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Perspective

Possibilities and Challenges of Wastewater Reuse—Planning Aspects and Realized Examples

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Abstract: Population growth and climate change has a huge impact on water availability. To ensure a secure water supply, water-reuse concepts and its implementation are gaining more and more importance. Additionally, water saving potentials to optimize the drinking and water reuse availability have to be considered. However, limited spatial planning opportunities and missing regulation to provide treated wastewater according to the "fit-for-purpose" principle are often hindering its application. Some countries, such as the USA or Singapore, have been leading the way for decades in implementing water-reuse concepts and in treating wastewater for potable and non-potable reuse. The wastewater treatment technologies are currently providing solutions for an adequate provision of reclaimed water. Consequently, the opportunities for water reuse are given, but the challenge is largely in the implementation, which becomes necessary in water-scarce regions. This perspective is thus presenting the current possibilities and challenges of wastewater reuse with respect to existing examples of implementations but also shows the need for action in the future. The relevance of this topic is also underlined in particular by the Sustainable Development Goals (SDG), especially Goal 6 which is related to "Ensure availability and sustainable management of water and sanitation for all".

Keywords: wastewater treatment; spatial planning; water-reuse concepts

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1. Introduction

1.1. The Impact of Population Growth and Climate Change on the Limited Resource Water

The growing population has a huge impact on the global water demand. The limited resources of water and land are increasingly being used, for example, for increased food production. Regarding this, it is assumed that global water demand will increase by about 1% per year until 2050 [1]. Nowadays, about half of the population worldwide is already temporarily affected by water scarcity [2]. Climate change further aggravates the situation since periods of drought are increasing. The total water demand is rising, especially for irrigating field crops. Therefore, water from natural resources such as ground- and surface water is often (over) used. Besides the higher food demand, both urban and industrial development is required to meet the challenges of the increasing population.

A well-known example for water scarcity is the U.S. State of California. It has to deal with the challenge of increasingly long drought periods [3]. A further example is China where huge regions particular in the north and the west have a high water-stress level due to the uneven distribution of natural water resources and the high levels of pollution of water bodies [4]. However, nowadays, countries, such as Germany, which are not well known for water shortages, are also increasingly dealing with this challenge. In particular, in 2018 and 2019, there were pronounced conflicts over the use of water as a resource in many regions of Germany. Here, conflicts have arisen over the use of water as a resource. Ground- and surface water were increasingly used for agricultural irrigation, but also for cooling and process water in the energy and manufacturing sectors, for public drinking water supplies and for shipping [5]. For example, the conflicts of use, caused by the low water level of the river Rhine, led to a reduction in production at the well-known worldwide operating chemical company BASF [6].

1.2. The Necessity to Ensure a Susainable Water Supply

The situations worldwide show that, especially in times of climate change, it is increasingly important to ensure a secure water supply. Only this way will it be possible to enable sustainable spatial development to meet the challenge of population growth and to secure human needs. For enabling a secure water supply, alternative water sources must be generated to tackle the challenge of increased water scarcity since ground- and surface water sources are frequently insufficient in many regions of the world. Currently, as in the past, new developments often take into account approaches to the storage of rainwater in order to use it for various purposes such as the irrigation of green spaces. However, this water source is uncertain because the quantity of required rainwater at a specific time is not available. Furthermore, storage tanks need a lot of space; however, in cities this space is limited and stored rainwater is definitely not enough to compensate water shortages.

Another alternative and sustainable resource is the reuse of treated wastewater. In contrast to the storage and use of rainwater, treated wastewater is a valuable resource, as it is available daily and in calculable quantities. Nowadays, concepts for water reuse are still rarely implemented [7]. In general, a distinction must be made between different fields of application for reused water: urban and industrial reuse, agricultural reuse, impoundments, environmental reuse, groundwater recharge as well as non-potable and potable reuse [8]. The focus in this paper lies on the type of municipal and industrial (non-potable) wastewater reuse relating to applications according to the “fit-for-purpose” principle with respect to urban, industrial and agricultural issues. Fit for purpose refers to wastewater treatment for the specific water reuse application. This means, for example, that reused water for toilet flushing requires a different and higher quality (disinfected) than water for the irrigation of green spaces.

Generally, the U.S. is leading the way [9], but countries such as China [10] and the EU [11], especially Spain [12], are also already practicing water reuse on a large scale and Spain in particular was ranked with the highest rates in the European Union in 2018 [1]. In the urban context, water reuse is practiced, for instance, for the irrigation of green spaces or for toilet flushing [1,9]. Regarding the industrial reuse, it mostly takes place within production processes [13] or cooling systems [14]. However, the reuse of recycled water for further purposes outside of production facilities, e.g., within an industrial park, is a new and efficient approach [15]. Applying reused water in agriculture is practiced worldwide and this sector is the major consumer of wastewater globally [16].

1.3. Possibilities for an Efficent Water Usage to Save Drinking and Reuse Water

Many ways exist to conserve water, but they are often neglected. For all areas of application, such as municipalities and households, industry and agriculture, there are possibilities to save water and to use the available, scarce water efficiently. Because consequently, more drinking water can be saved as well as the reuse water resource.

Municipalities and especially private households can save water by using water saving faucets and toilets. In addition, water can be saved by reducing existing leakage in the distribution network. Behavioral changes can also lead to water conservation, such as showering instead of bathing. Single-family house owners in particular can collect rainwater and use it for various purposes, such as watering the garden or even washing clothes. In addition, private gardens as well as public green spaces in cities can be planted with resilient greens that require only a small amount of water.

Water-saving measures can also be implemented in industrial parks and industrial sites. This includes, among other things, checking and if possible integrating water-saving production processes and/or using recycled water. Cooling towers are among the largest consumers of water in industry. However, the choice of cooling system affects the amount of water needed. Huge volumes of water can be saved by choosing a closed-circuit cooling system instead of a once-through cooling system. Here, only the evaporated water must be replenished.

Agriculture, the world's largest consumer of water, also has many opportunities to save water if irrigation becomes necessary. In particular, the best irrigation technology must be selected for the respective crop. For example, the efficient method of drip irrigation is often suitable for wine, vegetable and fruit cultivation. Optimal timing can also reduce evaporation losses, such as watering in the evening or during the night. Additionally, the way rainwater is stored also plays an important role in reducing evaporation. Cultivation of plants and crops in greenhouses can also reduce water requirements. In addition, it may be necessary to rethink the allocation of agricultural land in order to best implement irrigation techniques in relation to land use.

2. Methodology and Objectives

This perspective is intended to help explain the causes of water scarcity from a global perspective and to highlight the importance of water reuse for the future. The paper points out the different aspects for the planning, implementation and operation of water-reuse approaches and mentions the challenges of implementing water-reuse concepts due to different planning systems and regulations that exist worldwide. Therefore, different applications for water reuse are mentioned and planning concepts presented. The objective is to further show the enormous variety of different water-reuse solutions. Since water quality standards are essential for all water-reuse approaches, the paper gives an overview of the regulations of water reuse in selected countries as well as the state of the art in wastewater treatment for water reuse. Best-practice examples round off the topic to show the different possibilities that already exist in terms of implementation. Finally, the aim of this perspective is to show that, despite the many successfully implemented water-reuse approaches, transferability is not always possible due to the different legal requirements, and therefore there is still an essential need for action in order to realize water reuse.

3. Aspects for Planning, Implementing and Operation of Water-Reuse Approaches

Regarding the baselines for planning, implementation and operation, water reuse must take into account that water can be recovered from a variety of sources. Consequently, water reuse can provide an alternative to existing water supply systems and ensure water availability. Water reuse can be planned or unplanned. In unplanned water reuse, the water source consists largely of previously used water. An example of this are communities that draw their water from rivers into which previously treated wastewater from upstream communities has been discharged. Planned water reuse involves systems designed with the goal of putting treated wastewater to beneficial use [17].

Sources that are related to reuse include municipal wastewater, industrial processes and cooling water, stormwater, agricultural runoff and return flows and production water from natural resources. However, industrial wastewater that is particularly salty or toxic is not suitable for reuse and must be incinerated.

These water sources are treated as "fit for purpose" in a treatment plant. The use applications can vary widely. Common practices include irrigation for agriculture and landscaping such as parks, rights of way and golf courses. Further applications are the municipal water supply, process water for power plants, refineries, mills and factories, indoor uses such as toilet flushing, dust control or surface cleaning of roads, construction sites and other trafficked areas, concrete mixing and other construction processes, supplying artificial lakes and inland or coastal aquifers and environmental restoration [17].

An important question, whether in new developments or in already developed areas, is how to integrate water-reuse concepts into the environment and how ultimately reused water comes to the user. Various options are conceivable, such as the distribution via filling stations, which allows the reuse water to be transported by cars or trucks, or a separate network of pipes, which brings the product reuse water directly to the user or to the place of use. For the best possible use of the reuse water resource in both cases, implementations in planning strategies and instruments are necessary. Furthermore, the transportation infrastructure has to be designed appropriately. Consequently, for the provision of water reuse without a pipe network, specific issues have to be considered in integrated planning instruments on a city scale. Furthermore, approval issues for the installation of on-site advanced treatment units such as an additional chlorination or other disinfection systems for complying the quality requirements for reusing the water have to be considered. More complexity exists when the water is to be brought to the user via pipes. In this case, a holistic dual pipe network has to be implemented in the respective spatial situation. It is apparent that most use cases (see Section 5) of water reuse take place in cities with large water consumers such as universities, golf courses or large city parks. Many examples exist worldwide as to how reuse water is brought to the application through a second pipe system from the water resource recovery facility. Here, the city of Long Beach and Irvine in California with its dual pipe system are appropriate and prospective examples (see Section 5).

A long period of master planning enabled at least the city-wide provision of non-potable reuse water for irrigating large, landscaped areas such as parks, golf courses, community greenbelts and roadway medians. A separate system of pipes can deliver (drinking) water to homes and businesses [18]. In such cases, integrated planning is essential to drive water reuse in urban areas on a holistic scale.

Different use cases show that the implementation of water- reuse varies and therefore the planning steps also vary. An important question in this context is whether the reusable water is provided for private or public application, or whether it is used in a closed unit as it is the case within industrial parks as they have their own wastewater treatment plant on-site. Depending on this, water reuse must be integrated into the respective levels and (integrated) instruments of urban planning. Since nations around the world have different planning policies, it is necessary to analyze, for each system, at which planning levels water reuse can be implemented directly and indirectly. Integration at the regional and city level is particularly important in order to implement holistic approaches and thus integrate water-reuse sources, water scarcity and possible areas of application. In most countries, such approaches are missing so far.

For driving the efficient use of water, including reuse water, holistic water management approaches are required, and these have to be integrated in planning issues. In this context, water demands, availability, quality, regeneration and protections such as groundwater recharge have to be analyzed and included. Water as a sectoral specialist planning has to be considered in different planning strategies, guidelines or instruments. For instance, drought management plans, river basin management plans, drinking water protection areas, land-use planning instruments, irrigation plans as well as water supply and sanitation plans have to be taken into account. Further relevant plans can be also considered, such as rural development plans and infrastructure plans for utilities. These instruments are providing the basis for an integration of water reuse. This integrated approach shows the importance of cross-disciplinary collaboration among a wide range of stakeholders, such as wastewater treatment engineers, plant operators, urban planners and sociologists. The current challenge is that there is limited information available on how water reuse can be planned and integrated into planning instruments on different scales [19]. Since planning systems vary around the world, integrating water reuse into planning instruments is a major challenge for the future. Only through the implementation on different levels can an efficient water management be optimally realized. Furthermore, the issue of acceptance regarding the use of reuse water is very important especially in countries and regions where it has not been practiced so far. Consequently, the quality aspect is of great importance in the operation (see Section 4). To enable the use of reuse water (see Section 5), special quality requirements must be considered so that the use is safe and harmless to humans. Furthermore, the provision of reuse water according to the “fit-for-purpose” principle has to consider different quality requirements so that it can be directly applied for the subsequent use.

4. Regulations, State of the Art and Future Challenges for Municipal Wastewater Treatment and Water Reuse

Many regulations exist worldwide to meet the respective water quality requirements, e.g., discharging treated wastewater into water bodies or for groundwater recharge. Standards and thresholds vary depending on the respective country. Nevertheless, directives for discharging treated wastewater into waters is often the basis for the later developed reuse guidelines or regulations [1,20]. Although these guidelines are constantly evolving, the focus today is largely on developing new standards for the use of reuse water. In this context, water reuse is separated into potable and non-potable applications. Potable reuse generally refers to potable water supply augmentation, while non-potable reuse refers to all other (indoor and outdoor) uses such as toilet flushing or irrigation [9].

In the following considerations, the main focus is on quality requirements and treatment processes for non-potable water applications, since potable water reuse only accounts for a smaller portion of the total. In addition, industrial wastewater reuse, for instance, water reuse within the production process, will be excluded in the following, since there are different and specific quality requirements depending on the production plants and production process.

With regard to standards and guidelines, this section will only deal with the USA, the EU and China, and with global standards by way of example. This is due to the fact that the USA was one of the first countries to develop water-reuse standards at a very early stage. The EU is considered on the basis of the various different countries and situations and also in terms of how various sets of rules are implemented in national law. In China, there were different guidelines for specific reuse applications at an early stage. Well-known countries that implement water reuse such as Singapore, Australia, Israel are not considered in the following. Singapore is not included in the presentation of regulations and guidelines for water reuse, because it introduced recycled water very late in 2003, whereas the USA, among others, has been producing recycled water for several decades. Nevertheless, Singapore is mentioned in Section 5 because it is considered as one of the most innovative and well-known examples in the field of water reuse worldwide.

4.1. Regulations for Treated Wastewater into Water Bodies and for Reusing Water

4.1.1. Regulations for Wastewater Discharge into Waters

Many different standards and regulations for the discharge of pollutants into waters exist worldwide. In the United States, the Clean Water Act (CWA) is the basis for regulating discharges of pollutants into waters and was enacted in 1948 as the Federal Water Pollution Control Act. In 1972, it became the common name [21]. EPA has compiled water quality standards (WQS) from states, territories and authorized tribes. This will be updated as EPA approves new or revised WQS. The standards may contain additional provisions that fall outside the scope of the Clean Water Act. The EPA provides a tool to identify water quality criteria from different perspectives. Accordingly, the state specific WQS are provided online by state, territory or authorized tribe as well as by parameter [22].

Much later, in the European Union, the Council Directive 91/271/EEC was issued as early as 1991. The directive distinguishes effluent discharge requirements with respect to municipal and industrial wastewater into two categories: sensitive areas and less-sensitive areas. Accordingly, the requirements for wastewater treatment deviate with respect to the category. For sensitive areas, limit values for nitrogen and phosphorus concentrations are set in addition to the limit values for the parameters BOD_5, COD and suspended solids, which are set in less-sensitive areas. To achieve the required effluent quality, mechanical and biological as well as chemical treatment steps are necessary and used. The Council Directive from 1991 even integrates in Article 12 that treated wastewater shall be reused whenever appropriate. Additionally, it is said that by reusing the treated water the impact on the environment must be reduced to a minimum. Hence, a link was already made in 1991 in Europe to water reuse without having standards and treatment requirements for reuse water. Therefore, the definition of effluent discharge standards is often the baseline for additional treatment steps to receive the nowadays required standards for producing water reuse.

Furthermore, China started very early on with the regulation of water pollutant discharge. The country issued its first environmental protection standard, the Industrial Wastes Discharge Standards (GBJ 4-73), back in the 1970s due to rapid urbanization and industrialization. In the early 1980s, China enacted the first water quality standards: The Environmental Quality Standard for Surface Water (GB 3838-83) and Environmental Water Quality Standard for Sea Water (GB 3097-82). Afterwards, in the year 1988, the general water pollutant discharges standard, the Integrated Wastewater Discharge Standard (GB 8978-88) was issued. Further adjustments were made in the 1990s performed in the new Integrated Wastewater Discharge Standard (GB 8973-1996). Here, limits of ammonia and phosphate were integrated to reduce the eutrophication of surface water. In the 21st century, water pollution in China's major river basins has been devastating. Hence, further acting was required. In this context, the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002) was issued for setting stricter requirements for wastewater discharge from wastewater treatment plants [23].

Even though the Chinese government has made considerable efforts to improve water quality for return to water bodies, the pollution level is much higher compared to the USA or the EU. For example, the wastewater recycling rate for industrial wastewater in China is also much lower than in the aforementioned industrialized countries [23].

4.1.2. Regulations for the Application of Non-Potable Water Reuse

Quality requirements are a prerequisite for the safe application of reused water. Hence, specific and advanced wastewater treatment processes are essential before reusing the water. It must be taken into account that standards or regulations may vary from country to country. Some countries have standards that specify only one water quality for water reuse, while other countries have very detailed standards for the specific application. In the following section, the examples are listed chronologically.

The State of California enacted a regulation for water reuse in agriculture as early as 1918, making it the first state in the U.S., and indeed in the world, to enact such a regulation [8]. In the U.S., specific regulations are given by the states, there are no federal regulations specifically governing water reuse [9,24]. In general, even if no guidelines or regulations exist, producing reuse water is permissible in the US by meeting the requirements of the Safe Drinking Water Act (SDWA), the Clean Water Act (CWA) and state requirements [24]. Regarding the regulation in California, it distinguishes two different types of recycled water: non-potable applications and potable applications. Non-potable regulations are separated into four different levels of treatment referring to the respective application. The California Code of Regulations (CCR) specifies in Section 60304 until 60307 the following types of use of recycled water: for irrigation, for impoundments and for cooling for other purposes. Potable recycled water-use applications are managed by the California Water Code (Section 13561) and are separated into "direct potable reuse", "indirect potable reuse for groundwater recharge" and "reservoir water augmentation" [25].

Beside regulations and standards of specific nations, in 1973, the World Health Organization (WHO) was the first international organization that issued a guideline for water reuse in agriculture followed by the FAO and the World Bank [8]. Nevertheless, these global regulations were issued much later on than those in the United States.

Another country that has issued very detailed water-reuse standards is China. To support the development of water reuse, the Chinese government has enacted a series of regulations for a variety of reuse applications for about 20 years. These are the Standard for Environment Reuse (GBT 18921-2002), the Standard for Miscellaneous Urban Reuse (GBT 18920-2002), the Standard for Industrial Reuse (GBT 19923-2005), the Standard for Farmland

Irrigation Reuse (GB20922-2007) and the Standard for Green Space Irrigation Reuse (GB/T 25499-2010) [10]. Hence, all wastewater treatment facilities producing reused water have specific treatment steps to meet the respective requirements for the respective application.

Compared to other countries, the European Union (EU) issued a guideline for water-reuse very late on, whereas individual countries, such as Spain and Portugal, enacted their own regulations much earlier [8]. In 2020 the EU published the regulation on minimum requirements for water reuse. The guideline must be transposed in national law until 26 June 2023 [11,26].

4.2. State of the Art and Future Challenges for Wastewater Treatment and Reuse

4.2.1. Advanced Treatment Steps for Wastewater Treatment

A current challenge is to eliminate micropollutants and microplastics from the wastewater, such as pharmaceutical residues, cosmetics, household and industrial chemicals, antibiotic-resistant pathogens or specific chemicals. These have a potential negative impact on ecosystems. In addition, such substances could have an impact on drinking water hygiene. Consequently, new or complementary processes for wastewater treatment are required to avoid endangering human health and to further minimize water pollution. Thus, advanced treatment steps within wastewater treatment plants are required. These already exist and are operational. For example, the further reduction in micropollutants will improve conditions for aquatic life. Thus, residual risks arising from the consumption of fish are further mitigated.

For eliminating micropollutants, a basic treatment step today is adsorption using activated carbon (powdered activated carbon or granulated activated carbon). Oxidation processes such as ozone or advanced oxidation process (AOP) are a further or complementary option. The separation by means of membranes is a third possibility.

For the elimination of antibiotic-resistant pathogens, the aforementioned separation as a treatment step using a membrane is especially suitable, if it is used simultaneously for the elimination of micropollutants. If it is required that the wastewater treatment plant effluent is additionally disinfected, then disinfection processes are essential. UV or chlorine can be principally used here. However, chlorine is not used in many countries, although it is common in the USA [27]. This often depends on the specific regulations. Often the use of chlorine is avoided due to its negative environmental impacts. For instance, the chlorination of municipal wastewater as well as drinking water can produce toxic chemical by-products [28,29].

4.2.2. Wastewater Treatment Steps to Produce Reuse Water "Fit-for-Purpose"

To use treated wastewater for simple reuse purposes (for example irrigation of city parks and street cleaning), a conventional wastewater treatment plant (with mechanical and biological treatment steps) as described above is usually sufficient if no further disinfection is required due to low bacterial counts. This includes applications such as irrigation of green areas and street cleaning. However, if drip irrigation is used for irrigation purposes, a conventional wastewater treatment plant with an additional sand filter to remove suspended solids is required.

To achieve a good water quality for reuse purposes, such as toilet flushing, an advanced treatment step, such as adsorption (activated carbon) or oxidation (ozone), is required to eliminate micropollutants (see above). Desalination processes up to reverse osmosis (RO) are required to achieve higher water quality up to drinking water quality.

5. Existing and Innovative "Fit-for-Purpose" Water-Reuse Approaches

5.1. Selection of the Best-Practice Examples

In the following, some successful water-reuse implementations where the water is provided fit for purpose are presented.

Here, a comprehensive approach is presented that shows the recycled water system where the reused water is provided via purple pipes (internationally agreed color for pipes transporting reused water) and distributed by several filling stations. Another example shows a holistic water-reuse approach on a city scale. Therefore, examples from the U.S. are taken into account based on the respective water-reuse scale and dual pipe systems for providing recycled water. The dual pipe system is related to a separate pipe system for transporting reused water beside the pipe system for providing potable, drinking water. The first one relates to Long Beach and the second one to Irvine, both located in California. Examples from the U.S., particularly in California, show that treated wastewater is used intensively, in some cases even through a citywide water-reuse network. In comparison, examples in Europe tend to be on a smaller scale and will be not considered here.

The third example relates to Singapore with regard to the production of "fit-for-purpose" recycled water (potable and non-potable). Singapore should be mentioned here as an example, as it is one of the best known and most innovative examples worldwide.

5.2. Long Beach Recycled Water Expansion System

The Long Beach recycled water system is a suitable example for the provision of reusable water via filling stations. The reused wastewater is treated in the Long Beach Water Reclamation Plant, located on the east side of the city and treats approx. 68 million liters per day. The disinfected recycled water can be used for irrigating parks, golf courses, cemeteries and athletic fields. Furthermore, it can be used to recharge the groundwater basins or for sweeping streets. The program is primarily aimed at connecting the recycled water system to new customers and increasing the reliability of the distribution system. To this end, the construction of recycled water pipelines, new pumping stations, enlargement of the water storage system and completion of new service connections are included. When completed, the expansion program is aimed to meet 15 percent of the city's total water demand. Among others, customers with large irrigation systems such as California State University Long Beach and the Long Beach Unified School District, as well as large parks, golf courses, cemeteries and sports fields, will be connected to the system. The city also uses recycled water instead of potable water to clean streets, saving millions of liters of water annually [30]. The water can be collected at the distributed filling stations. This avoids, for instance, long transport routes for tank trucks. The pipe network provides the reclaimed water by filling stations for the respective water consumer such as parks or schools. By recycled meter systems, water consumptions and requirements can be analyzed [31,32].

5.3. Irvine Ranch in California

The example of Irvine Ranch in California was chosen because it shows very impressively how water reuse was already implemented on a large scale for an entire city in the 1960s. A special feature is that Irvine was planned as a satellite city at the time [33]. A municipal master planning enabled a holistic planning, so that, e.g., plants and trees can be irrigated completely with recycled water. The baseline is the integrated dual pipe system so that drinking water and recycled water is provided separately [18]. The holistic network of the purple pipe distribution with a length of round about 450 miles provides reusable water [34].

The non-potable water source is reclaimed water and is used for several non-potable purposes. Most of the water is used for landscape irrigation, such as road medians, golf courses, parks, playgrounds, residential areas and schools. Additionally, the reclaimed water is used for toilet flushing mostly in commercial and residential buildings as well as for cooling towers [35]. The system delivers up to 106 million liters per day. In total, 91% of the water which is required for landscape irrigation is recycled water. Furthermore, due to technological advances in indoor plumbing, new homes are 50% more water efficient than older ones. The water is also used in toilets and urinals [18].

5.4. Water Reuse in Singapore

In Singapore, the so-called NEWater is part of a comprehensive water resource policy. In general, the reuse of water covers up to 40 percent of the water demand. By 2060, this percentage is expected to increase to 55 percent. Singapore uses treated wastewater for potable and non-potable applications instead of discharging it into the ocean after treatment. This way, the water cycle has been completed, bringing significant economic, social and environmental benefits [36].

Singapore is home to about 5.5 million people and the population density is 7485 people per km^2 [37]. Despite an average annual precipitation of about 2340 mm, it is not possible to store the rainwater because of the limited area available for reservoirs and the lack of aquifers. As a result, Singapore relies on imported water from Malaysia, as well as the production of recycled and desalinated water [36]. Singapore's strategy to secure water supply began in 1965 after independence due to the scarcity of water resources. For both non-conventional water sources, the production of reused water from municipal sources (known as NEWater) and desalination, significant investments have been made since the 1970s in research and development to advance technological developments [36].

The current NEWater Technology consists of three stages. Stage 1 of the NEWater production process is known as microfiltration (MF) or ultrafiltration (UF). Microscopic particles and bacteria are filtered out by using membranes. Stage 2 is known as the process of reverse osmosis (RO). Therefore, a semi-permeable membrane is used, which has very small pores to allow only very small molecules such as water molecules to pass through. This prevents unwanted contaminants, including viruses, from passing through the membrane. The process of ultraviolet or UV disinfection constitutes the third stage of treatment. This process is able to eliminate bacteria and viruses and serves as an additional safety measure to ensure the purity of NEWater [38].

NEWater extends water resources to various non-domestic users. Water fabrication plants are the largest user. However, industrial and commercial buildings are also supplied with NEWater [36]. In dry periods, NEWater is also used for indirect drinking water purposes to conserve surface water. It is mixed with raw water and treated conventionally before it is distributed [36,39].

Singapore introduced recycled water in 2003, while Orange County in California, for example, has been producing recycled water for several decades. Singapore created its own system. Thanks to comprehensive education and communication strategies, it was able to achieve large-scale industrial implementation and broad public acceptance of indirect drinking water use [36,40]. Water reuse under the circular economy concept focuses on implementing a closed system where treated wastewater is not discharged into the ocean but is further treated to produce NEWater [36].

6. Conclusions

The increasing water scarcity worldwide highlights the urgency of implementing water-reuse concepts. Countries that have been under high water stress for decades, such as the USA or China, have already reacted at an early stage and introduced appropriate regulations for water reuse to ensure sufficient water quality. Hence, to achieve Goal 6 of the Sustainable Development Goals (SDG), it is essential to exploit all opportunities with respect to reuse water.

In general, the reuse of wastewater is not the only solution to improve the situation in water-stressed regions. It is especially important to save water in order to produce less reuse water. Since its production is expensive, this can generally save costs.

For municipalities, industry and agriculture, there are still far-reaching implementation possibilities to use water more efficiently. In addition to the reuse of treated wastewater, efficient water-use methods make a major contribution to reducing water consumption, including the use of reuse water. Furthermore, there is still a great need for research to establish various correlations between the disciplines. One approach is seen in agriculture, for example, to reconcile the use of reuse water, irrigation techniques and optimal distribution of land with specific land uses.

Generally, regulations for the discharge of treated wastewater into water bodies exist in most countries, but further regulations based on them to produce reuse water according to the “fit-for-purpose” principle are partly missing. In Europe, the regulations came relatively late. The 1991 Council Directive recommended the reuse of treated wastewater, but at that time there were no standards or quality requirements for reuse. It is not until 2023 that the new Regulation 2020/741 of the European Parliament and the Council has to be adapted into national law. Consequently, advanced requirements and treatment steps as well as their implementation are essential for wastewater treatment, as for instance evidenced by Singapore, so that the treated water has a quality corresponding to the “fit-for-purpose” principle.

However, a current challenge is the implementation of water-reuse concepts. Only a few countries have realized holistic-integrated water management concepts that also include water reuse. In Germany, for instance, as of yet there are no strategic spatial planning concepts on a city scale to drive water reuse. There is a need for further research in this area. Another challenge is the transferability of existing approaches to completely different planning systems in the respective countries. Thus, each situation must be considered individually. Nevertheless, water scarcity will drive this, as without new concepts and implementations, sufficient water supply will be jeopardized. Many discussions exist regarding costs for wastewater treatment for water reuse. This can be increasingly ignored, because costs, which are incurred for example from an energetic point of view for the treatment or for the wastewater treatment technology, will no longer play a role at a high water-stress level. In case of a high water scarcity, the focus is rather on being able to provide the water at all.

All in all, regions and cities affected by water scarcity need to analyze all aspects related to the local water supply situation as well as their potential and opportunities for water reuse. In general, the baseline with respect to regulations and technologies is given, but implementation is lacking. Here, planning and water management stakeholders must work closely together to advance water reuse. Only then will it be possible to achieve Goal 6 of the SDGs in the near future.

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