Optimizing water-reuse and increasing water-saving potentials by linking treated industrial and municipal wastewater for a sustainable urban development

S. Bauer, H. J. Linke and M. Wagner

ABSTRACT

New industrial and urban developments in water-scarce regions are often inhibited by their high demand for water from natural resources. In addition, there often is a lack of water for purposes that contribute to an improved quality of life, such as urban green spaces. Therefore, the integrated industrial-urban water-reuse concept presents a strategy by linking and reusing treated industrial and municipal wastewater flows to increase urban water-reuse potentials. The concept of combining different reuse water flows, from wastewater treatment plants from industrial parks, aims at significantly increasing the water-saving potentials compared to a separate consideration of the industrial wastewater flows.

Key words | municipal and industrial wastewater treatment for water-reuse, sustainable urban development, water-reuse for sustainable urban areas with high living standards, water-reuse in water-scarce regions, water-saving potential value

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HIGHLIGHTS

- The water-saving potential value increases enormously by combining industrial and municipal wastewater flows.
- Water-reuse for infrastructural purposes increases water resources and is an opportunity to create an environment worth living in.
- Water-reuse drives sustainable urban and industrial developments.
- The implementation of water-reuse requires a strong cooperation between urban planners and wastewater technology specialists.

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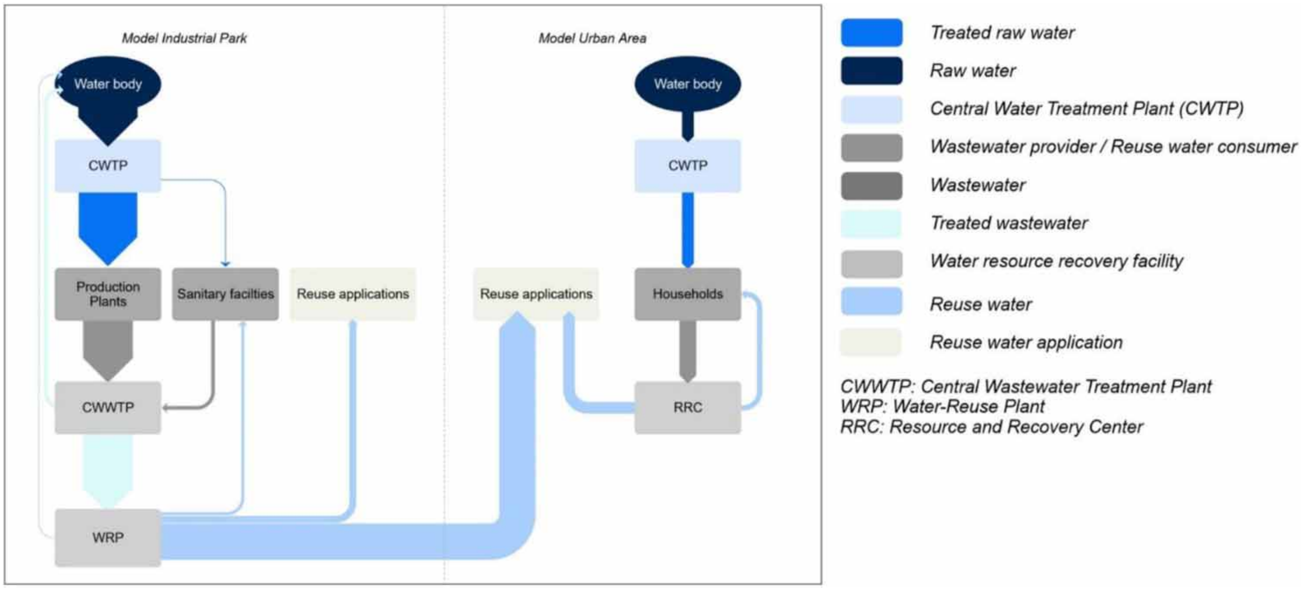
GRAPHICAL ABSTRACT



INTRODUCTION

Industrial parks are an integral factor for emerging urban developments in China (Zhao *et al.* 2017). Since industrial parks started forming so-called 'peripheral cities' (Dizikes 2017) in their surroundings and suburbs, it is especially important to ensure a sustainable water supply in these water-scarce regions. This encourages both urban and industrial development. Furthermore, the aspect of 'liveability' is increasingly important nowadays, especially for affluent societies. Accordingly, urban green spaces are an important indicator for liveable cities due to their impact on social issues, health, and climate (Earth System Knowledge Platform (ESKP) 2018). For instance, roadside vegetation, urban greens and green roofs (Hansen *et al.* 2017) can significantly increase the recreational factor of cities (Wang & Liu 2017). Especially in densely built-up areas, green roofs contribute to coping with the challenges of climate change (Li & Babcock 2014). Consequently, in order not only to facilitate urban and industrial development in general but also to provide appropriate green zones, large quantities of water are required, which cannot be supplied by natural resources in water-scarce regions. To meet these challenges, the integrated industrial-urban water-reuse concept (IU-WA-RE concept) offers a solution strategy to reduce water consumption from natural resources and enable a sustainable water supply taking the aforementioned questions of quality of life into consideration. This can be achieved by an efficient treatment of industrial and municipal wastewater according to the 'fit for purpose' principle. This way the treated water can be used directly for the intended subsequent purpose. The main idea of the integrated concept is to link treated industrial and municipal reuse water flows to optimize the water-reuse potential. For this reason, an industrial-urban reuse factor (IURF) is generated to evaluate the water-reuse potential. The IURF refers to all required reuse water flows for infrastructural applications and to all wastewater inflows to the respective wastewater treatment plant. On the basis of the IURF, the corresponding water-saving potential can be calculated from natural resources such as surface or groundwater. The water saving potential Value (WSPV) is developed to obtain information on the water-saving potential from natural resources.

METHODS

This paper briefly describes the development of the IU-WA-RE concept, as it is based on two innovative research approaches. In the next step, the paper provides insights on how the presented concept can be used to evaluate water-reuse and water-saving potentials.

Development of the industrial-urban water-reuse concept

The IU-WA-RE concept offers a solution strategy for new industrial and urban developments in heavily water-dependent regions. The strategy is based on reusing industrial and municipal wastewater for various infrastructural purposes and is the integrative result of two innovative reuse water management strategies.

The first basis for the IU-WA-RE concept is the Industrial Wastewater Management Concept with a focus on Reuse ($IW^2MC \rightarrow R$) (Bauer *et al.* 2020a), which deals with wastewater treatment in industrial parks according to the 'fit for purpose' principle. With regards to the $IW^2MC \rightarrow R$ concept, wastewater from production plants is treated in a Central Wastewater Treatment Plant (CWWTP) and in an additional Water-Reuse Plant (WRP) within the industrial park (Figure 1). Accordingly, the industrial wastewater is clustered according to its loads and treated in different treatment tracks inside the CWWTP. After treatment in the CWWTP the wastewater is discharged either into the receiving water body or into the additional WRP. There, the water is further treated according to its subsequent use considering the respective water quality since the quality standards may vary from country to country. Therefore, the reuse water must be controlled at the outflow of the WRP to ensure that the reuse water quality is in compliance with the quality requirements of the respective reuse water application.

The main idea of the $IW^2MC \rightarrow R$ is to reuse the treated wastewater for infrastructural purposes within the industrial park since large quantities of water are required for street cleaning, irrigation of green areas and toilet flushing. For the calculation of the reuse water demand as well as the water demand for the production plants, a Model Industrial Park (MIP) with six exemplary production plants for China was created as a case study. The area of green spaces within the industrial park in correlation with the specific water demand affects the required water flow for irrigation. Due to a governmental regulation, green spaces in industrial parks have to take up at least 20% of the park area in China (MoHURD 1994). To determine the water demand

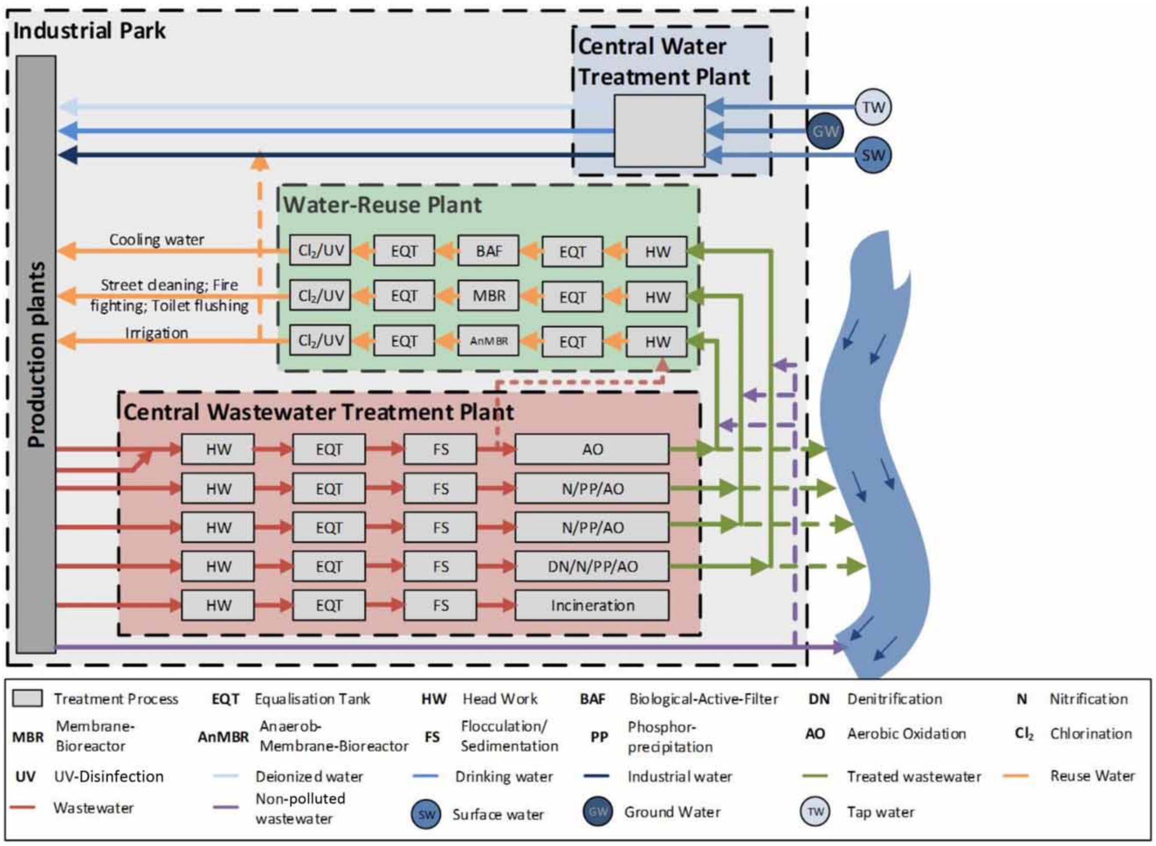


Figure 1 | Wastewater treatment 'fit for purpose' according to the $IW^2MC \rightarrow R$ (Bauer *et al.* 2020a).

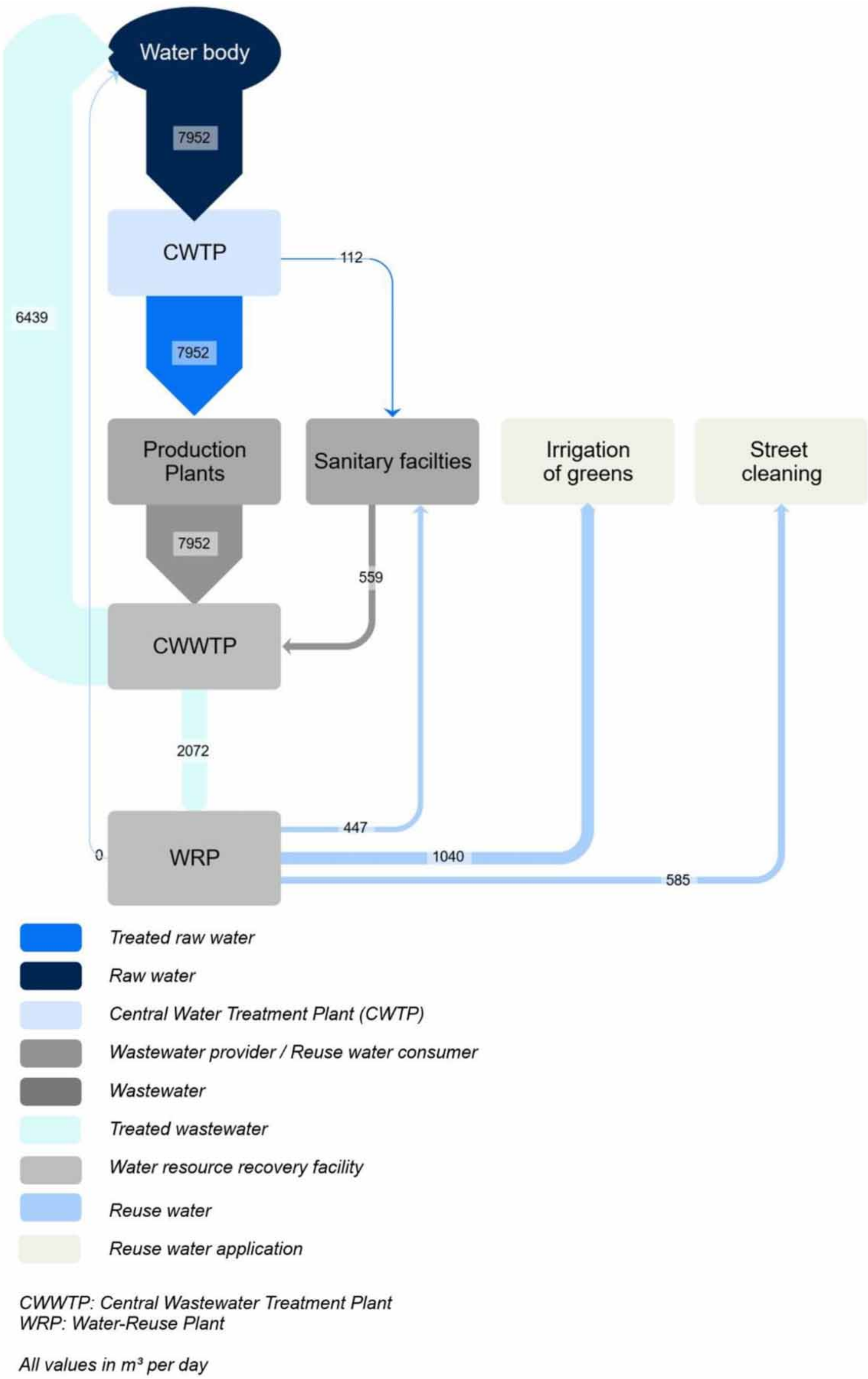


Figure 2 | Water-reuse potential of 25% according to the $IW^2MC \rightarrow R$ concept (distribution ratio of reuse water flows according to Bauer *et al.* (2020a)).

for street cleaning, the total area of streets (which is on average 9% of the industrial park area) and the required water demand per square metre are decisive. Including the described indicators, calculations for the MIP in China show that ~25% of the treated wastewater can be reused (wastewater flow: 8,511 m^3/d (depends on six realistic production plants and production capacities); reuse water demand: 2,072 m^3/d) (see Figure 2) (Bauer *et al.* 2020a). Consequently, this leads to 75% of the remaining treated wastewater either being discharged into the water body or being reused for further water-reuse applications.

Since the $IW^2MC \rightarrow R$ is based on the case study from China, Chinese quality standards for the respective wastewater treatment process are considered. According to the corresponding standards (GB/T 18920-2002 (MoHURD 2003) and GB/T 19923-2005 (MoHURD 2006)) the quality requirements of reuse water for irrigation, toilet flushing and street cleaning are very similar in China. Thus, to reach the required water quality, only one treatment technology of the WRP is necessary and sufficient. Therefore, the treated wastewater is filtrated by filters and disinfected by UV and chlorine dosing (Bauer *et al.* 2019a). In case of other quality requirements (for example in other countries) or in case further water-reuse applications are taken into account, parallel treatment tracks inside the WRP with advanced treatment steps are conceivable acccording to Figure 1.

The reuse of wastewater for internal production processes, such as process water, is not considered for internal water-reuse for production plants within the industrial park as the water-reuse for infrastructural purposes is a further reuse water opportunity. Since the reused water in the production plant later ends up in the treatment plant anyway, it is fed thus to a subsequent reuse application (Bauer *et al.* 2020b).

The second baseline is the SEMIZENTRAL approach with its resource recovery center (RRC), which was implemented at full scale for the first time worldwide in the Chinese city of Qingdao (Tolksdorf *et al.* 2016). The RRC treats municipal grey and black water from households within a defined catchment area around the wastewater treatment plant. All wastewater discharges into the RRC are based on the residential area counting 104,000 inhabitants (Bieker 2009), representing a suitable size for the treatment plant. Water consumption is based on the daily water demand of 109 liters per inhabitant of Qingdao (Tolksdorf *et al.* 2016). As a result, 11,336 m^3 of wastewater per day can be treated and reused by the RRC, of which 30% (3,432 m^3/d) can be discharged for flushing (see Figure 3).

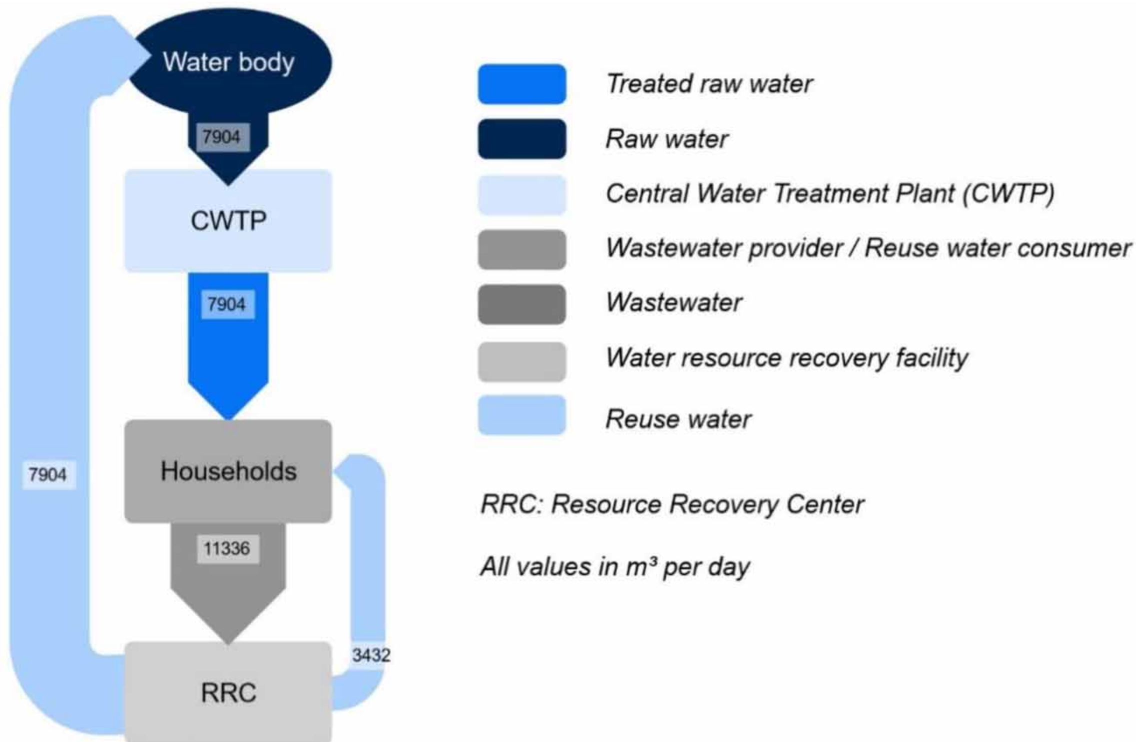


Figure 3 | Water-reuse for households according to SEMIZENTRAL.

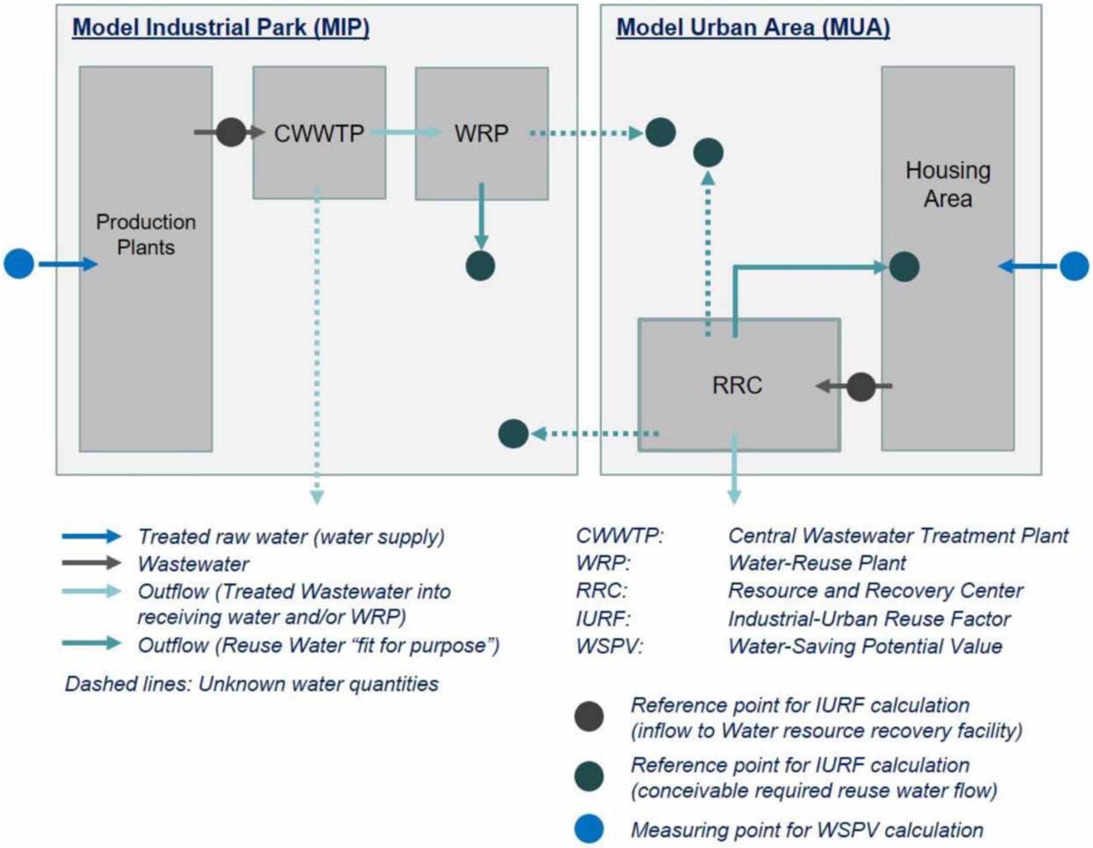


Figure 4 | The integrated industrial-urban water-reuse concept for evaluating water-reuse and water-savings.

Table 1 | Dimensioning of the MUA

Data referring to MUP		Percentage of total area
4,295 ha	Total area	
104,000	Inhabitants	
~541 ha	Size of city parks in Melbourne	12.7%
~378 ha	Roadside green space	9%
~16 ha	High-rise greenery	0.37%
~541 ha	Road spaces	12.6%

The reuse of water for flushing thus covers 30% of the water-reuse potential. Consequently, 70% of the treated wastewater remains and can be utilized for further infrastructural applications or discharged into the receiving water body. Because the SEMIZENTRAL approach is applied, it should be mentioned that according to Tolksdorf *et al.* (2019) a semi-central approach is the most cost-effective solution available. Compared to centralized or conventional systems, the semi-centralized

Table 2 | Dimensioning of the MUA and calculation of the reuse water requirements

Reuse application	Data referring to MUP		Percentage of total area (4,295 ha)	Calculation of required reuse water flows per day	
Toilet flushing	104,000	Inhabitants		33 L/(capita·d)	3,432 m^3/d
Irrigation	~541 ha	Size of city parks	12.7	2 L/(m^2·d)*	10,910 m^3/d
	~378 ha	Roadside green space	9	2 L/(m^2·d)*	7,733 m^3/d
	~16 ha	High-rise greenery	0.37	2 L/(m^2·d)*	314 m^3/d
Street cleaning	~541 ha	Road spaces	12.6	2.5 L/(m^2·d)*	13,530 m^3/d
Sum of all required reuse water flows					**35,919 m^3/d**

*GB 50282-2016 (MoHURD 2017): average value is taken into account.

approach correlates with wastewater presenting a cost- and energy-efficient source for raw water. This is especially true for natural raw water sources of inferior quality, and for long transport routes (Lazarova *et al.* 2012).

Evaluating water-reuse and water-saving potentials by means of the IU-WA-RE concept

With the aim of optimizing water-reuse potentials, the remaining treated wastewater from the WRP within the industrial park and the remaining residual water, provided by the RRC, can be reused for further infrastructural applications. The main idea is to combine industrial and municipal wastewater flows for further conceivable water-reuse applications. To adapt the approach to data, a holistic model consisting of two separate models must be established. Therefore, a Model Urban Area (MUA) and an MIP have to be designed, which allow an evaluation and calculation of the water-reuse and water-saving potential.

To assess the water-reuse potential, an IURF has to be generated, which relates to all required reuse water flows for defined infrastructure applications and to all inflows to the RRC and the CWWTP within the industrial park (see Figure 4). The IURF indicates the proportion of reused water from a water source, for instance, the RRC in an urban area and a water resource recovery facility within an industrial park. In a second step, the WSPV shows the fraction of water saved from natural resources such as ground and/or surface water. The value represents the ratio between the raw water flow for the water supply without water-reuse and the reuse of wastewater (see Figure 4).

To perform a detailed calculation, data must now be added to the set model. Thus, the size of a specific industrial park and an adjacent urban area needs to be visualized. Real data on treatment capacities or treated water flows have to be considered as well as realistic water requirements for specific reuse applications. The advantage of modeling is that individual elements are enlarged, modified or replaced to represent variations of water flows and their impact on the IURF and the WSPV.

Seeing as the IURF is relied upon to assess the water-reuse potential for this model, the reuse water flows provided or the inflows to the wastewater treatment plants as well as all required reuse water flows for defined

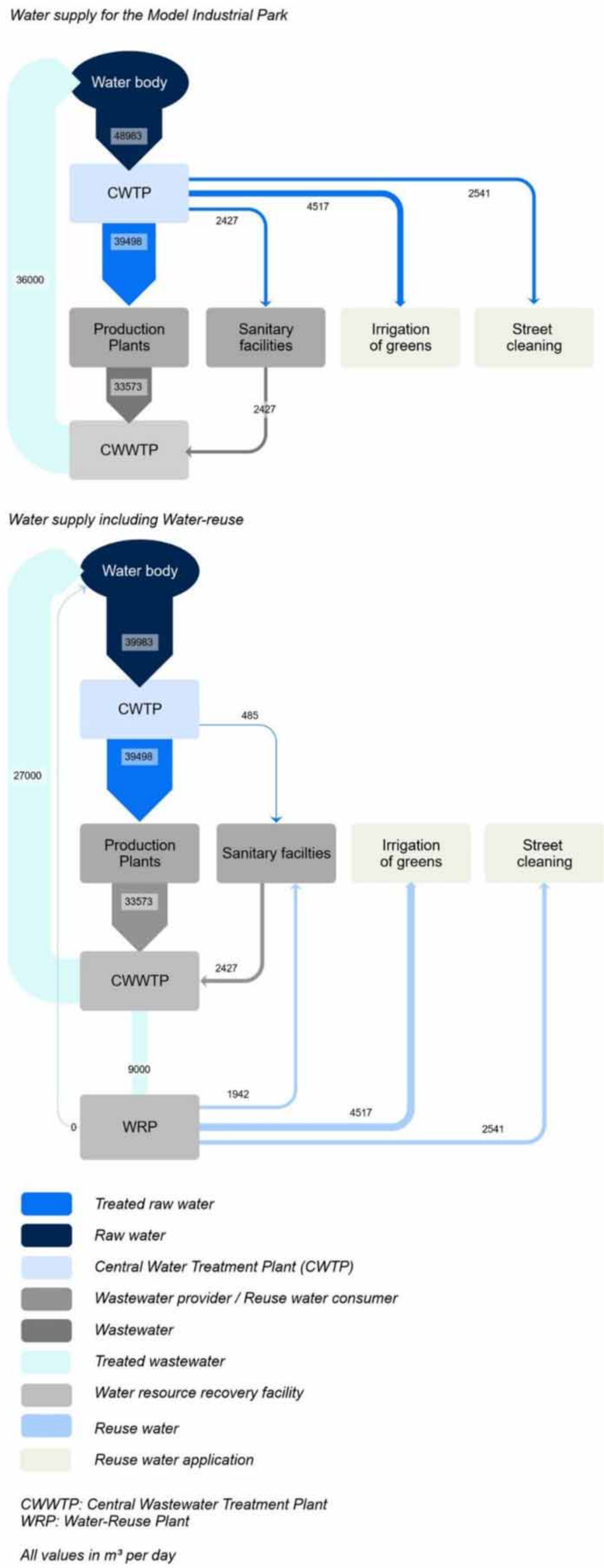


Figure 5 | Water flows for water supply and water-reuse in a Model Industrial Park.

Table 3 | Calculation of the water-saving potential value

Water 'consumer'	Water supply requirements without water-reuse [m^3/d]	Remarks	Water-reuse flow [m^3/d]	Wastewater flow [m^3/d]	Remaining raw water flow for water supply after water-reuse [m^3/d]
Production plants	39,498	15% water loss	–	33,573	39,498
Sanitary water	2,427	80% water-reuse	1,942	2,427	485
Irrigation	4,517	100% water-reuse	4,517	–	–
Street cleaning	2,541	100% water-reuse	2,541	–	–
Sum	**48,983**		9,000 (25%)	36,000	**39,983**
Calculation of the WSPV: (48,983−39,983)/48,983 * 100					
WSPV					**~ 18%**

infrastructural applications in the urban area, have to be defined. For the latter, the reuse for street cleaning, toilet flushing, and irrigation of city parks, high-rise greenery, and roadside green spaces is taken into account, as these purposes contribute to the quality of life as well as to sustainability (Bauer *et al.* 2020b). Regarding the industrial side, the MIP considers the reuse proportion of 25% relative to the $IW^2MC \rightarrow R$. In this case, the factor of 25% (Bauer *et al.* 2020a) is considered a fixed value but may vary in the case of other production facilities and capacities.

With regard to the surface of the MUA, which is essential for the calculation of the amount of reuse water, several Chinese cities are included and serve as the main basis for the calculations. Additionally, data from other cities known for their quality of life and sustainability issues are considered. The main area of the MUA is situated on green spaces in urban areas, which in China constitute 2% and 8.26 m^2 per capita (Wang & Liu 2017). Hence, the MUA covers an area of 4,295 ha based on its 104,000 inhabitants according to the urban area of SEMIZENTRAL. The Beijing example shows that roadside vegetation covers 9% (Syrbe & Chang 2018), whereas streets represent 12.6% of Chinese urban areas (UN-Habitat 2013). In order to improve well-being aspects in cities, further water-reuse possibilities with regard to urban greening must be identified, as, for example, city parks only cover comparatively small areas in China. Hence, data from cities with respect to their quality of life are taken into consideration, as this is becoming increasingly important in affluent societies. In this context, the city of Melbourne, which is famous for its green spaces covering 12.7% of its urban area (City of Melbourne 2018), is taken into account. For many years, Melbourne was the most liveable city in the world (*The Economist* 2018), in part because of its large green areas. Therefore, the inclusion of additional data from Melbourne for defining the model with life quality aspects related to urban green spaces is appropriate. Accordingly, the size of Melbourne's urban greens is considered in the following discussion. A further aspect, contributing to the quality of life in cities, is high-rise greens (e.g. rooftop gardens, green walls), for which Singapore is renowned. There, the area of high-rise greens currently amounts to 100 ha and is aimed to increase up to 200 ha in order to augment the appeal of the city's landscape (Sen 2017). With the built-up area covering 27,392 ha (Angel *et al.* 2016), the proportion of high-rise greenery constitutes 0.37%. This value is included in the model calculations. All required data referring to the MUP are presented in Table 1.

RESULTS

The following section describes the calculation of the IURF for the assessment of the water-reuse potential for sustainable urban development. This calculation lays the foundation for the additional computation of the potential water-saving value. The value is then determined separately for the MIP and the MUA, before a combined calculation for the implementation of the IU-WA-RE concept is conducted.

Calculating the IURF

When calculating the required daily reuse water quantities for the studied infrastructure applications, different average values from Chinese standards and regulations are taken

into account. For instance, a daily average of two liters per square metre is required for the irrigation of green spaces (see Table 2). This value may vary depending on climate data and respective water-stress levels.

For calculating the IURF, all wastewater inflows to the RRC within the MUA are considered. The inflow is based on all 'wastewater producers'. Water consumption in Qingdao, for example, is based on a daily 109 liters per capita, consequently resulting in 11,336 m^3 per day for 104,000 inhabitants. The total wastewater inflow, which roughly corresponds to the reuse water outflow, cannot cover the required water demand of 35,919 m^3 per day in the MUA (see Table 2).

In terms of the dimension of the industrial park, the wastewater inflows to the water treatment plant must be defined. Therefore, the Shanghai Chemical Industry Park (China) wastewater treatment capacity of 36,000 m^3 per day is considered for further calculations, given that this park represents a good Chinese average. Since the aforementioned 25% water-reuse within the MIP is considered a fixed value, further area calculations are not required in this case. The remaining reuse water from the WRP thus amounts to 27,000 m^3 daily, with an inflow of 36,000 m^3 into the CWWTP.

When calculating the IURF, the previously introduced data and water flows have to be considered as they relate to all inflows into the wastewater treatment plant (RRC and CWWTP plus WRP) and to all reuse water flows needed for infrastructural applications. Therefore, the total wastewater inflow equals 47,336 m^3 per day (inflows of 36,000 m^3 per day from the CWWTP and 11,336 m^3 per day from the RRC). The required reuse water flows consist of the flows used within the industrial park. According to the $IW^2MC \rightarrow R$, they constitute 25%, which again results in a daily flow rate of 9,000 m^3 with a daily wastewater treatment rate of 36,000 m^3. Since the reuse water flows for the infrastructural purposes inside the MUA cannot be covered by the reuse water provided from the RRC, water from the WRP has to be discharged from the industrial park into the MUA. Consequently, the discharge is sufficient to cover the demand. Taking all required reuse water flows for street cleaning, toilet flushing, and irrigation of urban greens into consideration (35,919 m^3/d) including city parks, roadside vegetation, and high-rise greenery and the aforementioned reuse water flow of 9,000 m^3/d for applications within the industrial park, the IURF yields 95% ((35,919 m^3/d + 9,000 m^3/d)/47,336 m^3/d).

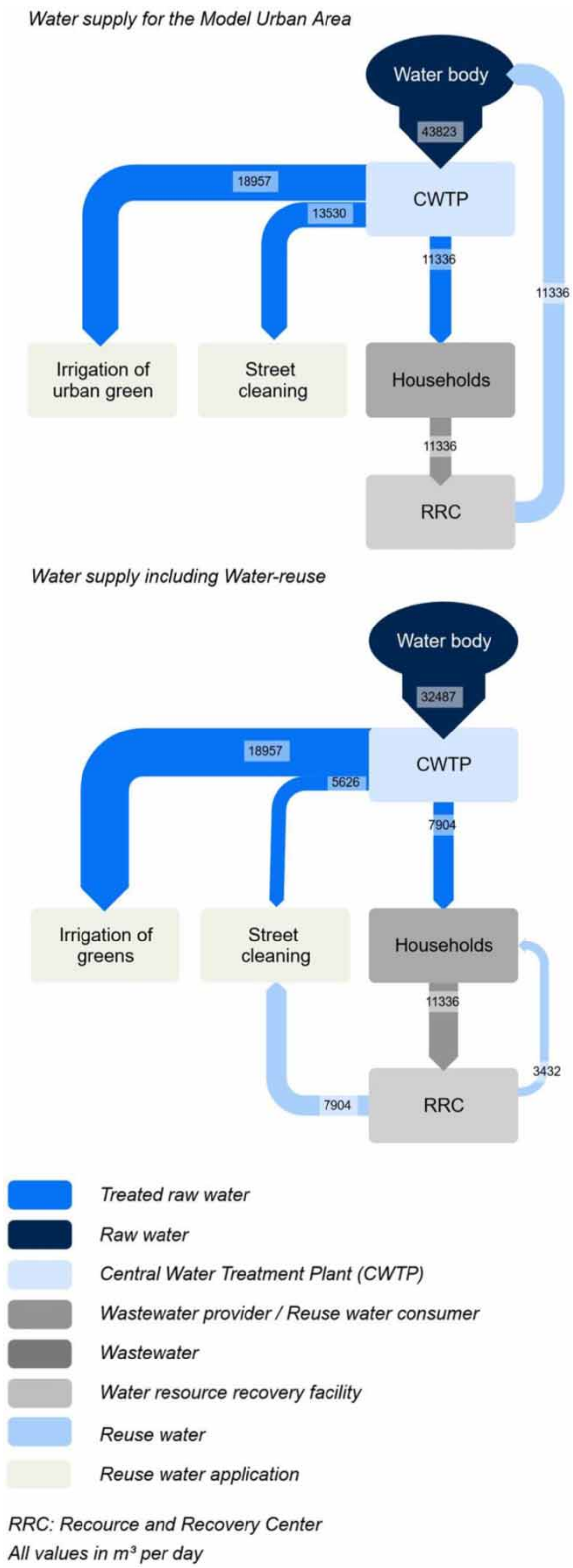


Figure 6 | Water flows for water supply and water-reuse in a Model Urban Area.

Calculating the WSPV for the MIP

In order to determine the WSPV, the required amount of raw water for the MIP and MUA, provided by the central water treatment plant (CWTP), is calculated. All following calculations are based on an IURF of 95%. The data of the previously introduced model are considered for the WSPV calculation. In addition to the water-reuse applications mentioned above, the entire raw water flow for the water supply, thus all further water 'consumers', have to be identified. The MIP includes all infrastructural water requirements that are considered for water-reuse, as well as the water supply to the production plants and further sanitary facilities. Water demands for purposes within the MIP are based on the required reuse water flows according to the $IW^2MC \rightarrow R$ calculations (Bauer *et al.* 2019b). Additionally, the distribution of the respective water flows is essential for the subsequent water-reuse application to determine the dimension of the MIP for calculating the raw water flows for the water supply. Accordingly, the resulting 25% for the reuse factor of the $IW^2MC \rightarrow R$, considering an MIP with six exemplary production plants, is divided into the following shares: 22% is considered for toilet flushing (80% of the estimated overall sanitary water in industrial parks, which represents 50 liters per employee per day, is assumed to be toilet flushing water, whereas 20% is used for washing hands, tea kitchens, and occasional showers). Irrigation purposes account for 50%, while street cleaning requires 28% of the reuse water (Bauer *et al.* 2020a). On the basis of this distribution and percentages, the raw water flows for the water supply can be calculated inversely (see Figure 5). The water requirements of the production plants and all sanitary facilities depend on the treatment capacity of the CWWTP. Water losses on the level of the production plants, such as evaporation during production processes, are taken into account with an estimated 15%. The water loss flow can vary due to different production plants and processes. Figure 5 shows the possible application of reuse water for irrigation, street cleaning, and toilet flushing. Hence, other than supplying water for the production plants and their processes, the CWTP only needs to provide the remaining water flow for washing hands, etc. Assuming that all required flows for the respective water 'consumer' and water-reuse are considered, the WSPV accounts for 18% (see Table 3).

Calculating the WSPV for the MUA

When calculating the WSPV for the MUA, the water supply of the households under consideration and the previously mentioned infrastructural requirements are taken into account (see Table 2). The water supply flows of the housing area and all further reuse water requirements within the MUA are based on SEMIZENTRAL (see Figure 6). Accordingly, the recovered water provided by the RRC can be reused but does not sufficiently cover the entire water demand. The remaining water must, therefore, be supplied by the CWTP. Consequently, the calculation of the WSPV for the MUA amounts to 26% by reusing all treated wastewater flows (see Table 4).

Calculating the WSPV for the IU-WA-RE concept

Since it is possible to cover the water demand of the urban area by discharging the remaining reuse water flows from inside the industrial park to the urban area, in particular, to cover the demands for irrigation and street cleaning, a holistic calculation of the WSPV can be performed. After taking all water requirements with respect to the water supply into account, the WSPV illustrates the effects of

Table 4 | Dimensioning of the MUA and calculation of the reuse water requirements

Water 'consumer'	Water supply requirements without water-reuse [m³/d]	Remarks	Water-reuse flow [m³/d]	Wastewater flow [m³/d]	Remaining water supply flow after water-reuse [m³/d]
Households	11,336	30% water-reuse	3,3432	11,336	7,904
Irrigation	18,957		7,904	–	24,583
Street cleaning	13,530			–	
Sum	**43,823**		11,336	11,336	**32,487**
Calculation of the WSPV: (43,823–32,487)/43,823 * 100					
WSPV					**~26%**

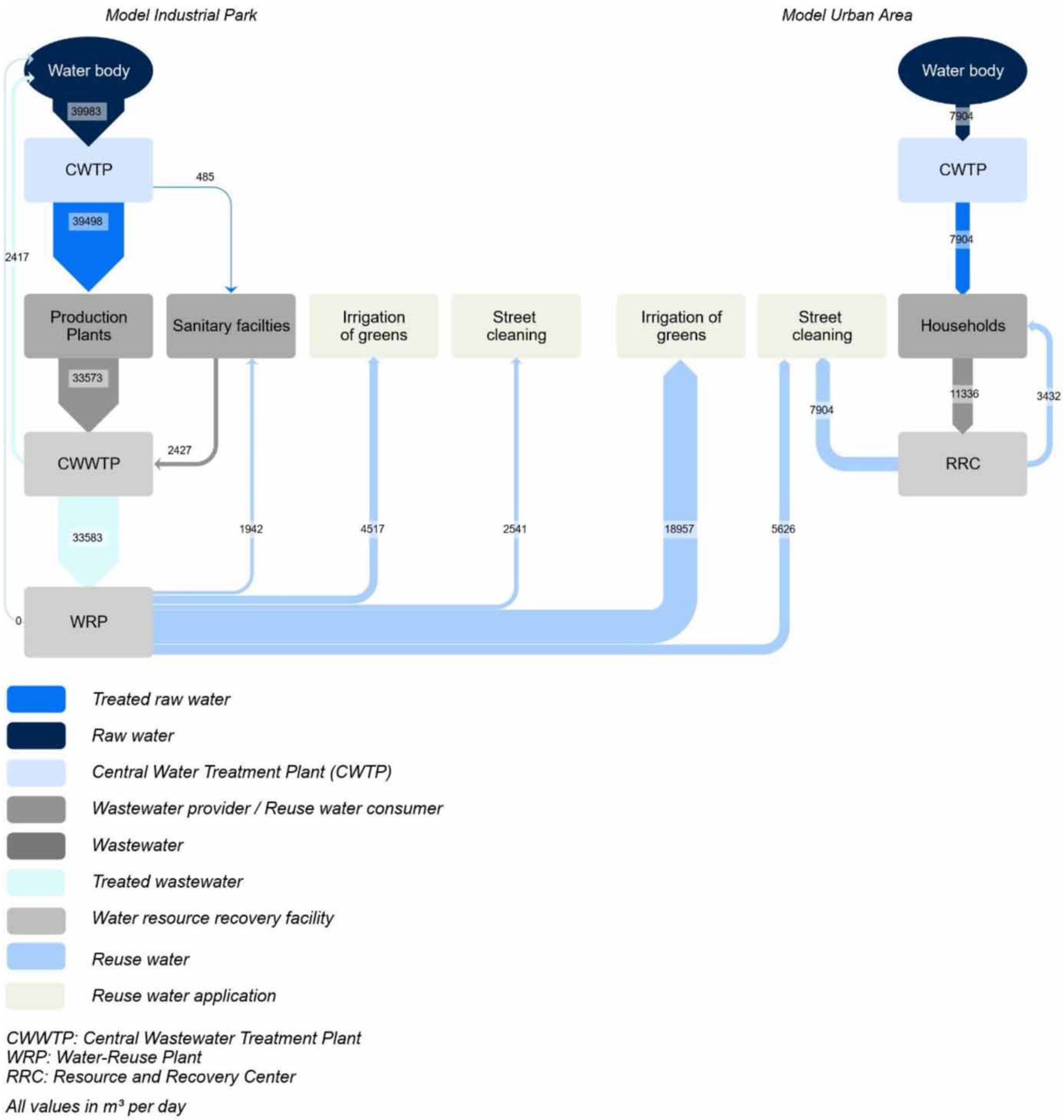


Figure 7 | Balancing the water-saving potential by using the IU-WA-RE concept.

linking all reuse water flows (see Figure 7). Consequently, only water for the production plants and parts of the water for sanitary facilities within the MIP and MUA need to be provided by the CWTP. All other water needs can be met by the reuse water allocated by the respective water treatment plant. With the integrated and holistic calculation, i.e. the combination of all reuse water flows and the consideration of all flows for the general water supply, the water-saving potential increases noticeably up to 48% (Table 5).

In a direct comparison, Table 6 shows the significantly increased water-saving potential when linking industrial and urban reuse water flows in comparison to separate considerations of the MIP and MUA.

Table 5 | Holistic calculation of water-savings and reuse water requirements under consideration of the IU-WA-RE concept

Water 'consumer'	Water supply requirements without water-reuse [m³/d]	Remarks	Water-reuse flow [m³/d]	Wastewater flow [m³/d]	Remaining water supply flow after water-reuse [m³/d]
Model Industrial Park					
Production plants	39,498	15% water loss	–	33,573	39,498
Sanitary water	2,427	80% water-reuse	1,942	2,427	485
Irrigation	4,517	100% water-reuse	4,517	–	–
Street cleaning	2,541	100% water-reuse	2,541	–	–
Model Urban Area					
Households	11,336	30% water-reuse	3,432	11,336	7,904
Irrigation	18,957	100% water-reuse	18,957	–	
Street cleaning	13,530	100% water-reuse	13,530	–	–
Sum	**92,806**		44,919		**47,887**
Calculation of the WSPV: (92,806–47,887)/92,806 * 100					
WSPV					**48%**

Table 6 | Comparing water-saving potentials

Required water flows	MIP	MUA	Integrated calculation (MIP + MUA)	
CWTP with reuse	39,983	32,487	39,983 + 7,904	47,887
CWTP without reuse	48,983	43,823	48,983 + 43,823	92,806
Water-savings	**18%**	**26%**	**48%**	

CONCLUSIONS

The IU-WA-RE concept provides a solution to drive new industrial and urban developments towards sustainability and quality of life, especially in water-stressed regions. The discharge of treated industrial wastewater for reuse in urban areas with generally high water demands is an opportunity to create an environment worth living in. Due to the fact that the water provided by the municipal water resource treatment plant is not sufficient for covering infrastructural purposes such as the irrigation of green areas or water for street cleaning, the usage of treated industrial wastewater with reuse water quality standards is a feasible solution. By linking all treated industrial and municipal wastewater flows, sufficient water amounts can finally be provided for all infrastructural purposes by the respective industrial and/or municipal water treatment plant. If all reuse water flows are linked, the water-reuse factor is increased from 25% in the industrial park and from 30% in the residential areas to a total of 95%. Furthermore, the high demand for irrigation of urban green spaces, street cleaning or toilet flushing with water of lower quality standards subsequently decreases the need for cost-intensive treatments of industrial wastewater for internal water-reuse in the production process. In addition, the results indicate a significant increase in the water-saving potential by linking industrial and urban reuse water flows in comparison to the separate consideration of the MIP and MUA. The concept thus facilitates new developments in water-scarce regions, for instance in Southeast Asia, and offers an answer to the challenges of climate change. An implementation of the concept is most likely conceivable on greenfield planning projects. Thus, an intersection of industrial developments and urban areas is easier to achieve than in existing areas. For example, the necessary pipe-network for water-reuse can be planned initially. The development potential of urban areas may therefore depend on the size of wastewater treatment plants (Bauer *et al.* 2020b) and the corresponding land uses. However, all this requires a strong cooperation between urban planners and wastewater technology specialists to take all necessary conditions into account during the planning phase.

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