Combining industrial and urban water-reuse concepts for increasing the water resources in water-scarce regions

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Abstract
Water scarcity is a huge challenge for industrial and urban developments. As such developments are based on a secure water supply, strategies to ensure the required water quantities must be put into effect. In this context, sustainability is becoming an increasingly important factor due to the worsening of pollution and climate change. The integrated industrial–urban water-reuse concept (IU-WA-RE) links gray and green infrastructures by providing reuse water for different infrastructural purposes. Municipal and industrial wastewater is treated separately in different water resource recovery facilities. As a baseline the SEMIZENTRAL approach with the Resource and Recovery Center (RRC) and the Industrial Wastewater Management Concept with a focus on Reuse (IW2MC→R) for the industrial wastewater treatment are taken into account. These approaches are new concepts for wastewater treatment “fit for purpose.” IU-WA-RE combines the water-reuse concepts by linking reuse water flows between the urban area and the adjacent industrial park, but focuses not on a production internal water reuse. The concept is designed to offer a holistic strategy to increase the water-reuse potential and thus the water resources. It offers a solution to cover the lack of water requirements in urban areas. It is therefore possible to drive sustainable urban developments.

Practitioner points
• The water-reuse potential increases enormously by combining industrial and municipal wastewater flows.
• Industrial wastewater should be treated “fit for purpose” and applied in the urban area since the municipal wastewater is not sufficient to cover its own water requirements for infrastructural purposes.
• Water-reuse for infrastructural purposes increases water resources.
• The application of reuse water drives sustainable urban developments.

Key words
increasing water resources; integrated industrial–urban water-reuse concepts; opportunities for an efficient water reuse; sustainable industrial and urban development

Introduction
Industrial park locations in China are a particularly significant factor for growing urban developments (Zhao, Bi, Zhong, & Li, 2017). Due to their location on the outskirt areas, spillover effects to the local environment can be determined based on the growth of the local employment. Housing developments in the surroundings of industrial parks are some of those effects (Zheng, Sun, Wu, & Kahn, 2017). Thus, industrial parks are creating “edge cities,” which generate their own centers of diverse economic activities and residential life (Dizikes, 2017). For new industrial park locations, and hence, for the resulting suburbanization, the
availability of water is essential due to their high and, steadily increasing needs. Especially in water-stressed regions, new industrial parks and urban developments are a big challenge for the Chinese government, due to the shortage of water. In China, the population urbanization level increased between 2004 and 2013 from 41.8% to 53.7% with a growth rate of 1.2% every year, and water use therefore also increased from 555 billion tons up to 618 billion tons (Lyu, Chen, Zhang, Fan, & Jiao, 2016). To ensure a sustainable water supply, several water-reuse and water management concepts were developed. A famous concept is, for example, the integrated urban water management (IUWM), which includes all aspects of the water cycle, wastewater and drinking water, stormwater, and evaporation (Sharma, Gray, Diaper, Liston, & Howe, 2008). The 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 the “urban metabolism,” which can be holistically understood according to Musango, Currie, and Robinson (2017) as a “collection of complex sociotechnical 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.” Furthermore, a new and innovative approach is the SEMIZENTRAL approach (Tolksdorf & Cornel, 2017; Tolksdorf, Lu, & Cornel, 2016) for a semi-centralized supply and treatment systems for fast-growing urban areas and the Industrial Wastewater Management Concept with a focus on Reuse (IW2MC→R) dealing with industrial wastewater treatment according to the “fit for purpose” principle (Bauer, Behnisch, et al., 2019).

These concepts deal in particular with holistic municipal water-reuse concepts, by considering not only industrial water-reuse concepts but also energy efficient approaches. To increase water-reuse potential, it is important to develop an approach which focuses on the link between industrial and municipal wastewater flows for water reuse. Furthermore, a new approach must focus on an intersection of grey infrastructure—water supply and wastewater treatment (plants and technologies)—with green infrastructure like public green spaces and roadside vegetation as necessary, since the latter is one of the several key strategies to achieve sustainability (Hansen, Rolf et al., 2017; Wang & Banzhaf, 2018). Hence, the treated wastewater is provided for water reuse to improve sustainability and quality of life issues, as the latter is becoming increasingly important for growing economies and affluent societies. For instance, the availability of urban green spaces is an important indicator for quality of life due to their impact on social issues, health, climate, and biodiversity (Earth System Knowledge Platform (ESKP), 2018).

**Objectives**

The integrated Industrial–Urban Water-Reuse concept (IU-WA-RE) provides a strategy for sustainable development by combining industrial and municipal wastewater flows as well as by linking gray and green infrastructures. Since industrial parks have high water requirements due to their production plants and processes, they also are able to produce in turn high wastewater flows. Via an adequate treatment of industrial wastewater, the water can be reused for further purposes. At the same, water demand from natural resources is reduced. The concept is aimed to provide a solution based on daily available and calculable wastewater flows, reusing it for infrastructural purposes such as the irrigation of urban greens since municipal water resource and recovery facilities are possibly not able to cover all water requirements. The future-oriented concept meets the requirements of the Sustainable Development Goals (SDGs), especially the SDG 6—Clean Water and Sanitation—ensure availability and sustainable management of water and sanitation for all.

**Scope of research**

Depending on the scientifically verified dependency between industrial park developments and new urban areas, the following research focuses basically on the case study of China, as the country is especially dynamic in the development of new industrial and urban areas. Many regions in China have a high water-stress level, which inhibits new developments. Due to the uneven distribution of natural water resources and the high levels of pollution of waterbodies, water scarcity is a challenge (WRI, 2018) for industrial and urban developments. Thus, the IU-WA-RE concept provides a strategy for water-scarce areas and arid to semi-arid regions. To point out the impact of the fluctuating rainfall situations, climate data are considered in further calculations regarding the reuse-water requirements with respect to water quantity. But the availability of rainwater is, especially in arid/semi-arid regions, unreliable. Its storage tends to be rather uneconomical (e.g., storage in tanks) and thus is excluded by the concept. To this effect, the Sponge City Concept is also omitted, although in certain cities with flooding from higher rainfall, respectively, it is still an important approach.

Specific economic analyses are excluded, as it is assumed that water reuse is more favorable at a certain water-stress level, or that reusing water is the only solution to drive necessary developments or a political directive. For instance, calculations have shown that the specific energy demand for the treatment and distribution of wastewater is more energy efficient than the production of raw water from natural resources (Bauer, Dell, Behnisch, Chen, et al., 2020). Thus, treated wastewater is an attractive water source. Additionally, the concept is not focusing on treatment processes for internal water reuse for production plants within the industrial park as the water reuse of infrastructural purposes is a further reuse water opportunity. Since the internally reused water in the production plant later ends up in the water resource recovery facility anyway, it is fed thus to a subsequent reuse application. Hence, water reuse for infrastructural purposes provides a strategy to increase water resources that contrasts with internal water-reuse productions. Furthermore, the concept refers generally to “greenfield developments” as its implementation in existing urban structures would be inefficient and uneconomical due to the subsequent addition of the extra pipelines for water reuse.
Baselines for the Development of the IU-WA-RE Concept

Sustainability and quality of life aspects play an important role for the further developed IU-WA-RE concept. It is therefore essential to discuss the initial and current definitions of green infrastructure (GI) and the delimitation of the concept behind them.

From the conceptual side, common municipal and industrial wastewater treatment systems have to be delimitated from new wastewater treatment and water-reuse management concepts. Therefore, common wastewater treatment systems are presented first. Hereafter, the new SEMIZENTRAL approach and the new Industrial Wastewater Management Concept with a focus on Reuse (IW³MC→R) will be briefly introduced and explained, as both serve as a main baseline for the IU-WA-RE concept inter alia due to the wastewater treatment “fit for purpose” approach.

Definitions of green infrastructure as a baseline

As GI has been discussed in different manners, a general overview about several definitions is essential for a holistic understanding. According to the widely adopted definition (Young, Zanders, Lieberknecht, & Fassman-Beck, 2014) of Benedict and McMahon (2006), GI is defined as “an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife.” Another definition from the Auckland University (United States Environmental Protection Agency, 2009) redefined green infrastructure as “Natural and engineered ecological systems that integrate with the built environment to provide the widest possible range of ecological, community and infrastructure services” (Boyle et al., 2014). A supplementary definition by Hansen, Rolf, et al. (2017) ties in with these interpretations and brings green and gray infrastructure together by illustrating that urban green infrastructure, which is defined as a planned network of natural and designed areas and elements in compact cities (Hansen, Olafsson, Jagt, Rall, & Pauleit, 2017), complements gray infrastructure, and can partially replace it. Furthermore, GI facilitates the high quality of life and attractiveness of cities (Hansen, Rolf, et al., 2017) and thus offers benefits to nature and society, whereas gray infrastructure approaches commonly refer to singular functions without considering environmental and ecological aspects (Nivala, Zehnsdorf, Afferden, & Müller, 2018).

As the definitions of the Auckland University and (Hansen, Olafsson, et al., 2017; Hansen, Rolf, et al., 2017) relate especially to the intersection of green and gray infrastructures, this paper focuses on these definitions. While most approaches and strategies which combine gray and green infrastructures and also deal with concepts for stormwater management, the concept developed here refers to an appropriate treatment of municipal and industrial wastewater. The IU-WA-RE concept focuses on reusing the treated effluents for different reuse purposes as the wastewater is treated “fit for purpose.” The concept refers to infrastructural water-reuse applications, for instance, the irrigation of urban green spaces to improve quality of life issues in dense urban areas. As wastewater is produced daily, it can be reused at any time after appropriate treatment for different purposes.

Common municipal and industrial wastewater treatment systems

Commonly, inside an industrial park, wastewater is treated in a CWWTP onsite, as industrial wastewater needs a specific treatment depending on its pollution. The quality of industrial wastewater can vary considerably, depending on the production processes. For example, wastewater can contain heavy metals or can be highly organic. Therefore, in some cases a production plant for internal pretreatment of wastewater is required. Municipal wastewater has varied treatment needs as well. For instance, in developed countries, wastewater is usually more contaminated with pharmaceutical residues than in developing countries.

Regarding combined wastewater treatment systems, the municipal wastewater of urban areas is often treated together with the industrial wastewater in the CWWTP inside the industrial park. This is due to the fact that industrial wastewater is difficult to treat without the addition of municipal wastewater in some cases. Furthermore, it is conceivable that the treatment of the industrial and municipal wastewater takes place in the MCWWTP in the urban area. This can be the case if the industrial wastewater is not heavily polluted. Here, too, the treated wastewater is discharged after treatment back into the receiving water body.

SEMIZENTRAL as a new approach to calculate water-reuse demands in suburban areas

For the development of the IU-WA-RE concept, the new SEMIZENTRAL approach (Tolksdorf et al., 2016) serves as one of two baselines. Accordingly, the municipal wastewater is treated in a semi-centralized Resource and Recovery Center (RRC). Instead of only one MCWWTP in a large urban area, the urban area is divided into smaller urban units, each of which has an RRC. The RRC provides water “fit for purpose.” Thus, the RRC provides both reuse water which can be applied directly for different purposes and the required effluent quality, in case treated wastewater is discharged after treatment back into the receiving water body (SEMIZENTRAL). Due to the construction of a first RRC in 2014 in the city of Qingdao (China), data from this center can be considered. Calculations have shown that the water consumption in housing areas can be reduced by treating different wastewater flows. The RRC integrates the sectors of water supply, wastewater treatment, and waste treatment in an in-house solution. Several modules in the RRC treat two influent wastewater qualities. One module treats wastewater from washing machines and showers (graywater), which can be reused for toilet flushing in the housing areas after treatment. Water demand for toilet flushing (33 L per day per capita) is approx. 30% of the whole water consumption in Qingdao (109 L per day per capita), whereas the wastewater volume for showers (33 L per day per capita) and washing machines (8 L per day per capita) amounts to 38%. By reusing the treated graywater...
for toilet flushing, the whole water consumption can be thus reduced by at least 30%. A second module of the RRC treats the blackwater, thus the wastewater from toilets (33 L per day per capita) and kitchen (25 L per day per capita), which accounts 53% of the total water consumption per capita (Cornel et al., 2013). This treated blackwater can be also reused for purposes in the same way as treated graywater, if treated adequately. Investigations of the inflows of graywater have shown that compared with planning the concentrations for COD, TN, and TP are higher measured. The deviation is between +130% for phosphorus and up to +1,025% for nitrogen. In contrast, blackwater is less contaminated than planned, with concentrations of −18% (ammonium) to −51% (phosphorus) (Engelhart et al., 2018). The effluent of the RRC has the required reuse water quality, which could otherwise be received by a MWWTP and an additional WRP. These two treatment modules are providing the reuse water “fit for purpose.”

To evaluate the water-reuse potential in urban areas a reuse factor has to be calculated. The so-called Urban Reuse Factor (URF) has to be determined, depending on the respective subsequent Reuse Application (RA). Due to SEMIZENTRAL, the URF results in 30% referring to reuse water for toilet flushing. The URF can be increased by considering further reuse application (undefined application: Reuse Application → RAx), for example, water for the irrigation of green spaces.

The Industrial Wastewater Management Concept with a focus on reuse as one basis for infrastructural water-reuse calculations

The IW²MC→R developed by the project “Water-Reuse in Industrial Parks” (WaReIp) (Bauer, Behnisch, et al., 2019) serves as a second baseline for the integrated IU-WA-RE concept. It includes sustainable wastewater treatment in a CWWTP. The wastewater is discharged in separated pipes to the CWWTP, and it is treated based on the specific loads in different treatment tracks (see Figure 1). Therefore, the flows are divided into categories (A to C) according to their carbon, nitrogen, and phosphorus content (see Table 1 and Figure 1). Thus, the wastewater is treated according to its contents in different treatment tracks inside the CWWTP before it can be discharged back into the water body or into the WRP, where it is additionally treated for its subsequent purpose, for example, for irrigation, street cleaning, or toilet flushing. The produced quality of the reuse water depends on the respective governmental regulation which may vary from country to country (Bauer, Dell, Behnisch, Chen, et al., 2020).

The sustainable IW²MC→R is aimed at a high reuse factor, which describes the relation between the wastewater inflow to the CWWTP and the reuse water outflow for different water-reuse applications. The so-called Industrial Reuse Factor (IRF) relates to infrastructural reuse applications such as water for irrigation, street cleaning, or toilet flushing inside an industrial park. The IW²MC→R enables the calculation of the IRF using a Model Industrial Park (MIP) composed of six production plants. For the calculation, the following reuse applications are considered: water for irrigation of green spaces (20% of the whole industrial park), water for street cleaning (in general 9% of the whole park is roadway), and water for toilet flushing (depends on the number of employees of the production plants). For the water requirements, the current valid governmental regulations and directives were taken into account. The IRF results in ~25% by considering the aforementioned applications (Bauer, Behnisch, et al., 2019). Further investigations have shown that the IRF calculation is valid and also transferable to other industrial parks in other countries. A calculation for an existing industrial park in Vietnam is resulting in an IRF of 22%.

Linking gray and green infrastructures for the development of an integrated industrial–urban water-reuse concept

The new IU-WA-RE concept is based on the one hand on the different existing common wastewater treatment systems and on the other hand on the aforementioned research baselines (see SEMIZENTRAL; see WaReIP). The peculiarity of this innovative concept is that it links all water flows of the urban area and the industrial park to improve the subsequent reuse opportunities.

The new concept refers to the situation in which the municipal wastewater is treated in the semicentral RRC according to the new SEMIZENTRAL infrastructure approach, whereby the treated effluent has the quality for water reuse. The industrial wastewater is treated in a CWWTP and an additional WRP inside the industrial park. Like the RRC, the WRP provides reuse water “fit for purpose.” This water can be applied depending on the respective requirement for different purposes inside the urban area and/or industrial park. The concept considers the implementation of further RRCs in defined urban areas without an intersection of a CWWTP. This is conceivable for the expansion of an existing urban area. Regarding the treatment of municipal wastewater, the new integrated industrial–urban water-reuse concept focuses only on the treatment in a semicentral RRC, as this is the most suitable and cost-effective solution (Tolksdorf, Shen, Blach, Leinhos, & Wagner, 2019).

The Development of the IU-WA-RE Concept

In this chapter, the research hypothesis is presented as well as the general idea and the development of the IU-WA-RE concept. To calculate the water-reuse potential, it is necessary to identify different water-reuse opportunities which can be provided by the concept. They are presented in the following section. Hereafter, required infrastructural water-reuse applications for sustainability and livability must be identified, as they are necessary for the ongoing calculations of the water-reuse potential, with respect to the different aforementioned opportunities. At the end of the chapter, the Model Urban Area (MUA) will be defined, which is the baseline for all calculations in the chapter “results.”

Research hypothesis

The main idea of the new concept is to combine the aforementioned IW²MC→R concept and the SEMIZENTRAL approach to increase the water-reuse potential. Both water resource and
recovery facilities are providing reuse water “fit for purpose,” whereas only few flows are reused. Since both approaches have high remaining treated wastewater flows which can be used for further purposes, the hypothesis is as follows:

1. A separate consideration of the wastewater from the urban area and the industrial park makes it possible to use reuse water, but the potential can be significantly increased. The industrial park only requires a certain amount of water for infrastructural purposes. The internal water reuse for production plants can confidently be left out, as this water is finally also fed into the CWWTP and thus cannot significantly influence the IRF. Consequently, depending on the production plants, the industrial park provides a certain amount of residual wastewater that can be used for other purposes.

2. The remaining water from the RRC can also be used for further purposes in urban areas, such as irrigation, as only 30% is returned to households and reused for toilet flushing. As the water demand for infrastructural purposes such as street cleaning and irrigation is enormous, the water from the municipal water resource and recovery facility is not sufficient.

3. By combining all wastewater flows, it is possible to drive sustainable urban development. The reuse factor is thus increased and as a consequence, the water consumption of natural resources is reduced.

Water-reuse opportunities provided by the integrated industrial–urban water-reuse concept
As described before the IU-WA-RE concept links different water flows. Due to specific wastewater treatment of the industrial wastewater within the industrial park which relates to the respective quality requirements, the water can be applied as well for infrastructural purposes. The prerequisite for linking water flows is that the water is not entirely applied to the corresponding urban area or industrial park area, that is, the URF or IRF is not 100%.

The concept considers the IRF of 25% according to WaReIp based on an inflow of 100% to the CWWTP. The


| CATEGORY A (wastewater flow with carbon as a main component) |  |
|---|---|
| NO. | WASTEWATER ORIGIN (PRODUCTION PROCESS/OTHER) | ANNUAL OUT-PUT [T/A] | FLOW [M³/DAY] | COD [KG/DAY] | N [KG/DAY] | P [KG/DAY] | TSS [KG/DAY] | TDS [KG/DAY] | TS [KG/DAY] | REFERENCE |
| 4 | Fruit juice | 40,000 | 147 | 250 | 3 | 1 | nda | nda | nda | DWA-M766 & Rosenwinkel et al. (2015) |
| 12 | Canteen | – | 375 | 709 | 4 | 2 | nda | nda | nda | DWA M 775 |
| 13 | Butchery (cattle) | 100,000 | 260 | 1,822 | 137 | 14 | nda | nda | nda | DWA-M 767 & Rosenwinkel et al. (2015) |
| 16 | Filament Glass fiber | 500,000 | 8,904 | 601 | 89 | 0 | nda | 11,037 | nda | BVT Manufacture of Glass (2013) |
| 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) |

| CATEGORY B (wastewater flow with carbon and nitrogen as main component) |  |
|---|---|
| NO. | WASTEWATER ORIGIN (PRODUCTION PROCESS/OTHER) | ANNUAL OUT-PUT [T/A] | FLOW [M³/DAY] | COD [KG/DAY] | N [KG/DAY] | P [KG/DAY] | TSS [KG/DAY] | TDS [KG/DAY] | TS [KG/DAY] | REFERENCE |
| 1 | H₂O₂ | 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) |
| 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 & Rosenwinkel et al. (2015) |

(Continues)
| WASTEWATER ORIGIN (PRODUCTION PROCESS/OTHER) | ANNUAL OUTPUT [T/A] | FLOW [M³/DAY] | COD [KG/DAY] | N [KG/DAY] | P [KG/DAY] | TSS [KG/DAY] | TDS [KG/DAY] | TS [KG/DAY] | REFERENCE |
|---------------------------------------------|---------------------|--------------|--------------|-------------|------------|-------------|-------------|-------------|-----------|
| 8 Sugar (beets)                             | 1,000,000           |              | 2,740        | 23,973      | 370        | 0           | nda         | nda         | nda       | DWA-M 713 & Rosenwinkel et al. (2015) & Südzucker Werk-Offenau |
| 9 Silicone                                  | 50,000              |              | 3,288        | 1,973       | 0          | 0           | nda         | 29,451      | nda       | BVT Production of Speciality Inorganic Chemicals (2007) |
| 11 Paper                                    | 300,000             |              | 10,274       | 8,527       | 0          | 0           | nda         | nda         | nda       | DWA-M 731 |
| 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         | 52          | nda         | nda         | nda       | DWA-M 710 |
| CATEGORY C (wastewater with carbon, nitrogen and phosphorous as main component) | | | | | | | | | |
| 10 Ethanol                                  | 800,000             |              | 25,001       | 2,387,624   | 118,756    | 8,876       | nda         | nda         | 2,250,117 | Rosenwinkel et al. (2015) |
| 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) |
| Sum                                        |                     |              |              |             |            |             |             |             |           | 94,658    |

Note. COD, chemical oxygen demand; N, total nitrogen; nda, no data available; P, total phosphorus; TDS, total dissolved solids; TS, total solids; TSS, total suspended solids.
corresponding raw water flow can be thus higher (see Figure 2). The remaining treated reuse water can be discharged into the urban area and can be applied for further reuse applications there. The treated reuse water effluent of the RRC is applied according to SEMIZENTRAL for the reuse application “toilet flushing” with an URF of 30% as well based on an inflow to the RRC of 100%. The remaining reuse water effluent of the RRC can also be applied for further water-reuse applications inside the urban area and/or inside the industrial park (see Figure 2).

The IU-WA-RE concept provides three different reuse application opportunities to gain an increased reuse factor by the correlation of industrial and urban reuse applications, depending on the water supply from the respective water resource recovery facility.

1. The first water-reuse opportunity is the extension of the URF (URFextended) by considering further reuse applications (RAx) inside the urban area and additionally inside the industrial park. In this case, remaining reuse water from the RRC is discharged from the urban area to the industrial park (see Figure 2).

\[
URF_{\text{extended}} = \frac{RAx + URF}{\text{Whole wastewater inflow to RRC}}
\]

2. The second opportunity is the extension of the IRF (IRFextended). In this case, the reuse water provided by the CWWTP/WRP is applied for infrastructural purposes inside the industrial park. The remaining reuse water from the CWWTP/WRP is discharged from the industrial park to the urban area for further infrastructural reuse applications (RAx) in the urban area (see Figure 2). The reuse water is provided by the RRC and the CWWTP/WRP.

\[
IRF_{\text{extended}} = \frac{RAx + IRF}{\text{Whole wastewater inflow to CWWTP}}
\]

3. The third opportunity is a holistic approach combining the aforementioned opportunities by calculating the Industrial–Urban Reuse Factor (IURF). The IURF relates to all water-reuse outflows for further applications (RAx) inside the industrial park and inside the urban area (see Figure 2). The reuse water is provided by the RRC and the CWWTP/WRP.

\[
IURF = \frac{RAx + IRF + URF}{\text{Whole wastewater inflow to CWWTP and RRC}}
\]

**Infrastructural water-reuse applications with regard to sustainability and livability**

Due to SEMIZENTRAL and WaRelp, the URF and IRF can be easily calculated. The calculation of further reuse applications is now necessary. Because a sustainable industrial and urban development with a focus on quality of life is the main baseline for the integrated concept, different water-reuse applications must be defined and specified to contribute to a significant improvement of those aspects.

![Figure 2. Water flows of the new integrated industrial–urban water-reuse concept.](image-url)
1. The first reuse application (RA1) relates to clean streets, as they have a huge contribution to sustainability and quality of life. If waste is not removed from streets, there is a risk that it will end up in stormwater systems and become mixed with surface water. Without street cleaning measures, water from natural sources is vulnerable to contamination by many pollutants from human activities (Graham & Brinkmann, 2004). Chinese regulations are very strict in this regard, which means they have high reuse water demands for street cleaning. Thus, utilizing reused water contributes to the sustainability of the street cleaning service.

2. The second application (RA2) is the irrigation of urban green spaces, as it enables their expansion, especially in the water-stressed regions on which this concept focuses. For example, public green spaces like “city parks as pivotal public spaces and vital green infrastructure are of strategic importance in the pursuit of the sustainable city and the well-being of urban dwellers” (Wang & Liu, 2017) are an important application of water reuse.

3. Urban streetscapes, especially roadside vegetation, which affect human well-being (Vries, Dillen, Groenewegen, & Spreewenberg, 2013; Säumel, Weber, & Kowarik, 2016), can help to deliver ecosystem services in the areas near where people live, as public green spaces are scarce in many cities (Weber, Kowarik, & Säumel, 2014). Consequently, the irrigation of roadside green spaces is the third application (RA3) and also important for the calculation of the IURF.

The Dimensions of the Model Urban Area (MUA) for the calculation of the IURF
A Model Urban Area (MUA) serves as an initial precise calculation for water-reuse requirements in an urban area. Therefore, available data from Shanghai and Beijing were taken into account, as these cities have high urbanization rates. Thus, these data are suitable for the following calculation. Additionally, analyzed data from Qingdao were considered, as it was there that the first RRC was implemented in 2014 for 12,000 inhabitants. If data were otherwise not available, data from the country as a whole were taken into account. Thus, the aforementioned infrastructural reuse application from the integrated concept can be determined later on, so that an intersection of all water flows is possible. For the dimensioning of the MUA, the following literature-based data were used:

1. The MUA is expected to have 104,000 inhabitants, which is, according to the SEMIZENTRAL approach, the most suitable dimension with respect to sustainability for a semi-centralized RRC in Qingdao (Bieker, 2009). Due to detailed analyses, which were conducted during SEMIZENTRAL, such an exact number was chosen for further analysis.
2. For all of China, 8.26 m² city park area per capita was analyzed in 2014, which is 2% of the total urban area (Wang & Liu, 2017). Therefore, the MUA has a size of 4,295 ha with approx. 86 ha of public urban city parks. These values are comparable to the city of Shanghai, which is verified by the given data from Syrbe and Chang (2018).
3. For calculating the roadside green spaces, available values from Beijing are taken into account (ebd.). Beijing has an area of 61,695 ha of green spaces, 19.7% of which make up the roadside green spaces, from a total urban area of 1,350 km². Accordingly, green spaces in Beijing account for ~46% of the total urban area, 121.54 km² of which are roadside green spaces. This is a proportion of 9% of the total area of Beijing. Hence, the MUA has as a roadside green space area of approx. 387 ha.
4. Regarding the proportion of land allocated to streets, the total for the whole of China is 12.6% (UN-Habitat, 2013). Thus, the MUA allocates a surface of approx. 541 ha for road spaces.

Calculation of Reuse Water Requirements in Water-Stressed Urban Areas Considering Different Conditions
This chapter presents different IURF calculations depending on various data. The first IURF calculation is a neutral calculation considering the MUA without further specific data. Afterward, additional aspects are included in the calculation. Thus, the effects on the water demand of an urban area are taken into account under consideration of aspects of an improved quality of life. A further calculation then shows the effects of taking climate data into account. Consequently, an IURF calculation has to consider the local and regional conditions which can have a notable impact on water resources and water demand. The following calculations therefore show only one model to proceed.

The calculation of the IURF for the Model Urban Area
Before calculating the holistic IURF, the URF has to be recalculated by considering further reuse applications inside the urban area. Therefore, the total wastewater inflow to the RRC has to be determined, which is based on the analyzed water consumption of 109 L/day for the city of Qingdao. Presuming 104,000 inhabitants, 11,336 m³/day wastewater can be treated and provided as reuse water by the RRC. The total reuse water demand for the MUA (toilet flushing, irrigation of public green spaces, irrigation of roadside green space, and street cleaning) amounts to 26,413 m³/day (see Table 2). Hence, the water demand for the infrastructural reuse application in the urban area is higher than the provided reuse water flow from the RRC (11,336 m³/day).

Thus, the whole outflow of the RRC is needed for parts of the RA1,2,3 (see Figure 3). Consequently, the URF is calculated to be 100%. The URFextended, with respect to the first opportunity which includes reuse applications inside the urban area and inside the industrial park as well as the IRF, cannot be calculated, as the URF is already 100%. This is due to the fact that no remaining reuse water from the urban area exists to be discharged to the industrial park (see Figure 3).
Thus, to meet the water requirement of the urban area, the required water flow for the RA1,2,3 (22,981 m$^3$/day), has to be provided from the CWWTP of the industrial park for the MUA. Nevertheless, there is still a surplus of reuse water from the CWWTP/WRP (see Figure 3). Either this flow can be used for further water-reuse applications or it can be discharged into the receiving water body.

Hence, the IRFextended for the second opportunity has to be calculated. Therefore, the dimension of the CWWTP must first be determined. As an example, the wastewater treatment capacity of the CWWTP in the Shanghai Chemical Industrial Park (SCIP) with of 36,000 m$^3$/day wastewater per day is considered. The SCIP is chosen as an example as it represents a suitable and realistic industrial park size in China. All other analyzed data according to the infrastructural reuse application were considered and can be calculated according to the known water-reuse demand (see Table 2). Consequently, the IRFextended is calculated by considering the required reuse water flow of the IRF, as well as parts of RA1,2,3 and the wastewater flow of 36,000 m$^3$/day. It results in 67%.

### Table 2. Calculation of the reuse water demand for the MUA in China

| REUSE APPLICATION | DATA REFERRING TO MUA (TOTAL AREA 4,295 HA) | CALCULATION OF REUSE WATER DEMAND PER DAY | REFERRING TO IRF | % REUSE IN MUA$^a$ |
|-------------------|--------------------------------------------|------------------------------------------|-----------------|-------------------|
| Toilet flushing   | 104,000 Inhabitants                        | 33 L per capita per day                  | URF             | 30%               |
| Street cleaning   | 541 ha Road spaces                         | 2.5 L m$^{-2}$ day$^{-1}$$^b$            | RA$_1$          | 119%              |
| Irrigation city parks | 86 ha Size of city parks                | 2 L m$^{-2}$ day$^{-1}$$^b$             | RA$_2$          | 15%               |
| Irrigation roadside green space | 387 ha Size of roadside green space | 2 L m$^{-2}$ day$^{-1}$$^b$ | RA$_3$          | 68%               |

Sum of all reuse water demands 26,413 m$^3$/day RA$_{1,2,3,URF}$ 232%

$^a$The percentage is based on the provided reuse water outflows of the RRC, which is 11,336 m$^3$/day by considering 104,000 inhabitants and 109 L water consumption per inhabitant and day.

$^b$GB 50282-2016 Code for Urban Water Supply Engineering Planning (China): average value is taken into account.
IURF is omitted as it is similar to Figure 3. The IURF results in 94%. A spatial representation here of the reuse water demand in the industrial park, 35,605 m$^3$/day.

The RRC (47,336 m$^3$/day). Hence, the IURF results in 75%. The IURF consists of all necessary reuse water flows (9,000 and 26,413 m$^3$/day). Accordingly, there is a remaining reuse water flow of 25% (11,923 m$^3$/day).

Finally, the IURF as a third opportunity to gain an increased reuse factor can now be calculated. The IURF consists of all necessary reuse water flows (9,000 and 26,413 m$^3$/day) and the wastewater inflow to the CWWTP as well as to the RRC (47,336 m$^3$/day). Hence, the IURF results in 75%. Accordingly, there is a remaining reuse water flow of 25% (11,923 m$^3$/day).

### The calculation of the IURF focusing on quality of life aspects

In China, the 2% proportion of city parks is comparatively small in relation to other cities. Comparing it to the two most livable cities of the world, Vienna and Melbourne, the proportion of public gardens is very small. Vienna, voted in 2018 to be the most livable city of the world, records 6% of land use for city parks. Melbourne, which held the title for the years 2011 up to 2017 (The Economist, 2018), has an even higher value of 12.7% (city of Melbourne: 3,770 ha, parks and gardens: 480 ha). Melbourne is particularly famous for its gardens, parks, and tree-lined streets. These characteristics are part of the green infrastructure and provide a significant contribution to the livability of the city (City of Melbourne, 2018). Hence, by taking the size of Melbourne’s city parks (545 ha) into account, the reuse water demand for the irrigation of green spaces rises from 15% (size of Chinese city parks: 86 ha) to 96% (see Table 3). Consequently, the reuse water demand increases from 26,413 m$^3$/day (see Table 2) to 35,605 m$^3$/day.

Consequently, considering the higher reuse water demand for the MUA and the reuse water demand in the industrial park, the IURF results in 94%. A spatial representation here of the IURF is omitted as it is similar to Figure 3.

### Adaption of the IURF by considering climate data

In a next step, the previous calculations (which exclude climate data) are extended to show the impact on the reuse water requirements, for example, for the irrigation of green spaces and street cleaning. For this purpose, climate data of an arid/semi-arid region are used to highlight the influence of the respective precipitation and evapotranspiration on the IURF. Therefore, climate data of the city Yinchuan (maximum rainfall of 193 mm/a, 318 day without rainfall; World Meteorological Organization, 2019) were taken into account as a representative for an arid to semi-arid region in the northwest of China. The calculation for the determination of the total water requirement for irrigation is conducted according to the Food and Agriculture Organization of the United Nations (FAO). The provided calculation tools (CLIMAWAT and ETo Calculator) consider a plant-specific evapotranspiration, the effective precipitation, as well as soil conditions. In order to calculate the water demand for street cleaning, only days without (enough) rainfall are considered in the following calculation. The calculated IURF (see Table 4) represents year-round average values with the exception of the example of the month with the highest (June) and lowest (January) water requirements for irrigation.

Due to the uneven monthly distribution of precipitation and the variable evapotranspiration, it is obvious that the reuse water requirements fluctuate. The results show that in summer, despite the higher precipitation in Yinchuan, reuse water requirements are higher than in winter months due to higher evapotranspiration in summer. The IURF for Yinchuan in June, which is higher than 100%, shows that the reuse water requirements for the indicated purposes are not sufficient. Hence, the calculation of the month-specific IURF shows the limit of urban development with respect to the size of green spaces, in case other water supply sources are not available. In addition, the choice of plant species has an impact on the height of the IURF, as they require different amounts of water. Consequently, adjustments can be made during the planning process to reduce the reuse factor if it is, for example, higher than 100%. In addition, it must be taken into account that the soil conditions also have an influence on the water demand. Furthermore, depending on the local

### Table 3. Calculation of the reuse water demand in the MUA in China in comparison to size of city parks in Melbourne

| REUSE APPLICATION | DATA REFERRING TO MUA (TOTAL AREA 4,295 HA) | CALCULATION OF REUSE WATER DEMAND PER DAY | REFERRING TO IURF | % REUSE IN MUA$^a$ |
|------------------|---------------------------------------------|-------------------------------------------|------------------|-------------------|
| Toilet flushing  | 104,000 Inhabitants                         | 33 L per capita per day                   | URF              | 30%               |
| Street cleaning  |                                             | 2.5 L m$^{-2}$ day$^{-1}$$^b$           | RA$_1$           | 119%              |
| Irrigation city parks$^c$ | 86 ha Size of city parks (China) | 2 L m$^{-2}$ day$^{-1}$$^b$ | RA$_1$ | 15%               |
| Irrigation city parks | 545 ha Size of city parks (Melbourne) | 10,910 m$^3$/day | RA$_2$ | 96%               |
| Irrigation roadside green space | 387 ha Size of roadside green space | 7,733 m$^3$/day | RA$_3$ | 68%               |
| Sum of all reuse waters demands | | 35,605 m$^3$/day | RA$_{1,2,3,URF}$ | 313%               |

$^a$The percentage is based on the provided reuse water outflows of the RRC, which is 11,336 m$^3$/day by considering 104,000 inhabitants and 109 L water consumption per inhabitant and day.

$^b$GB 50282-2016 Code for Urban Water Supply Engineering Planning (China): average value is taken into account.

$^c$Comparative value from Table 2 (not considered in calculation of reuse water demand per day).
situation or discharge permits for water bodies, an IURF of 100% is in some cases not possible, if parts of the surface water must be re-discharged into the water body. In months with lower reuse water requirements, the unnecessary water can be discharged after treatment in the CWWTP (without treatment in the WRP) into the water body.

**DISCUSSION: DEVELOPMENT POTENTIAL FOR URBAN AREAS AND INDUSTRIAL PARKS BY REUSING TREATED WASTEWATER**

**Correlation between the IURF and the corresponding urban area if reusing all water flows**

The previous analyses have shown that fluctuations in water demand for reuse water depend on the respective local or regional situation. For instance, the IRF calculation according to the IW2MC→R on a smaller scale as the IRF varies depending on the respective industrial park situation. Hence, the more water is required for the industrial park, the less water can be applied for further purposes. Hence, the following descriptions present primarily a neutral situation without consideration of specific data. In the case of a real transfer to a certain region, climate data and other conditions such as local vegetation must therefore be taken into account.

In the following, the results show the development potential of urban areas with a certain water demand by considering a certain wastewater inflow to the CWWTP. The following analyses assume an IURF of 100% (in the case that local permits allow a reuse of 100%). The calculation of the size of the MUA is conducted exemplary for the case study of China (following previous chapters). Additionally, the size of Melbourne's public city parks is taken into account to present increased water requirements for larger urban green spaces.

For a certain wastewater treatment flow, the example of the Shanghai Chemical Industry Park (SCIP) with a treatment capacity of 36,000 m³/day is considered, as it represents a suitable industrial park area (see Figure 4). The example shows that the size of the basic MUA increases up to 186,241 inhabitants with an area of 7,692 ha by an entire water reuse in case that the CWWTP/WRP provides 36,000 m³ reuse water per day. By adapting the dimensions of the MUA to Melbourne's amount of public city parks, an entire reuse is possible when considering an amount of 115,703 inhabitants with an area of 4,779 ha. Hence, the example shows that the expansion potential is rather limited if larger green areas are taken into account, due to the higher water consumption. Thus, an IURF of 100% is achieved with fewer inhabitants.

By considering a larger CWWTP, for example, an industrial park with 100,000 m³/day (see Figure 4), which is quite conceivable (for instance, the Nanjing Chemical Industrial Park represents the mentioned treatment capacity) an entire water reuse, and thus an IURF of 100%, is achieved with 517,336 inhabitants (more than four times as large as the MUA), or respectively 321,398 (more than two times as large as the MUA) by adapting the data to Melbourne's size of public city parks (assumed that the outflow of the CWWTP is 100,000 m³/day). Thus, a larger treatment capacity of the CWWTP allows a larger sustainable urban development (see Figure 4).

Consequently, the urban development potential depends significantly on the size of the industrial park, and, respectively, on the outflows of the CWWTP, as the wastewater from households and thus the reuse water effluent from the RRC is not sufficient for the water-reuse demand in the MUA. The necessary remaining reuse water has to be provided by the CWWTP of the industrial park. Therefore, the concept enables the calculation of different urban development possibilities, depending on different treatment capacities of CWWTPs. Thus, the larger the treatment capacity of the CWWTP, the larger the city can be successively developed (see Figure 4). Figure 4 shows additionally that, when measures are implemented to improve the quality of life through the development of green areas in the city, the reuse water demand increases.

**Calculation of the optimum reuse water outflow of the CWWTP depending on the development potential of the urban area**

Inversely to the previous section, this concept enables the calculation of the required wastewater outflows of the CWWTP based on the size of a required urban area. In case that the development of a certain number of housing units under sustainability conditions to cover demand is essential, the calculation can define the size of an industrial park to cover the required reuse water flows. Just as in the previous chapter, climate data are not considered. Depending on the amount of precipitation, the development potential can therefore depend proportionally on it.

The first example (see Figure 5), based on the basic data of China, shows the required treatment capacity of the CWWTP/WRP inside the industrial park for an entire water

| CLIMATE DATA | IRF | IURF (DATA CHINA) | IURF (DATA ADAPTED MELBOURNE'S SIZE OF CITY PARKS) |
|--------------|-----|------------------|--------------------------------------------------|
| No consideration, year-round | 25% | 75% | 94% |
| Yinchuan | | | |
| Year-round | 23% | 69% | 85% |
| January | 59% | 64% | |
| June | 87% | 120% | |

Table 4. Impact of climate data to the IURF

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reuse. Thus, for the reuse water supply of only one MUA, a reuse water flow of 20,103 m$^3$ per day is required. By considering larger city parks, 32,359 m$^3$/day is required for the same urban area and number of inhabitants. Consequently, the larger the housing requirements in terms of size, sustainability, and quality of life, the larger is the reuse water demand, which can be covered by discharging reuse water from the corresponding industrial park to the urban area.

Hence, larger industrial parks are required for a sustainable water supply in urban areas.

**Conclusion**

In conclusion, the integrated IU-WA-RE concept provides a solution to drive sustainable developments by the efficient reuse of water for water-stressed regions. The concept contributes to
sustainable development and the quality of life. The main findings are the following:

1. By linking treated industrial and municipal wastewater flows and applying them for all conceivable infrastructural water-reuse purposes, the reuse factor can be increased, instead of a separate consideration. Regarding the industrial park, the IRF results in 25%, while regarding the urban area, the URF results in 30%. Combining all reuse water flows, the IURF increases up to 75% and, respectively, to 94% by considering quality of life issues. Thus, the IU-WA-RE concept provides a strategy to improve the water-reuse potential. Management units of industrial parks have thus to work more closely together with urban planners so that the water-reuse potential can be increased.

2. The conducted analyses and calculations verify that wastewater of an urban area is not sufficient to cover its own reuse water demand. Hence, discharging the remaining industrial reuse water is essential to cover the required reuse water demand for purposes inside the urban area. It is obvious that considering climate data with respect to rainfall decreases the IURF. Variations of the IURF between summer and winter show very clear the limits for the spaces of urban greens. Urban planners must therefore know the required plant-specific reuse water flows for the month with the highest requirements to plan the corresponding water-reuse requiring area.

3. Regarding the development possibilities of an urban area, the treated outflow of the respective CWWTP of the industrial park has to be taken into account as this can limit development potential. The larger the treatment capacity, the larger the remaining reuse water flow, which can be discharged into the urban area for further reuse applications. Hence, the development potential for the urban area can be estimated for a specific demand for new production plant facilities. Inversely, as the realization of a newly planned settlement depends on the amount of the remaining reuse

Figure 5. Optimum reuse water outflow of the CWWTP for an entire water reuse depending on the development potential of the urban area.
water of the CWWTP, the concept also allows the calculation of the required water-reuse flows from industrial parks.

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