Water Reuse Fit for Purpose by a Sustainable Industrial Wastewater Management Concept

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Water shortage is often a challenge for industrial park developments. To ensure a more sustainable water supply, the Industrial Wastewater Management Concept with a focus on Reuse ($IW^2MC \rightarrow R$) provides a strategy to meet the challenges. Main requirements to achieve water reuse fit for purpose are optimized wastewater treatment, an optimized sewer and pipe system, and an innovative water quality monitoring concept. To evaluate water-reuse concepts, a reuse factor is calculated, which relates to all wastewater inflows to the central wastewater treatment plant and all reuse-water flows.

Keywords: Industrial parks, Industrial wastewater treatment, Water quality monitoring, Water reuse

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1 Introduction

The megacities of Southeast Asia make it one of the world's fastest growing regions. Such tendencies of urbanization have a large influence on the development of industrial parks (IPs). However, IP developments are also a significant factor for urban development [1]. Spillover effects to the local environment are scientifically verified [2]. Referring to the water shortages in several regions, such as China, a sustainable water supply is becoming more and more important, especially in this era of climate change. As IPs have high water requirements depending on their individual production plants and processes, new developments are often hindered. IPs also need water for infrastructural purposes, i.e., for street cleaning or irrigation of green spaces. Thus, it is important to develop a sustainable water-reuse concept for IPs to reduce their high water consumption from natural resources. It enables more flexible and sustainable IP developments, especially in regions suffering from water scarcity, e.g., western or northern parts of China. By employing an optimized treatment of industrial wastewater by a central wastewater treatment plant (CWWTP) including an additional water-reuse plant (WRP), reuse water can be provided for different applications according to the fit-for-purpose principle.

The Industrial Wastewater Management Concept with a focus on Reuse ($IW^2MC \rightarrow R$) is developed based on this principle [3]. It provides reuse water for its subsequent reuse application, e.g., for toilet flushing, the irrigation of greens, or for street cleaning. Therefore, the WRP contains different parallel treatment tracks with treatment steps, which are optimized and adapted to the inflowing treated wastewater types and required reuse-water qualities. The wastewater types, as well as the reuse-water qualities, can be differentiated according to their concentrations of the contents. The concept aims to achieve an industrial park reuse factor (IPRF) higher than 25 %, which is the ratio between all of the wastewater inflows to the CWWTP and all water-reuse flows inside the IP. Depending on the intended purpose for the reuse of the treated water, the IPRF consists of an infrastructure reuse factor (IRF) and a production plant reuse factor (PPRF) (see Sect. 3.4). To accomplish further objectives of a sustainable $IW^2MC \rightarrow R$, the energy consumption of the CWWTP and the WRP has to be less than that of the central water treatment plant (CWTP) due to shorter transport routes (see Sect. 3.1). To achieve an economic implementation of the water-reuse concept, different solutions for a needs-oriented, dynamic pipeline network are developed (see Sect. 3.2). Additionally, a high automation level of the treatment processes must be achieved to secure a high quality level of the reuse water produced by innovative measurement concepts (see Sect. 3.3).

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2 Development of the $IW^2MC \rightarrow R$

The development of the $IW^2MC \rightarrow R$ is based on the results of different investigations in Germany, China, and Vietnam. But the focus lies on the case study of China with respect to further analyses, which show that new industrial park developments in China are much more common and the water-stress level is very high especially in the northern and western parts of China. Thus, these regions are particularly suitable for the implementation of the concept. Hence, Chinese data, e.g., guidelines and governmental regulations, are serving as a basis for the following results [3]. Reuse regulations of the EU can show clear differences, although only a reuse standard for agricultural irrigation is currently being developed [4] while in China there are already standards for different purposes.

During the investigations, two typical IP systems for wastewater treatment were deduced (Fig. 1). In both systems, the CWTP uses ground-, surface, or tap water as raw water source and usually provides three different water qualities (drinking, industrial, and deionized water). Wastewater from the different production plants is treated in a CWWTP, which subsequently discharges the water into the receiving water body, e.g., into the river. Additionally, depending on their wastewater type, production plants have their own on-site pretreatment. The main difference between both systems is that the production plants discharge their wastewater either into one collective sewer (IP System 1) or into separated sewers (IP System 2) to the CWWTP. Generally, it is more common to use gravity sewers for the discharge of wastewater but depending on the framework conditions pressure or vacuum pipelines are also possible.

Separated sewers (IP System 2) allow more precise control over the wastewater inflows from each production plant to the CWWTP for wastewater types with different contents, e.g., COD, nitrogen, and salts. Depending on these different concentration levels, the wastewater flows can also be treated differently in adapted parallel treatment tracks instead of treating them all equally in one track (see Sect. 3.1). Another positive aspect is the higher operational stability of the CWWTP in case of an accident in one of the production plants, e.g., highly polluted wastewater can be separated immediately. Hence, the system avoids a production stop at the other production plants. However, currently, the system described above with separated sewers is still not common in IPs [3].

The development of the sustainable $IW^2MC \rightarrow R$ is based on these two IP systems. Implementing an additional water-reuse plant (WRP) after the CWWTP offers the possibility to provide reuse water in different qualities for different purposes (Fig. 2). Therefore, the WRP in both approaches contains parallel treatment tracks with different treatment steps, which are optimized and adapted to the inflowing wastewater types and required reuse-water qualities. Regarding the provision of reuse water, which is fit for purpose, Water-Reuse Approach 2, with separated inflows to the CWWTP, offers a higher optimization potential. Depending on the wastewater type, different treatment steps could possibly be skipped. For example, for irrigation of green spaces, treatment without aerobic oxidation could be more suitable (see Sect. 3.1). Wastewater treatment optimized according to the principle fit for purpose is one of the main sustainability objectives of the $IW^2MC \rightarrow R$ and contributes to a high water-reuse factor. That is why the second approach is preferable for implementing the $IW^2MC \rightarrow R$ and it is mainly focused on in the following chapters.

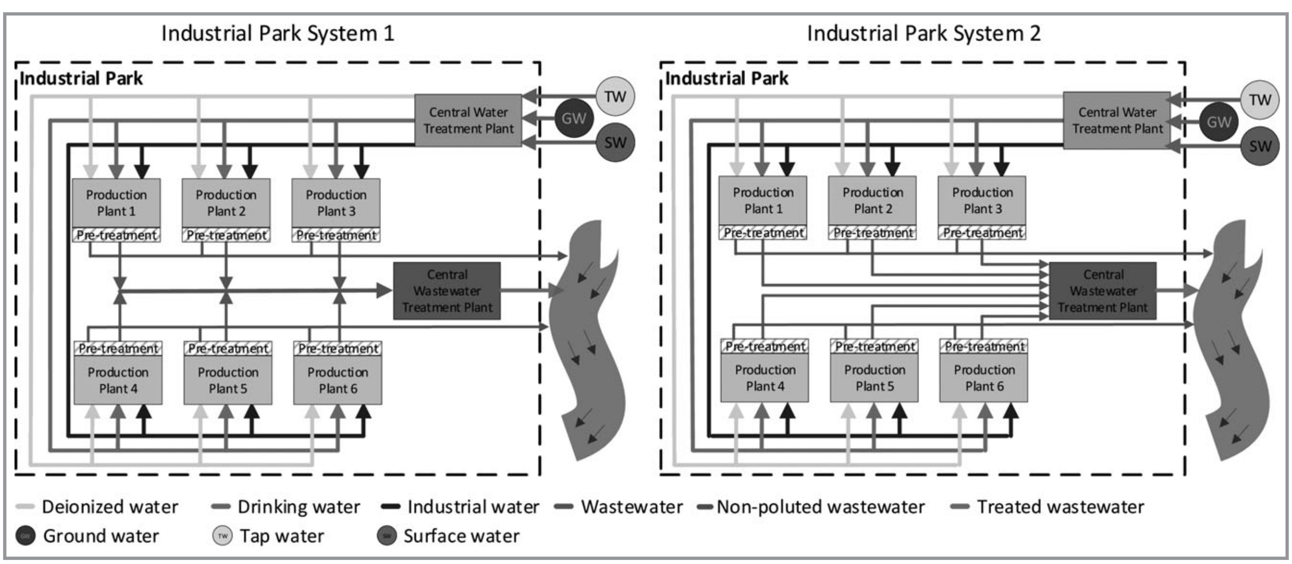

Figure 1. Typical industrial park systems.

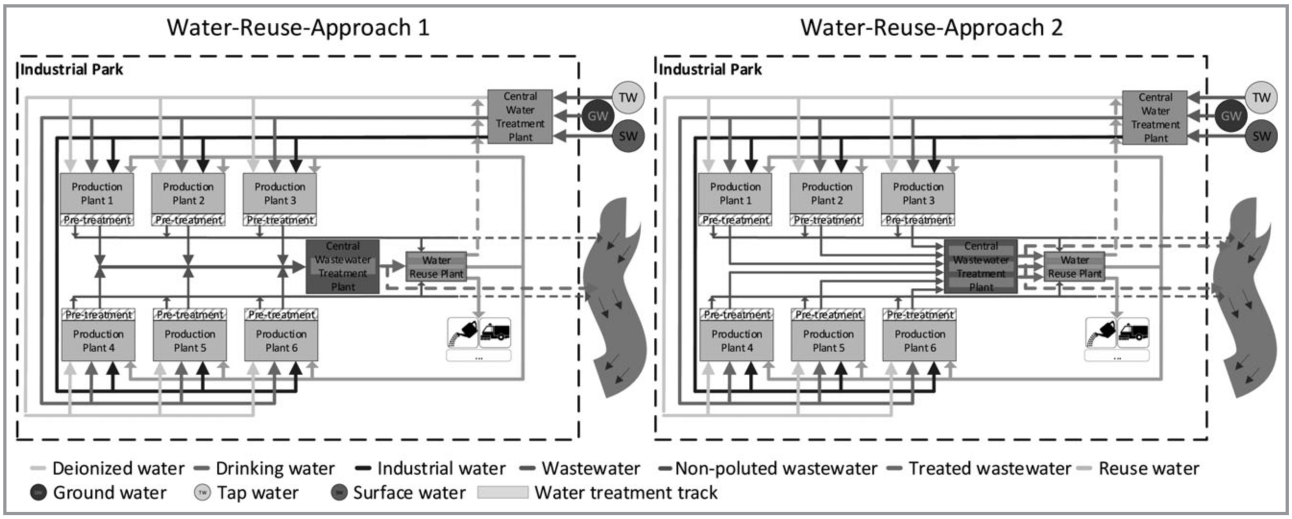

Figure 2. Water-reuse approaches of the $IW^2MC \rightarrow R$.

3 Gaining Sustainability by Providing Reuse Water Fit for Purpose

To provide reuse water, which is fit for purpose, several requirements have to be considered to achieve sustainability. First, an optimized wastewater treatment process is required to achieve the different water qualities needed for different subsequent reuse-water applications. With respect to these water qualities, an optimized sewer and pipeline system is essential either to discharge the different wastewater flows to the respective treatment track inside the CWWTP and WRP or to bring the reuse-water flows to their subsequent consumers. To secure high water quality, the implementation of innovative measurement concepts is necessary. Calculating a reuse factor is the best methodology to evaluate different reuse-water opportunities and suitable framework conditions (like the combination of several production plants and the expansion limits).

3.1 Adapting the Wastewater Treatment to Achieve Reuse Water Fit for Purpose

A precondition for an adapted wastewater treatment is a characterization and classification of the (partial) wastewater flows. A classification should be made with a view to the biological treatment process, as this usually forms the central treatment step of every wastewater treatment concept. Thus, most wastewater partial flows can be subdivided according to their content of carbon, nitrogen, and phosphorus. In this way, the biological treatment method can be selected initially. Wastewater from the food industry, e.g., is often highly loaded with organics, which makes anaerobic treatment attractive due to the production of biogas and the low energy consumption for treatment. On the other hand, wastewater from the chemical-pharmaceutical industry has often high nitrogen concentrations, which makes biological nutrient removal necessary. Further classification is necessary to determine which wastewater flows are suitable for producing reuse water, and which make its production more difficult. Therefore, wastewater flows with high concentrations of salt or poorly degradable/toxic compounds must be treated separately.

Previous studies have already shown that water reuse in IPs not only reduces the strain on natural water resources, but also saves considerable amounts of energy [3]. The energy saving results from the fact that it is often more energy-efficient to use reuse water instead of treating raw water in a CWTP to produce drinking water [5]. This applies in particular when raw water extraction is very complex and energy-intensive due to long transport distances [3].

In the concept presented here, the effluent quality of the CWWTP has the quality required to discharge the wastewater either into the receiving water or for discharge into the WRP to produce the required reuse-water quality [3]. The treatment processes are to be selected specifically according to the quality requirements for the reuse water, e.g., for street cleaning, firefighting, toilet flushing, and irrigation. This treatment concept is referred to as fit-for-purpose wastewater treatment and is already well-known in the field of reclaimed water recovery from municipal wastewater [6]. The concept aims to avoid over- and undertreatment of water, i.e., exceeding the limit levels, thereby achieving both high economic efficiency and environmental sustainability [7].

The advantages of the fit-for-purpose concept are illustrated by the provision of water for irrigation purposes. Irrigation is the most common application for reclaimed wastewater. Worldwide 52 % of reclaimed wastewater is used for irrigation, whereby a further distinction is made between agricultural irrigation (32 %) and landscape and garden irrigation (20 %) [7]. The Chinese "Water Quality Standard for Urban Miscellaneous Water Consumption" [8] includes an ammonia limit of 20 mg L^{-1} for irrigation water, whereas for water to be discharged to the surface a limit of almost 0 mg L^{-1} is usually the aim. Based on the ammonium concentration present in the wastewater, either none, or only part of, the nitrogen load must be removed.

The process most frequently used for nitrogen elimination is the combination of aerobic nitrification and anoxic denitrification. The specific energy consumption of nitrification/denitrification is between 3.5 and 5.7 kWh per kg of nitrogen [9]. The amount of energy saved during the treatment process depends on the amount of nitrogen that does not have to be removed by nitrification and denitrification. However, the energy demand will probably decrease in the near future if new processes such as deammonification can be used to eliminate nitrogen. Nevertheless, today these processes can only be used under very special boundary conditions. However, it is not only energy which is saved during the treatment process: fertilizer is also substituted by the nitrogen applied to the green areas by the reuse water. To manufacture 1 kg of nitrogen fertilizer, 11.1 kWh of electrical energy is required plus 0.28 kWh for transport and 0.83 kWh for spreading on the green areas [10]. In total, energy savings of between 12.2 and 17.9 kWh per kg of nitrogen can be achieved, which does not have to be nitrified or denitrified during wastewater treatment but is brought directly to the green areas with the reuse water.

3.2 Innovative Sewer and Pipeline Systems to Optimize the Fit-for-Purpose Principle

A differentiation between wastewater types as resources for different water-reuse purposes can optimize the CWWTP and WRP by allowing an adapted treatment concept depending on the wastewater type and required reuse-water quality.

3.2.1 Wastewater Discharge Systems

Hence, the necessity of a separate collection of wastewaters with different ingredients and concentration levels might arise. Referring to the water-reuse approaches described in Sect. 2, only the second one offers the possibility to collect wastewater flows separately. But this approach needs a lot of space and investment for the high number of sewers.

To cover the limitations of Reuse Approach 2, which is the more suitable solution for fit for purpose, new needs-oriented and dynamic sewers and pipeline systems are required. Two different options for the separate discharge of wastewater types with different concentration levels are developed, taking into account cost and/or development situations in IPs.

Discharge option 1: In the first option, all wastewater qualities are discharged to the same pressure pipeline network, but at different times (Fig. 3). Additional storage tanks, as well as pumping stations at production sites, are required, which will be operated centrally, e.g., by the operator of the CWWTP. Between the discharge of two different wastewater types, the pipeline system needs to be either emptied (use of pressured air) or flushed with wastewater, which is not harmful for the wastewater treatment processes. Therefore, this option is a time-based solution for the Water-Reuse Approach 2 and avoids the high space requirement for separated parallel pipelines.

Discharge option 2: The second solution is generally a separate pipeline network for each wastewater type referring to the Water-Reuse Approach 2 (see Sect. 2, Fig. 2). The only

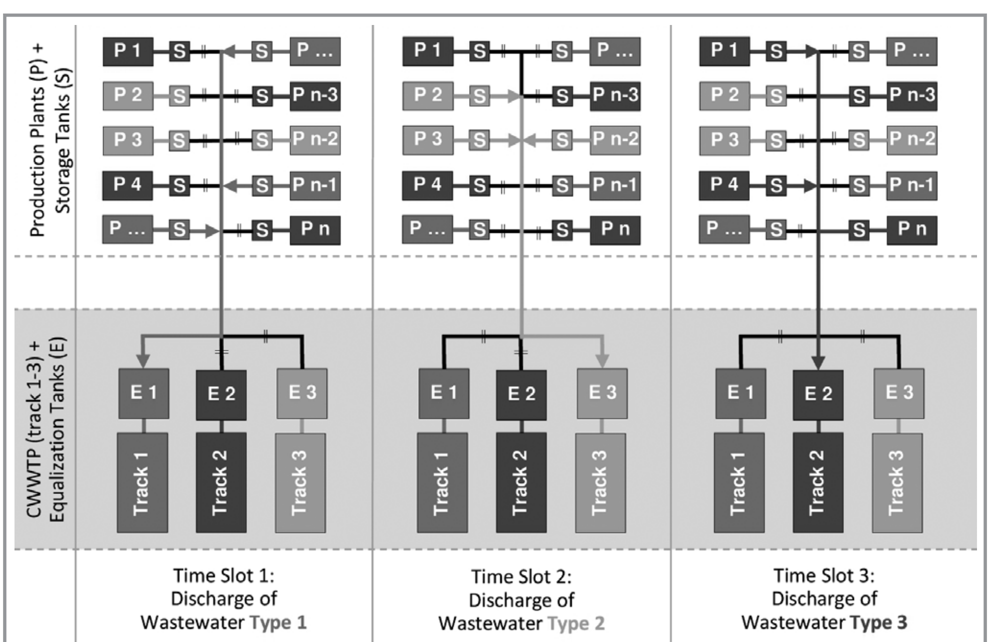

Figure 3. Time-based discharge option of the wastewater.

difference is, that parallel sewers discharging the same wastewater type are avoided by combining them. This is realized by a clustered location of production plants with the same wastewater types, so that subsidiary sewers can discharge only one wastewater type (Fig. 4). This has a high impact on the settlement policy for new production plants. But as IPs mostly have a phased development it could be realized step by step.

In the first development phase of an IP, it is likely that different treatment tracks and separate discharge sewers are not economically feasible because of the small scale. Hence, only one main sewer is realized, into which all wastewater flows are discharged. In this first development phase, the sewer network equates to the Water-Reuse Approach 1 (see Sect. 2, Fig. 2). In the second development phase of the IP, the need for the expansion of the wastewater system can be used to separate one wastewater type by realizing a second main sewer for this type, to which all subsidiary sewers with wastewater with the same concentration levels are connected. The third development phase allows the separation of a further wastewater type through an additional sewer. Thus, after completing all expansion phases, the situation is comparable to an optimized Water-Reuse Approach 2 (see Sect. 2, Fig. 2).

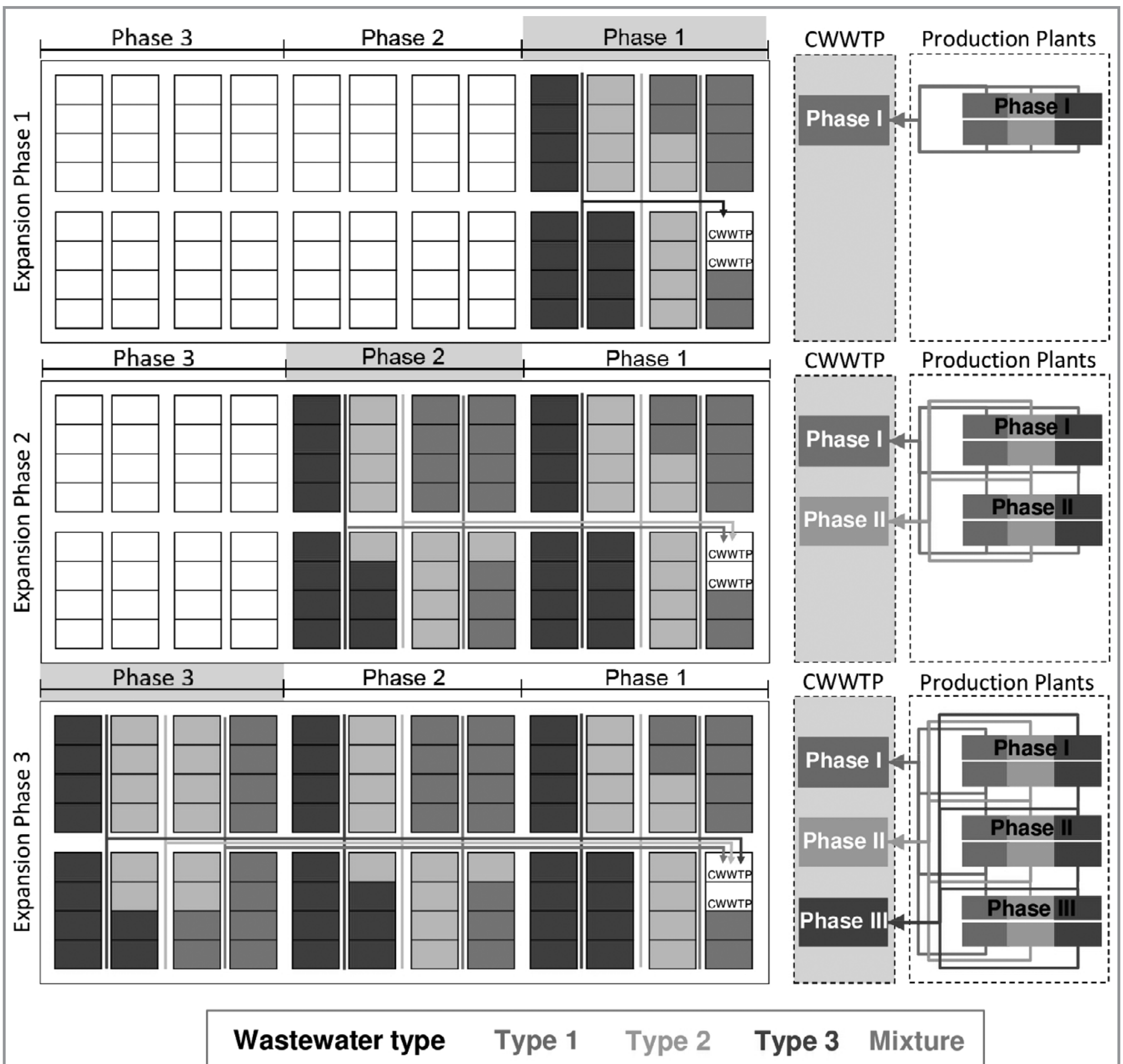

Figure 4. Separated sewer discharge option realized by a phased industrial park development.

3.2.2 Reuse-Water Supply Systems

After the conventional wastewater treatment in the CWWTP for the provision of reuse water, an additional WRP is established in both water-reuse approaches (see Sect. 2, Fig. 2). This water also needs to reach the consumer. Therefore, it can either be transported to the user by truck (e.g., for irrigation or street cleaning) or by a pipeline system (e.g., for toilet flushing or cooling). In the first case, only water taps at the WRP have to be provided in addition to the conventional water supply system. In the case of an additional pipeline system, two options are possible if more than one water quality is to be supplied via pipe. Both options are conceivable for the Water-Reuse Approaches 1 and 2.

Supply option 1: In the case of long distances between WRP and water users, it might be more efficient to realize only one reuse-water pipe to supply all different reuse-water qualities. The different water qualities are separated by time, similar to the discharge option 1 (see Sect. 3.2.1). The reuse-water pipe leads to decentralized storage tanks for reuse water (Fig. 5, left side) and has to be emptied and/or flushed between the discharge of two water qualities. A pipeline system for each quality leads from these decentralized water storage tanks to the production plants.

Supply option 2: For each reuse-water quality, a pipeline network is realized. Storage tanks are only required near the WRP for equalization of the produced reuse water (Fig. 5, right side).

The separate collection of different wastewater types, as well as additional reuse-water distribution systems, will increase the costs for the water conveyance compared to a system with no wastewater separation and water reuse. These additional costs have to be compensated by reduced costs for the wastewater treatment and/or reuse-water production and by lowering the costs of fresh water supply and production in the CWTP.

3.3 Ensuring High-Quality Reuse Water with Innovative Monitoring Concepts

One of the core tasks of the $IW^2MC \rightarrow R$ is to monitor the water flows according to their specific treatment and utilization in consideration of the requirements of the IPs. Hence, a key goal of the joint project is the development of an adapted online monitoring concept. To apply a water quality control concept, at least two measurement points are decisive (Fig. 6). On the one hand, the water quality of treated outflows of the CWWTP and the water inflows to the WRP have to be monitored continuously to ensure an optimum water quality for the subsequent treatment process inside the WRP. On the other hand, the reuse water has to be controlled at the outlet of the WRP to make sure that the reuse-water quality is in compliance with the quality requirements of the specific reuse-water application. The safety chlorination for water disinfection, which is required for some reuse purposes, e.g., irrigation of green spaces, street cleaning, and toilet flushing [8], is an essential treatment step before the consumer can use the supplied reuse water directly for the intended purpose. Thus, the inspection of this safety chlorination is an example of one of the important processes to be monitored continuously. Besides common measurement parameters like pH or temperature, an additional monitoring of turbidity or color could be necessary and could provide important indicators for treatment processes that are not working properly in the WRP. If irregularities in the reuse-water supply are detected, the water supply must be stopped automatically.

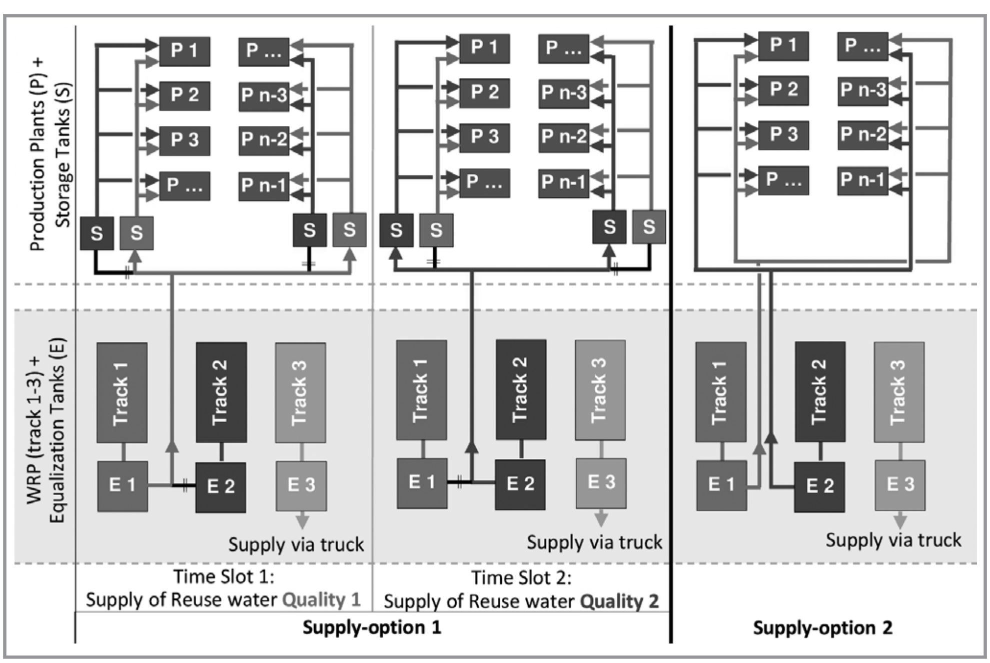

Figure 5. Reuse-water supply options.

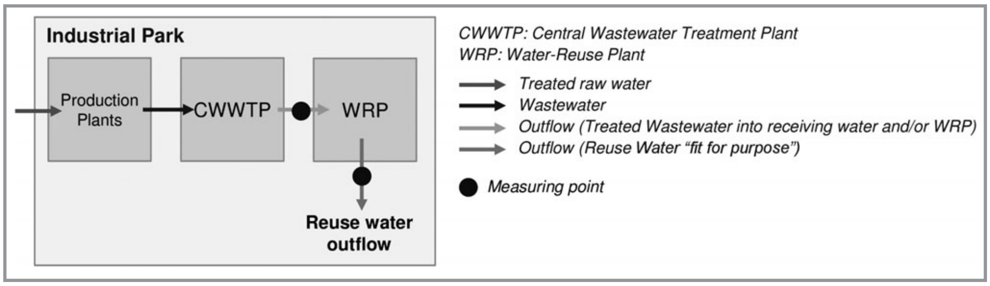

Figure 6. Measurement points for a water quality control concept.

From a technical point of view, the monitoring concept is based on a three-step data management approach that covers the different levels of process automation, from data collection to decision making on management level. The philosophy behind this approach is the provision of high-quality sensor data for successive data management processes, such as the collection, evaluation, transformation, consumption, and visualization of data.

The first step in acquiring high data quality begins at the field instrumentation level. As a prerequisite, the right monitoring devices need to be selected for the measuring tasks, they need to be located in the right places, to be professionally installed, and to be properly calibrated. With this in mind, an installation guide for water-reuse applications will be established to support on-site technicians. If the aforementioned requirements are fulfilled, mathematical algorithms can be applied to the raw data to identify implausible measurement values (so-called plausibility check).

The second step comprises the collection of both valid sensor and plant data. Customized algorithms transform those data into further operational information, such as water quality indicators. This information supports service technicians, plant operators, or process managers in their decision-making. The required algorithms have to be specifically designed according to the intended use of the water flow and the treatment process.

The third and final step focuses on the visualization of the individually prepared data and process information. These must be easy for the consumer to understand and to use.

3.4 The Industrial Park Reuse Factor: Water-Reuse Opportunities to Reduce the Water Demand from Natural Resources

For the evaluation of water-reuse opportunities in IPs, the IPRF (see Sect. 1) has to be calculated. It describes the ratio between the sum of the wastewater flows entering the CWWTP and the sum of the water being reused for different purposes after treatment. Other external water flows, such as rainwater, are not considered. Depending on the purpose for which the treated water is to be reused, the IPRF can be divided into an infrastructure reuse factor (IRF) and a production plant reuse factor (PPRF). The IRF is related to specified infrastructural reuse applications, e.g., irrigation of green spaces, firefighting, street cleaning, or toilet flushing, and the PPRF includes all water-reuse applications inside the production plants, e.g., reuse of process water [3]. The IW^{2}MC$\rightarrow$R is focusing on the IRF, thus, referring to the infrastructural reuse-water applications. Calculating the PPRF needs further analysis of the required process water qualities and quantities which could be a second research step.

By using an adaptable model industrial park (MIP), instead of a real case study IP, this approach analyses the framework conditions that lead to the highest possible IPRF. The effect of modifying production types and using supplementary expansion areas is investigated as well as the implementation of different water-reuse purposes. An MIP with six exemplary production plants adapted to Chinese framework conditions serves as a first theoretical basis. Considering only three reuse purposes, i.e., irrigation of green spaces, street cleaning, and toilet flushing, the calculation of the IRF results in ~25 %. This means that 25 % of the wastewater can be used to generate reuse water, thus, reducing the raw water demand considerably. According to the considered treated raw-water flows, an IRF of 25 % results in a water-saving potential of ~18 %. The indicators, calculations, and assumptions used were therefore also based on Chinese standards and investigations conducted in China [3]. Transferring this model to the data of an existing Vietnamese industrial park with almost 100 production plants close to Ho Chi Minh City an IRF of ~22 % could be calculated. This illustrates the high potential of the IW^{2}MC$\rightarrow$R for Southeast Asia. Even when only three water-reuse options are included, there is already a high water-saving potential. If further water-reuse options were taken into account, e.g., cooling or firefighting water, the total IPRF could be even higher.

4 Conclusion

The IW^{2}MC$\rightarrow$R represents a sustainable strategy for IPs by providing reuse water, which is fit for purpose. The calculation of the IPRF and the IRF allows the general determination and specification of reuse-water opportunities in IPs and provides a basis to optimize the water-reuse potential within IPs. Thus, the calculation of the IPRF enables a precise evaluation of existing wastewater and water-reuse management systems. However, the basis for achieving the highest possible reuse factor is, on the one hand, an optimized wastewater treatment process with respect to the CWWTP and WRP, and, on the other hand, the optimized sewer and pipeline network. Both are important for the sustainable collection and treatment of wastewater, e.g., energy can be reduced in comparison to conventional wastewater management systems, as well as for the suitable production and distribution of high-quality reuse water for subsequent reuse-water applications. Furthermore, the wastewater treatment according to the principle fit for purpose allows the flexible treatment and provision of reuse water by using different treatment technologies. By implementing measurement concepts, the required water quality can be guaranteed for the respective consumer and its application. Overall, the innovative $IW^2MC \rightarrow R$ provides a sustainable solution strategy for IP developments, especially in water-stressed regions, by reusing wastewater where new developments or expansions are otherwise hindered. Hence, it contributes to a noteworthy improvement to the reduction of water consumption from natural resources. Thus, the implementation of the $IW^2MC \rightarrow R$ meets the challenges caused by climate change.

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