plants		19
Surface area	43.3 ha/company	823 ha
Employees	43 employees/ha	35,389 employees
Area of green spaces	min. 20%	165 ha
Area of roads	9%	74 ha

**Table 4** | Calculation of the reuse water flows in the MIP with 19 production plants (own table)

	Specific water demand	Data referring to the MIP	Calculated reuse water demand (m <sup>3</sup> /d)
Toilet flushing	40 L/employee × day	35,389 employees	1,416
Street cleaning	2.5 L/m <sup>2</sup> × day	74 ha (=0.09 × 823 ha)	1,850
Irrigation of green spaces	2.0 L/m <sup>2</sup> × day	165 ha (=0.2 × 823 ha)	3,300
Firefighting			60
Cooling tower make-up water (2%) for:			
H <sub>2</sub> O <sub>2</sub> production	9 m <sup>3</sup> /t <sub>Product</sub>	230,000 t/a	113
Polystyrene production	50 m <sup>3</sup> /t <sub>Product</sub>	300,000 t/a	822
Sodium carbonate	75 m <sup>3</sup> /t <sub>Product</sub>	1,200,000 t/a	4,932
Filament glass fibre	1.5 m <sup>3</sup> /t <sub>Product</sub>	500,000 t/a	41
Cooling tower make-up water average for other production plants	67 m <sup>3</sup> /production plant × day*	15 production plants	1,005
<b>Sum reuse water demand</b>			<b>13,539</b>

\*Source: Average cooling tower make-up water demand of two industrial parks assuming evaporation of 2%.

**Figure 2** | Water balance for the MIP.

WRP have to be minimized via optimized treatment processes. Analyses of ten Chinese CWWTPs in different industrial parks show that the average size in relation to their treatment capacity is about 2.0 m<sup>2</sup>/m<sup>3</sup>. Calculated with the sum of the wastewater flow of the MIP (94,658 m<sup>3</sup>/d, see Table 1) the CWWTP would have a size of approximately 19 ha (~2% of the total industrial park area). Due to low inflow loads from the CWWTP to the WRP, and thus due to an appropriate treatment process to

provide reuse water 'fit for purpose', the area of the latter is expected to be substantially smaller than the area of the CWWTP. For a first appraisal, aerial photographs of three existing water-reuse projects in different parts of the world are analyzed. These projects also use additional filters and disinfection after the conventional treatment processes to provide reuse water with a similar quantity, e.g., for irrigation or toilet flushing. The average capacity is about 0.5 m<sup>2</sup>/m<sup>3</sup>. With a reuse water flow of 13,539 m<sup>3</sup>/d (see

Table 4), the WRP would have a size of less than 5% of the calculated CWWTP size.

## CONCLUSIONS

Regarding the required surface of the CWWTP and WRP, an optimized treatment process reduces the required area inside the industrial park. A technical upgrade of a CWWTP with a WRP could be conceivable due to its low land consumption. The results, regarding the IRF, show that depending on the production plants, the reuse factor can be lower despite further reuse applications, which is due to the different wastewater flows of the respective production plants. However, a previous study showed that reuse opportunities can increase by additional reuse applications in the adjacent urban areas which is required for enabling such developments in water-scarce regions (Bauer et al. 2020b). Additionally, the IRF can be increased by optimized industrial park management by controlling new production plant settlements concerning their wastewater effluents. Optimized industrial park management can thus compensate the production plants higher or lower wastewater effluents (Bauer et al. 2019). Providing a solution to enable new developments in water-stressed regions, the  $IW^2MC \rightarrow R$  has to fulfill diverse sustainability requirements. Hence, via an optimized treatment technology providing reuse water 'fit for purpose,' the concept tackles these challenges.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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