DIRECT POTABLE REUSE WATER MANAGEMENT STRATEGY AS THE MOST SUITABLE POTABLE WATER SUPPLY AND WASTEWATER DISPOSAL SOLUTION FOR THE ARTIFICIALLY CONSTRUCTED ISLAND IN THE BALTIC SEA

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ABSTRACT

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ABSTRACT

The purpose of this Bachelor's thesis was to make an attempt to theoretically prove that a closed-cycle water management strategy based on the concept of direct potable reuse (i.e., reapplication of highly-treated wastewater produced by a sequence of wastewater treatment and advanced water treatment for potable purposes) will be the most suitable water management solution for the artificial island planned to be constructed in the Baltic Sea. This is because the implementation of other water management strategies based on more traditional linear water management models or implementation of another closed-cycle water management model based on the concept of indirect potable reuse will be limited by the specific characteristics of the island, the aquatic environment surrounding the island, and the available water sources.

In order to provide a more meaningful rationale for the consideration and proposition of the concept of direct potable reuse as the most suitable water management solution for the planned island, the thesis contains a description of all other possible water management strategies based on the available water sources and delineating the probable impediments hampering their implementation in the project setting. Also, since there are two possible direct potable reuse scheme configurations, two available environmental water sources, and two possible application bases of these water sources, the thesis also considered all possible direct potable reuse water management strategies based on the aforementioned parameters and selecting the most suitable for the planned island from them all.

Keywords Direct potable reuse, wastewater reuse

Pages 55 pages including appendices 5 pages

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1 INTRODUCTION

Despite its initially controversial character, direct potable reuse is not a recently emerged concept of water and wastewater management practice. With the commissioning of the first direct potable reuse facility in the city of Windhoek, Namibia in 1969, it was tested and has been implemented in a variety of municipalities of the United States, such as the cities of Big Spring and Wichita Falls, Texas, the city of Denver, Colorado, and the village of Cloudcroft, New Mexico, and the Republic of South Africa, such as the town of Beaufort West and the city of eMalahleni. The data gained from all DPR projects, which were or are in operation, suggests that current wastewater treatment and advanced water treatment technologies are capable of producing reclaimed water, the quality parameters of which can be equal or even exceed the required quality parameters of drinking water applied in areas of direct potable reuse projects. These factors are favouring the consideration of direct potable reuse in the planned island case.

In the project case, direct potable reuse water management strategies represent only several possible options from a variety of water management strategies which can be potentially implemented on the planned island. Since there are no operational direct potable reuse projects in Finland and in Europe, it is essential to provide a comparison with alternative water management strategies in order to prove reasonability, suitability, and achievable benefits of direct potable reuse in the island setting.

Direct potable reuse water management strategies offer an application of additional inexhaustible source of raw potable water with relatively uniform quality which is located directly on the island. These closed-cycle water management strategies can simultaneously address the issues of resilient and sustainable potable water production, enhanced wastewater processing and neutralization, and prevention of further pollution of the Baltic Sea through the incorporation of complex managerial, operational, and treatment measures. Taking into a more detailed consideration the possible potable water production and wastewater disposal limitations caused by the island location and urban planning, available water sources, and impaired quality of the Baltic Sea aquatic environment, the advantages of direct potable reuse are almost making these closed-cycled strategies the only possible solution to the issue of water management on the planned island.

2 OVERVIEW OF DIRECT POTABLE REUSE

Direct potable reuse (DPR) represents a purposeful augmentation of a community's water supply through the introduction of highly-treated community's wastewater (or reclaimed water) produced by a sequence of wastewater treatment and advanced water treatment directly into a water supply system (Figure 1).

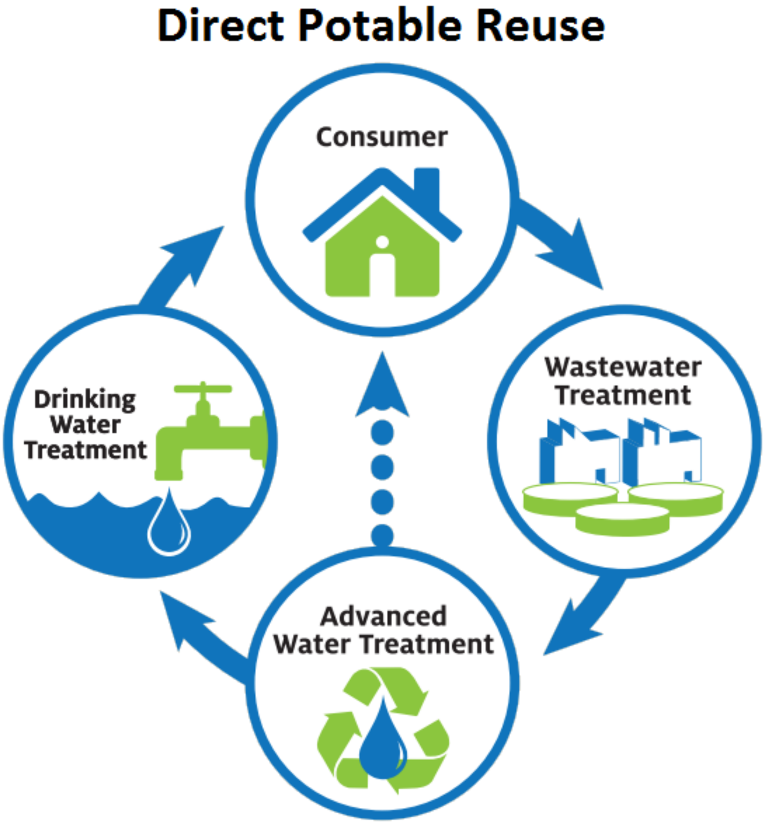

Figure 1. Graphical representation of DPR (Hummer & Eden, 2016, p. 3)

The intentional introduction of reclaimed water can be performed in two possible locations of a water supply system:

1. **Raw potable water supply system**
   The introduction of highly-treated wastewater is performed immediately upstream of a drinking water treatment plant (Leverenz, Tchobanoglous, & Asano, 2011, p. 2; NWRI, 2015a, p. 5; WHO, 2017a, pp. 22-23). Reclaimed water is blended with untreated source water and the resulting blend is subjected to subsequent drinking water treatment prior to be distributed for potable purposes.
2. **Drinking water distribution system**
   The introduction of highly-treated wastewater is performed either downstream of a drinking water treatment plant or directly in a drinking water distribution system (Leverenz, Tchobanoglous, &

Asano, 2011, p. 2; NWRI, 2015a, p. 5; WHO, 2017a, pp. 22-23). Reclaimed water is blended with treated drinking water and the resulting blend is distributed for potable purposes.

2.1 Fundamental Elements of a DPR Scheme

Any DPR scheme configuration consists of five core elements and one optional element. The core elements include water source, drinking water treatment plant, consumption, wastewater treatment plant, and advanced water treatment plant. The optional element is an engineered (i.e., constructed) storage buffer (Figure 2).

Figure 2. Fundamental elements of a DPR scheme (NWRI, 2015a, p. 6)

2.1.1 Water Source

The first fundamental element of any DPR scheme is source water (Figure 3).

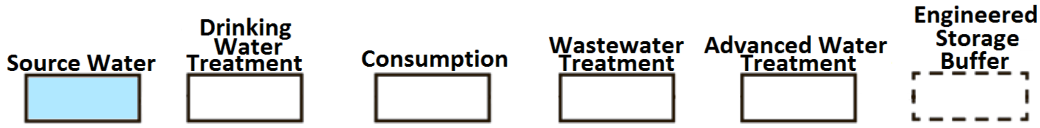

Figure 3. Fundamental elements of a DPR scheme: water source

It is impossible to establish any potable water reuse scheme which will be solely based on an infinite recirculation of ‘used’ water (i.e., wastewater). This impossibility is justified by water losses occurring due to two main reasons:

1. Due to a large continuum of consumptive uses present within a community and leakages from a wastewater collection system (Tchobanoglous, Burton, & Metcalf & Eddy, Inc., 1991, p. 16), not all supplied drinking water will ultimately become wastewater (Tchobanoglous, Burton, & Metcalf & Eddy, Inc., 1991, pp. 25-26; Tchobanoglous, Stensel, Tsuchihashi, Burton, & Metcalf & Eddy, Inc., 2014, pp. 186-187); and
2. Due to the generation of semi-liquid or liquid treatment by-products (e.g., sludge, brine, etc.) during treatment by sequence of wastewater and advanced water treatment, not all generated and collected wastewater will ultimately become reclaimed water.

Therefore, an application of at least one additional source of raw potable water to compensate for the losses occurring during drinking water consumption, wastewater treatment, and reclaimed water production is necessary to create a DPR water supply system (Khan, 2013a, p. 3; Khan, 2013c, p. 13; NWRI, 2015b, p. 2).

2.1.2 Drinking Water Treatment

The second fundamental element of any DPR scheme is drinking water treatment (Figure 4).

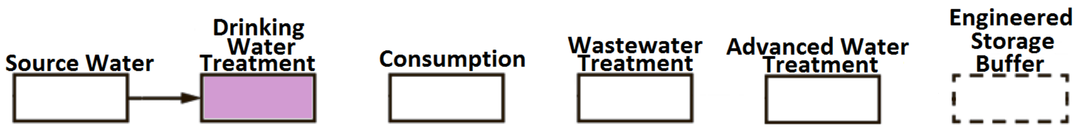

Figure 4. Fundamental elements of a DPR scheme: drinking water treatment

Processes and operations required to be incorporated into a drinking water treatment train will mainly depend on an exact quality of withdrawn source water and, in the case of the augmentation with reclaimed water upstream of a drinking water treatment plant, they may also depend on exact constituents contained in reclaimed water.

Treatment performed at a drinking water treatment plant will create another barrier to contaminants in reclaimed water and provide an added factor of treatment redundancy and, hence, safety (Khan, 2013c, p. 14; NWRI, 2015a, p. 6). However, the primary objective of drinking water treatment is to remove, reduce, alter, and attenuate contaminants present in source water (Khan, 2013c, p. 14), rather than in reclaimed water since sequences of advanced water treatment technologies, especially sequences which incorporates technologies addressing dissolved solids (e.g., reverse osmosis, etc.), are capable of producing reclaimed water that can meet all drinking water quality standards (NWRI, 2015a, p. 8).

2.1.3 Consumption

The third fundamental element of any DPR scheme is consumption (Figure 5).

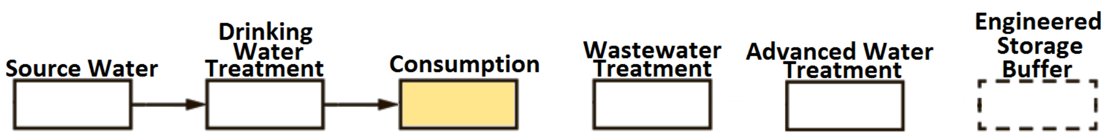

Figure 5. Fundamental elements of a DPR scheme: consumption

In any DPR scheme, the fundamental element of consumption (Figure 5) is of great importance not only because it appears to be the main source of wastewater, which is intended to be reused for potable purposes, but also because it necessarily incorporates certain measures aimed to improve a quality of wastewater being generated, collected, treated, and subsequently reintroduced into potable water system. Quality-improving measures can be represented by a variety of operational and managerial procedures and, in certain conditions, also by treatment practices – all of which are established to selectively prevent or reduce introduction (i.e., discharge) of specific difficult-to-treat constituents into wastewater collection and treatment system (Tchobanoglous, Nellor, Leverenz, & Crook, 2011a, pp. 39-40; NWRI, 2015c, pp. 45, 47-48), thereby increasing efficiency and reliability of wastewater and advanced water treatment performance (i.e., less constituents to be treated) and decreasing an environmental impact of discharged (if necessary) wastewater treatment effluent (i.e., less constituents can be potentially discharged into environment).

Consumption, especially in highly-developed urban areas, can be represented by a variety of water users, including

- residences (e.g., apartments, hotels, individual houses, etc.),
- commercial facilities (e.g., bars, stores, offices, restaurants, etc.),
- institutional facilities (e.g., hospitals, schools, etc.),
- recreational facilities (e.g., theatres, swimming pools, etc.),
- industrial facilities (e.g., food and beverage production plants, etc.),
- public service (e.g., firefighting, landscape irrigation, etc.).

In some cases, surface runoff (i.e., stormwater that did not percolate into soil or ground) can also contribute a certain amount water to wastewater.

All possible and diverse measures attempting to improve quality of raw sewage at the point of generation are components of a general program which establishes control over all drinking water users and wastewater producers. In the case of DPR, application of this program is a compulsory requirement since the program limits or even eliminates discharges of constituents possessing certain characteristics, such as

- Resistance to wastewater and advanced water treatment and, in some cases, to drinking water treatment,
- Triggering of operational or technical maintenance problems of the treatments.

Reduction or elimination of these constituents is important since they can impair quality of reclaimed water supplied to a community as a fraction of drinking water by reason of not being adequately treated or causing underperformance of treatment unit processes or operations.

Partial or complete divergence of recalcitrant constituents from the wastewater collection system is accomplished, as it was already mentioned, through a variety of quality-improving measures which can be operational (e.g., routine monitoring program, etc.), managerial (e.g., discharge permits, restriction of usage of certain substances within a wastewater collection system service area, etc.) and technical (e.g., pretreatment or separate treatment of industrial or health-care facility wastewater flows, etc.) (NWRI, 2015d, pp. 24-25; NWRI, 2015c, pp. 45, 47-48; U.S. EPA, CDM Smith, Inc., 2017a, pp. 2-3).

2.1.4 Wastewater Treatment

The fourth fundamental element of any DPR scheme is wastewater treatment (Figure 6).

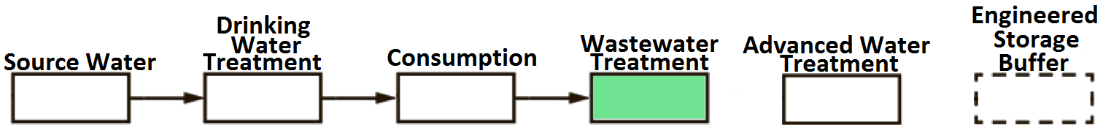

Figure 6. Fundamental elements of a DPR scheme: wastewater treatment

The element of wastewater treatment is the next step following the oversighted generation of wastewater flows (Figure 6). In DPR water management strategies, the main objective of wastewater treatment lies in a production of effluent which can be further reliably treated and converted into reclaimed water by advanced water treatment (NWRI, 2015e, p. 55).

Depending on some variations brought in by a variety of advanced water treatment technologies, the main objective of wastewater treatment is usually achieved by the accomplishment of specific treatment steps through the application of various physical unit operations (e.g., screening, sedimentation, media filtration, etc.), chemical unit processes (e.g., coagulation and flocculation, etc.), and suspended- or attached-growth biological unit processes (e.g., activated sludge treatment, trickling filtration, etc.). According to National Water Research Institute (2015e, p. 56), the specific wastewater treatment steps to be accomplished are as follows:

- Removal of coarse and settleable constituents;
- Transformation of dissolved and particulate biodegradable constituents into acceptable end products;
- Incorporation of suspended and non-settleable colloidal solids into a biological floc or biofilm;
- Transformation or removal of nutrients;
- Transformation or removal of trace organic constituents;
- Reduction of pathogenic microorganisms.

2.1.5 Advanced Water Treatment

The fifth fundamental element of any DPR scheme is advanced water treatment (Figure 7).

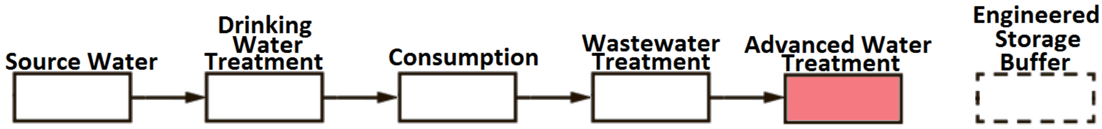

Figure 7. Fundamental elements of a DPR scheme: advanced water treatment

The cornerstone of any DPR scheme is advanced water treatment (Khan, 2013c, p. 13; NWRI, 2015f, p. 69) which is responsible for the conversion of wastewater treatment effluent into reclaimed water. This treatment is applied directly after the component of wastewater treatment (Figure 7) and removes, alters, or attenuates residual constituents which are contained in wastewater treatment effluent by a range of treatment technologies.

Advanced water treatment trains, despite a variability in arrangements, are predominantly designed to achieve four main treatment objectives (Khan, 2013c, p. 15; U.S. EPA, CDM Smith, Inc., 2017b, p. 1):

1. **Removal of suspended solids remaining in wastewater treatment effluent**

This treatment target is usually achieved by an application of one or several of the following treatment processes and operations (NRC, 2012a, pp. 72-73; Khan, 2013c, pp. 15-17; U.S. EPA, CDM Smith, Inc., 2017b, pp. 1, 2-5):
- Coagulation and flocculation
- Media filtration
- Microfiltration
- Ultrafiltration

2. **Reduction of dissolved substances remaining in wastewater treatment effluent**

This treatment target is usually achieved by an application of one or several of the following treatment processes and operations (NRC, 2012a, pp. 73-78; Khan, 2013c, pp. 18-21; U.S. EPA, CDM Smith, Inc., 2017b, pp. 1, 5-9):
- Reverse osmosis
- Nanofiltration
- Electrodialysis
- Electrodialysis reversal
- Granular activated carbon
- Ion exchange

– Biologically active filtration

3. **Elimination or inactivation of pathogenic microorganisms and attenuation or alteration of trace organic compounds remaining in wastewater treatment effluent via disinfection and oxidation**

This treatment target is usually achieved by an application of one or several of the following treatment processes (NRC, 2012a, pp. 70-71, 77-78; Khan, 2013c, pp. 21-24; U.S. EPA, CDM Smith, Inc., 2017b, pp. 1, 9-14):
– Ultraviolet irradiation
– Chlorination (chlorine or chlorine dioxide) or chloramination
– Ozonation
– Advanced oxidation processes (UV/Hydrogen peroxide, Ozone/Hydrogen peroxide, UV/Chlorine)

4. **Reclaimed water quality parameters stabilisation and remineralization** (required only after reverse osmosis and nanofiltration)

This treatment target is usually achieved by an application of one or several of the following treatment processes and operations (Khan, 2013c, pp. 21-24; U.S. EPA, CDM Smith, Inc., 2017b, pp. 1, 15-17):
– Decarbonation
– Addition of sodium hydroxide
– Lime stabilization
– Blending with other waters

2.1.6 Engineered Storage Buffer

The sixth fundamental element of any DPR scheme is engineered storage buffer (Figure 8).

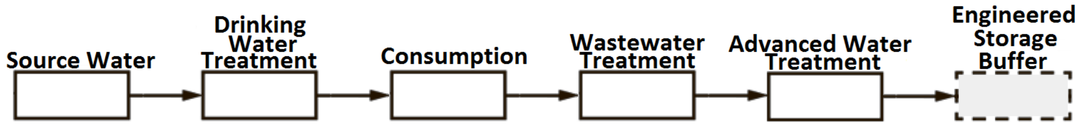

Figure 8. Fundamental elements of a DPR scheme: engineered storage buffer

An engineered storage buffer (ESB) (shown as a dashed box in Figure 8) is the last component of a DPR scheme, but its application is optional and will mostly depend on site-specific conditions, such as capabilities of treatment technologies and monitoring equipment employed at all plants involved in a DPR scheme, presence of specific constituents in wastewater, and regulatory requirements.

An ESB represents a water storage containment facility which is established directly after advanced water treatment. This facility must be designed to have a sufficient volumetric capacity to retain reclaimed water for a time period required by execution of all necessary water quality monitoring and validation procedures (to ensure that quality of reclaimed water is compliant with all applicable standards and criteria) and, simultaneously, maintain flow continuity (NWRI, 2015a, p. 6). In some DPR schemes, disruptions of reclaimed water supply induced by inadequate ESB design or operation can adversely impact drinking water production since a drinking water treatment plant is calibrated to specific proportions of reclaimed water and 'compensating' water blend. The application of an ESB provides an opportunity to increase monitoring along the entire DPR scheme and, hence, increase control over augmenting reclaimed water and augmented potable water qualities and, hence, increase safety of the entire scheme. In some DPR schemes (especially in the case of a DPR scheme, in which reclaimed water is augmenting treated drinking water, an ESB and monitoring conducted in it can be considered as the final 'safeguard' prior to distribution. In the case of water, which is not meeting necessary specifications, an ESB can be designed to envisage infrastructure providing discharge of off-specification water into environment or its diversion back to treatment.

Necessity of the ESB application after advanced water treatment will depend on the following design characteristics of the treatment:

1. Absence (necessary application) or presence (unnecessary application) of redundant treatment (i.e., an application of multiple unit treatment processes and/or operations which provide removal, alteration, or attenuation of the same type of constituent (NWRI, 2015f, p. 85)) which allows continuous production of reclaimed water even if one of the major treatment processes or operations is out of specification (NWRI, 2015a, pp. 6-7); and
2. Absence (necessary application) or presence (unnecessary application) of comprehensive monitoring (which includes routine monitoring of critical treatment processes and online metering of treatment performance along with other methods) providing accurate evaluation of advanced water treatment performance and reclaimed water quality and verifying the safety of reclaimed water utilization for water supply (NWRI, 2015a, pp. 6-7).

2.2 DPR Scheme Configurations

There are two possible DPR scheme configurations which differ in the location of augmentation with reclaimed water. For purposes of convenience and understanding, reclaimed water, which is augmenting source water prior to drinking water treatment, is referred to as *advanced treated water* (*ATW*), whereas reclaimed water, which is augmenting produced drinking water downstream of a drinking water treatment plant or in a potable water distribution system, is referred to as *finished water*.

Figure 9 represents two possible DPR scheme configurations based on the two locations of water supply augmentation with ATW or finished water.

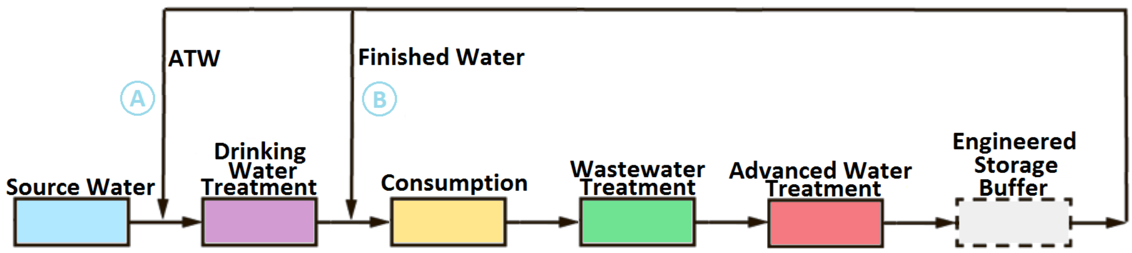

Figure 9. Two possible DPR scheme configurations based on two locations of water supply augmentation with reclaimed water: A) augmentation of raw source water with ATW upstream of a drinking water treatment plant and B) augmentation of drinking water with finished water downstream of a drinking water treatment plant (Khan, 2013c, p. 14; NWRI, 2015a, p. 6)

The main difference between ATW and finished water lies in applicable regulations. Finished water (Figure 9B) can only be produced by an advanced water treatment plant which is permitted as drinking water treatment plant (NWRI, 2015a, p. 7) since the produced water is directly supplementing water utilized for potable purposes. ATW (Figure 9A) is produced by an advanced water treatment plant which can treat wastewater treatment effluent to a quality of drinking water but does not require to be permitted as drinking water treatment plant since ATW will be blended with source water and treated (once again) by a drinking water treatment plant. In the case of ATW, the quality of which is lower than required by drinking water quality regulations, drinking water treatment must be equipped with treatment technologies that will provide treatment of constituents not treated by advanced water treatment.

2.2.1 Source Water Augmentation

The first reported DPR scheme configuration involves the augmentation of conventionally sourced raw potable water with ATW prior to drinking water treatment (Figure 9A and Figure 10). In this DPR scheme configuration, drinking water treatment constitutes another barrier to contaminants, which can occur in ATW in the case of advanced water treatment and ESB monitoring failure, but, as it was already mentioned in section 2.1.2, the main objective of drinking water treatment is to provide treatment of contaminants present in source water.

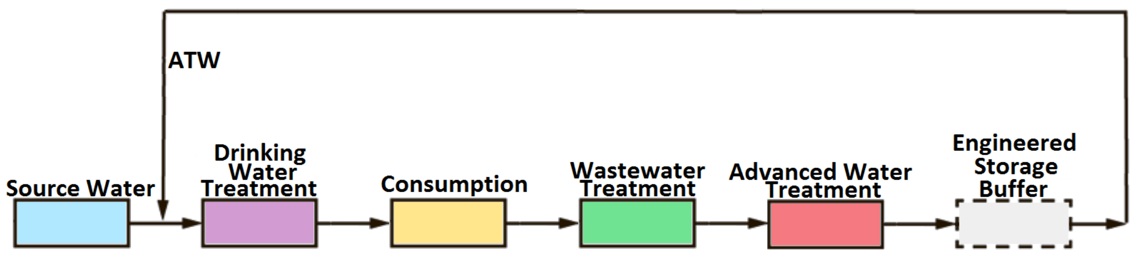

Figure 10. DPR scheme configuration based on the augmentation of raw potable water with ATW prior to drinking water treatment (Khan, 2013c, p. 14; NWRI, 2015a, p. 6)

This DPR scheme configuration is implemented in the city of Big Spring, Texas, United States and in the village of Cloudcroft, New Mexico, United States (Khan, 2013c, p. 14).

Public perception. From the standpoint of public acceptance and opposition, this DPR scheme configuration, in comparison with the second one, may possess an advantage of a higher public acceptance or, in other words, of a lower public opposition. This advantage will be firstly based on the fact that ATW is subjected to blending with and dilution by 'environmental' or 'natural' water which facilitates a 'loss of identity' (Tchobanoglous, Nellor, Leverenz, & Crook, 2011a, p. 38) and abates negative connotations related to the initial source of ATW (i.e., wastewater collection system and wastewater treatment plant). Secondly, the advantage of lowered public opposition will be based on the fact that the resultant blend of ATW and 'natural' water is subjected to drinking water treatment which, in its turn, can be considered as additional protection even in the case if quality of ATW is compliant with all drinking water quality standards.

Public health protection. In the case of advanced water treatment failure and late or no detection by monitoring applied in an ESB, drinking water treatment, depending on employed treatment technologies, can also remove, reduce, alter, and attenuate broke-through contaminants. In the breakthrough scenario, a degree of treatment brought about by drinking water treatment will highly depend on employed treatment technologies which can substantially differ from advanced water treatment technologies and can be simply not designed, adjusted, or aimed to treat the same contaminants that are usually treated by advanced water treatment; therefore, drinking water treatment can have no or extremely small impact on the contaminants. In theory, this can be overcome by an application of the same or similar treatment technologies by drinking water treatment plant and advanced water treatment plant (e.g., an application of membrane filtration on both plants, etc.).

Blending issues. In the case when drinking water treatment is calibrated to provide treatment, which is solely based on characteristics of a source water quality, application of the source water augmentation location (Figure 10) can induce some potential negative impacts on the treatment. These impacts are caused by a difference between quality of a resultant blend (of ATW and raw potable water) and initial quality of raw potable water. Blending of the waters, which brings about seemingly ‘positive’ changes by providing a dilution of concentrations of constituent, will also complicate a provision or even cause a decrease in effectiveness of drinking water treatment since the treatment was initially adjusted to a raw source water quality (rather than to a blend quality). For instance, if ATW contains a lower level of suspended solids (total suspended solids (TSS)) than a source water, blending of these waters will result in a decrease of a source water TSS level. This decrease will adversely affect coagulation process (NWRI, 2015g, p. 91)) – an addition of a chemical substance (coagulant) which promotes formation of aggregations of contaminants (flocs) (WRc, 1997, p. 41) – applied as a part of drinking water treatment since it was initially calibrated to a source water TSS level. Other potential negative impacts related to a blend quality and drinking water treatment performance will depend on applied advanced water treatment technologies (e.g., ATW produced without an application of reverse osmosis could increase a blend organic (total organic carbon (TOC)) and dissolved solids (total dissolved solids (TDS)) content (NWRI, 2015f, pp. 73-74; NWRI, 2015g, pp. 91-93)) and applied drinking water treatment technologies (e.g., an application of reverse osmosis will remove TOC and TDS). Also, aesthetic parameters of supplied water can be negatively impacted by blending of waters due to temperature difference between ATW and source water (NWRI, 2015g, p. 92)). To overcome a potential occurrence of these negative impacts, drinking water treatment must be specifically adjusted to a resultant blend quality but this adjustment will probably increase a degree of operational complexity since it will require specific engineering systems (e.g., flow equalization system) in order to constantly maintain uniform blend proportions.

Drinking water treatment. Required drinking water treatment technologies will depend on exact quality parameters of applied source water, augmenting ATW constituents, and their mixture.

Advanced water treatment. Required advanced water treatment technologies must produce reclaimed water (ATW), the quality of which can either be compliant with all applicable drinking water standards (i.e., drinking water), or, at least, must be not lower than a quality of raw potable water. In the case when advanced water treatment produces ATW, the quality of which is not lower than a quality of raw source water, this DPR scheme configuration also potentially possesses an advantageous opportunity of ‘reallocation’ or ‘redistribution’ of certain final treatment elements of advanced water treatment between a drinking water treatment plant and advanced water treatment plant (Figure 11) resulting in lesser energy consumption of the entire scheme and reduction of technical maintenance costs.

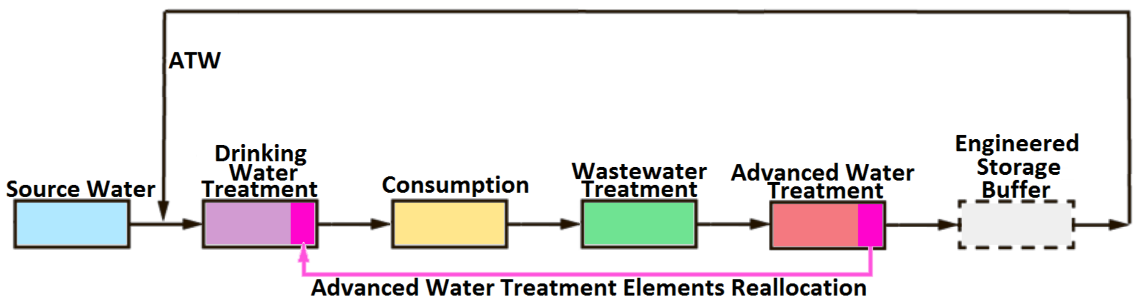

Figure 11. Possible reallocation of advanced water treatment elements between a drinking water treatment plant and advanced water treatment plant in the DPR scheme configuration based on the augmentation of raw potable water with ATW prior to drinking water treatment

Regardless of produced ATW quality, a drinking water treatment plant should be calibrated to a quality of resultant blend of ATW and source water and provide treatment which will convert the blend into safe drinking water.

Wastewater treatment. Wastewater treatment must employ technologies which by meeting specific wastewater treatment steps mentioned in section 2.1.4 will produce wastewater treatment effluent, the quality of which will be suitable for the reliable production of ATW of required quality.

ESB application. In this DPR scheme configuration, the application of ESB is optional and will depend on the design characteristics of advanced water treatment described in section 2.1.6.

2.2.2 Drinking Water Augmentation

The second reported DPR scheme configuration involves the augmentation of treated drinking water with finished water (Figure 9C and Figure 12). The augmentation can be performed downstream of a drinking water treatment plant or directly within a potable water distribution system (Khan, 2013c, p. 14; NWRI, 2015a, p. 7). In the case of this DPR scheme configuration, an advanced water treatment plant must be permitted as drinking water treatment plant.

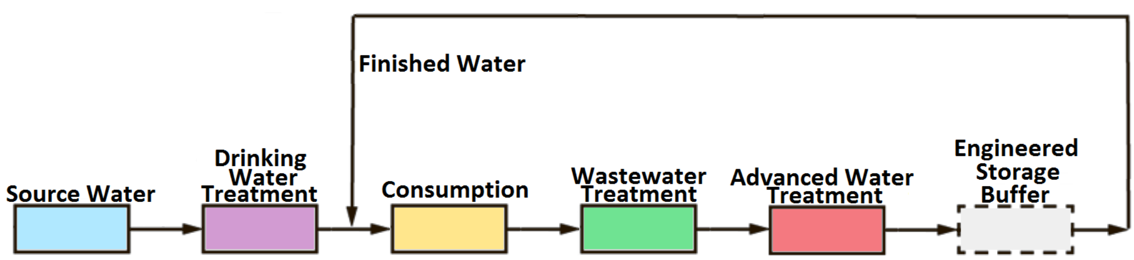

Figure 12. DPR scheme configuration based on the augmentation of drinking water with finished water downstream of a drinking water treatment plant (Khan, 2013c, p. 14; NWRI, 2015a, p. 6)

This DPR scheme configuration is implemented in the town of Beaufort West, South Africa (Khan, 2013c, p. 14) and in the city of Windhoek, Namibia (NWRI, 2015a, p. 5).

Public perception and blending issues. The situation related to the particular advantages and disadvantages of this DPR scheme configuration will be exactly the opposite to the situation described for the DPR scheme configuration based on the augmentation of raw potable water with ATW (section 2.2.1). The DPR scheme configuration based on the augmentation of potable water with finished water (Figure 12) may incur high public opposition since finished water is augmenting drinking water without being blended with and diluted by 'environmental' water and being subsequently treated by drinking water treatment, regardless of the fact that an advanced water treatment plant is permitted as drinking water treatment plant (i.e., drinking water production facility). The negative impacts on drinking water treatment induced by blending can be neglected since blending is performed downstream of a drinking water treatment plant, but possible aesthetic issues induced by temperature difference of waters (treated drinking water and finished water) being blended in drinking water distribution network can significantly stimulate an aggravation of public opposition. Also, other negative blending impacts such as an increase in TOC or TDS level (section 2.2.1) and its corresponding public health hazards will depend on applied advanced water treatment technologies. In this DPR scheme configuration, advanced water treatment must provide the highest possible degree of treatment to mitigate the potential problems related to an addition of wastewater constituents.

Public health protection. From the standpoint of risk management, in the case of advanced water treatment and an ESB monitoring failure, which can occur due to design deficiencies, mismanagement, or inadequate operation, this DPR scheme configuration can incur the highest risk for public health protection since finished water is introduced directly into a drinking water distribution system without being treated by drinking water treatment.

Drinking water treatment. Required drinking water treatment technologies will entirely depend on exact quality parameters of applied source water.

Advanced water treatment. In this DPR scheme configuration, required advanced water treatment technologies must produce finished water, the quality of which must always be compliant with all applicable drinking water quality standards and criteria. Therefore, the 'reallocation' of advanced water treatment elements is impossible between a drinking water and advanced water treatment plant.

Wastewater treatment. Wastewater treatment must employ technologies which by meeting specific wastewater treatment steps mentioned in section 2.1.4 will produce wastewater treatment effluent, the quality of which will be suitable for the reliable production of ATW of required quality.

ESB application. In this DPR scheme, the application of an ESB is optional and will be governed by the advanced water treatment characteristics described in section 2.1.6 (NWRI, 2015a, pp. 6-7).

2.2.3 Comparison of DPR Scheme Configurations

A degree of public acceptance, degree of public health protection in the case of advanced water treatment and ESB monitoring failure, magnitude of blending impacts on drinking water treatment, reallocation of advanced water treatment elements, and required quality of produced reclaimed water of the described DPR scheme configurations are compared in Appendix 1.

3 WATER MANAGEMENT STRATEGIES IN THE PROJECT SETTING

Since possible water management strategies based on the described DPR scheme configurations are only several options from a variety of water supply solutions available in the project setting, it is essential to delineate other potential solutions in order to prove that the concept of DPR will be the most suitable among all other options in a more meaningful way.

3.1 **Project Area Description**

The project area will represent an artificially constructed island in the Baltic Sea (Figure 13). Construction of the island is planned as a part of the bigger project, the main objective of which is to construct a tunnel linking the city of Tallinn with mainland Finland. The main material for the island construction will be components of the Baltic Sea bottom extracted during the tunnel construction. The island is planned to be located 15 km away from the coast of mainland Finland. The closest Finnish urban center will be the city of Espoo (Figure 14) which will also be connected to the island by the tunnel (Vesterbacka & Valtonen, 2018, p. 2). Expected population of the island is 50,000 people and planned size is 3-5 km^2 with a relatively dense urban development (Valtonen & Vanhanen, 2018).

Figure 13. Graphical representation of the planned island (Vanhanen, 2018)

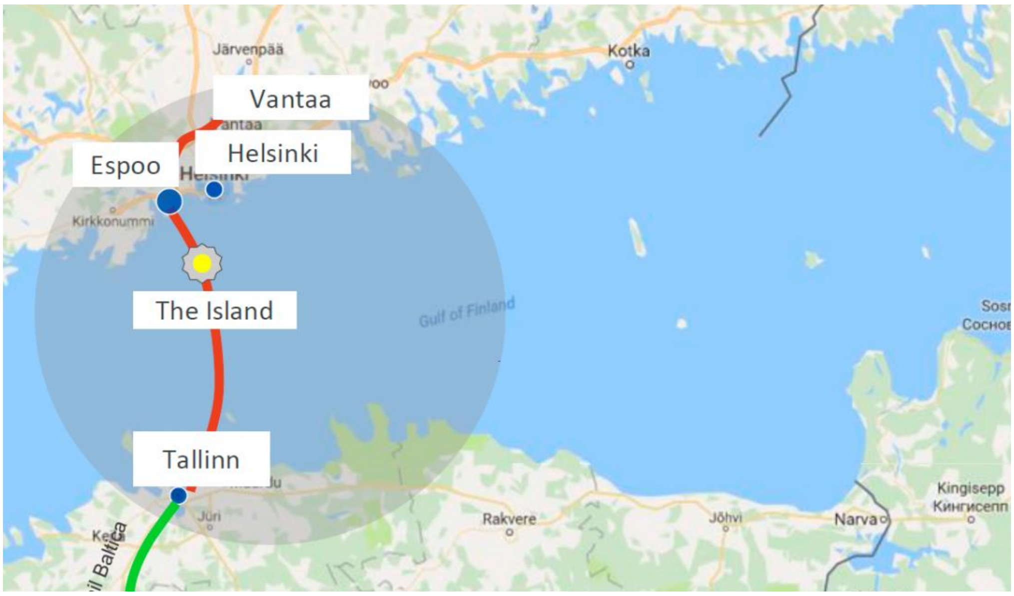

Figure 14. Location of the planned island (Vesterbacka & Valtonen, 2018, p. 2)

3.2 Possible Potable Water Sources

In any circumstances, development of a possible water management strategy will always begin with the determination of a suitable water source. In the project case, there are three possible water sources which will be theoretically available for the island population (Table 1).

Table 1. Possible water sources in the project area

Source	Source water	Abstraction
The Baltic Sea	Seawater	Directly from the sea
Water body in mainland Finland	Surface water or groundwater (freshwater)	Importation via pipeline
Wastewater collection system	Wastewater	From wastewater collection system

A groundwater aquifer, which contains either brackish or pristine groundwater, can also be added to the list of the theoretically available sources, but its existence and presence directly under the island or the connecting tunnel (or in the immediate vicinity of the island or the connecting tunnel) is neither proven in theory nor in practice. Therefore, it is not considered as a potential water source.

3.2.1 The Baltic Sea Seawater

The Baltic Sea represents an unlimited source of raw potable water located in the immediate vicinity of the island. This source is available on the permanent basis but will require a special submerged seawater intake system (i.e., source water abstraction system) which will not be adversely impacted in the case of ice formation.

As a source water, the seawater can be characterised by

- A relatively poor quality,
- Possible quality fluctuations, and
- Possible future quality deterioration.

These source water quality characteristics – poorness, variability, and possible deterioration – are resulting from geographical location and ecological situation of the Baltic Sea.

The Baltic Sea is a semi-enclosed sea, the catchment area of which encompasses 14 countries (Finnish Environment Institute, 2014a). The sea receives water from 250 rivers (Finnish Environment Institute, 2014b) and for decades has been receiving and accumulating all wastewater, including urban and agricultural surface runoff, discharged into the flowing through the 14 countries debouching watercourses. The Baltic Sea was repeatedly termed as “*one of the most polluted seas*” (Kryda, 2014; Haavisto, 2017; SIWI, 2018). In addition to concerns raised about a possible wide range of chemical and even microbiological contaminants potentially present in untreated wastewater or inadequately treated wastewater effluent, concerns regarding dumped chemical warfare and conventional weapons (HELCOM, 2013, pp. 28-29; Osiński , 2019) and presence of radioactive substances (HELCOM, n.d.; Lüning, Ilus, & Herrmann, 2009, pp. 9-13) can also be potentially raised.

Possible quality fluctuations and possible future deterioration of the seawater quality can be caused by the occurrence of several microorganisms, namely diatoms, dinoflagellates, and cyanobacteria, in the seawater (HELCOM, 2018, p. 10; ENVIRONMENT.fi, 2020). These microorganisms can temporarily exhibit patterns of an exponential and uncontrollable growth (i.e., algal bloom) in suitable conditions, such as an abundance of chemical substances required for their growth and reproduction. These chemical substances can be generally referred to as nutrients. Nutrients, such as nitrogen and phosphorus, are abundant in wastewater discharges (e.g., contained in organic and inorganic chemical constituents) and agricultural surface runoff (e.g., contained in fertilizers) (NRC, 2012b, p. 60). As the Baltic Sea receives more discharged wastewater, it, by definition, receives more chemical substances supporting the growth of the microorganisms. In addition to treatment issues caused by an increased amount of biomass in the seawater during an algal bloom, lifecycle of some species and strains of the mentioned microorganisms involves production of toxic substances which are potentially harmful for humans (e.g., domoic acid is a toxic substance produced by certain diatoms (Dhar, et al., 2015, pp. 4921-4922), yessotoxin is a toxin produced by certain dinoflagellates (Wang, 2008, p. 350), and microcystin-LR is toxin produced by cyanobacteria (Post, Atherholt, & Cohn, 2011, p. 2.18), etc.). The uncontrollable growth of these microorganisms can be also supported by an increase in global and local temperatures caused by climate change (Finnish Environment Institute, 2019).

3.2.2 Imported Water

As it was already mentioned in section 3.1, the island will be connected to mainland Finland by means of the tunnel, which creates an opportunity of establishment of a water transfer piping (within a tunnel) to import water for potable purposes from mainland Finland. The imported water can be raw potable water (i.e. source water), partially treated source water, or treated drinking water. The selection of the exact imported water quality will depend on a variety of economic and technical reasons.

Despite a conceivable and attractive ease of the transfer piping establishment, the application of this water source can potentially encounter certain constrains since the tunnel will have a limited space which must also accommodate transport infrastructure and its ancillary engineering systems (see schematic drawings of the tunnel in Appendix 2). The tunnel may not simply have a sufficient space to also accommodate a pipeline of suitable size to supply water to 50,000 inhabitants. The establishment of the approximately 15-km long pipeline (tunnel elevation differences are not considered) can also possibly incur additional technical risks (e.g., flooding of the tunnel in the case of pipe break) and difficulties in technical maintenance of the pipeline (taking into consideration an approximate pipeline length and relatively limited tunnel space). Moreover, continuous pumping of water through the possible pipeline will probably be very energy-consuming and will have a large carbon footprint.

3.2.3 Wastewater

Since the island is planned to be inhabited (section 3.1), consumption and usage of drinking water by inhabitants will inevitably result in wastewater generation. Conversion of drinking water into wastewater occurring in residential premises, commercial and industrial facilities, and in other sources (section 2.1.3) is always accompanied by addition of significant amounts of chemical and microbiological constituents. Some of these constituents are added not only during direct application of supplied drinking water for potable and household purposes but also during drinking water treatment and distribution (WHO, 2017a, pp. 11-12). Although thousands of chemical substances and a variety of microorganisms potentially present in wastewater are contributing to its extremely poor initial quality, it is possible to process the water to a drinking water quality by the application of comprehensive source control program, wastewater treatment, and advanced water treatment (sections 2.1.3, 2.1.4, 2.1.5).

Wastewater will be constantly generated by the island population and will always be available for reprocessing into reclaimed water directly on the island. Application of this unlimited water resource will possess an advantage of reduced infrastructural requirements since wastewater collection system (which must be established regardless of a selected water source) will be used as the main part of required raw water conveyance infrastructure. Also, providing that a source control program was implemented and is enforced, wastewater, as a raw potable water, will possess an advantage of a relatively stable quality which will not be influenced by events occurring outside of the island. Stable quality allows to better optimize treatment processes and operations and to more reliably produce water of a required quality.

3.3 Application Bases of the Water Sources

The described source waters can be applied on the single basis (i.e., application of only one water source (Figure 15A)) or on the combined basis (i.e., simultaneous application of multiple sources of water (Figure 15B)). The exception must be made in the case of the application of wastewater since it must be always applied on the combined basis with one or several other sources of raw potable water to offset the water losses (section **Ошибка! Источник ссылки не найден.**).

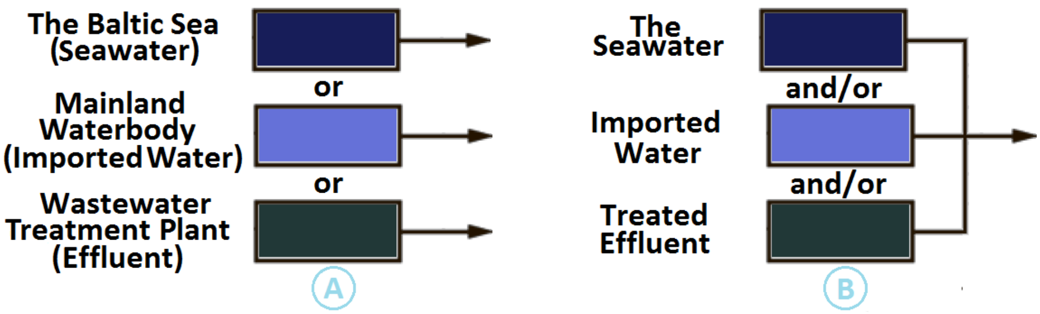

Figure 15. Application bases of the theoretically available sources of raw potable water on the A) single basis and B) combined basis

The rationale for the combined-basis application of the raw potable water sources other than wastewater will be built upon an amount of source water available for abstraction.

3.4 Water Management Strategies Based on the Available Sources Water

As it was already mentioned, the described DPR scheme configurations (sections 2.2.1 and 2.2.2) represent only several potential solutions to the issue of a possible water supply system and water management strategy, which can be implemented on the planned island. A description of other potentially viable solutions based on the same water sources (Table 1) and delineation of their limitations in the project setting are essential to fully conceive the rationale involved in the consideration and proposition of the DPR concept as the most suitable solution.

The concept of DPR and other potential solutions based on the same sources of water can be divided into two general categories:

1. **Linear water management strategies**
   In these strategies, potable water production and supply is based on the application of only ‘new’ water derived from one or several environmental water sources, while wastewater disposal is based on treatment and subsequent discharge of treated effluent into environment.
2. **Closed-cycle water management strategies**
   In these strategies, potable water production is based on the application of ‘used’ water (i.e., wastewater treatment effluent) as raw potable water in combination with the application of ‘new’ or ‘compensating’ water as another raw potable water which can be withdrawn from one or several environmental sources. This category of water management strategies embraces the concept of DPR.

Excluding DPR, there are three linear water management strategies and one closed-cycle water management strategy based on the described available water sources (section 3.2) and application basis (section 3.3) which can be considered as potentially viable in the project setting and as 'adversaries' of DPR.

3.5 Linear Water Management Strategies

In contrast to closed-cycled water management strategies, such as DPR (Figure 10 andFigure 12), linear water management strategies represent a 'straightforward pathway' of drinking water production and wastewater disposal. These strategies utilize only 'new' water derived from environmental sources (e.g., river, sea, groundwater aquifer, etc.) for production of drinking water, while generated wastewater is regarded as non-recyclable waste and discharged into environment after processing by wastewater treatment (Figure 16).

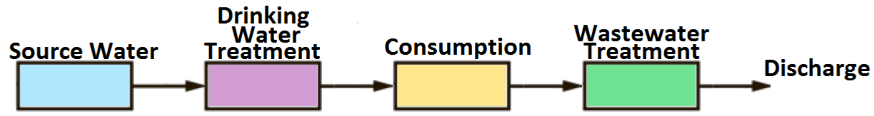

Figure 16. Linear water management strategy

In these strategies, sources of 'new' water can be applied solely (i.e., single basis (Figure 15A)) or in combination with each other (i.e., combined basis (Figure 15B)). A linear water management strategy, which utilizes only one source of potable water can be referred to as *single-source linear water management strategy* (Figure 17A), while a linear water management strategy, which simultaneously utilizes several sources of potable water, can be referred to as *multiple-source linear water management strategy* (Figure 17B). In the latter case, the exact number of applied potable water sources can vary from only two to any possible number of available sources.

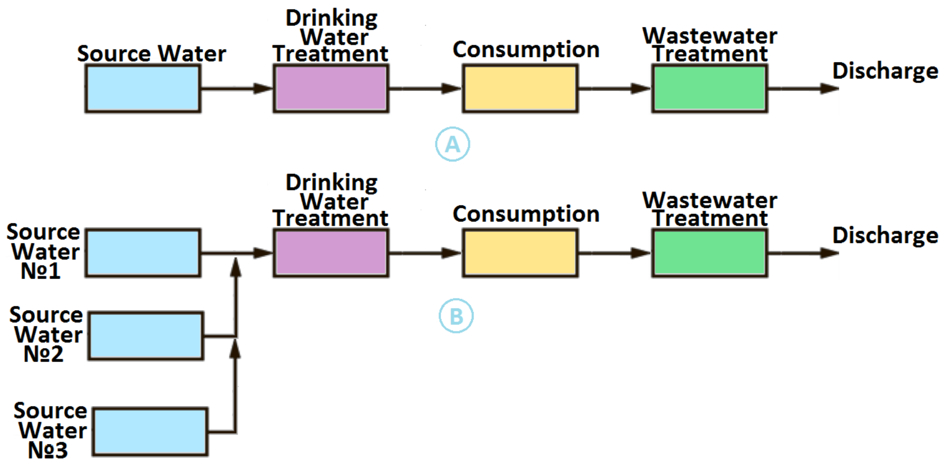

Figure 17. Linear water management strategies: A) single-source linear water management strategy and B) multiple-source linear water management strategy

From the standpoint of wastewater disposal, linear water management strategies (at least in a majority of industrialized and developed countries) are only aimed to minimize adverse ecological impacts, which can be induced by a discharge of raw or inadequately treated wastewater, and prevent adverse health ramifications, which can be caused by an accidental contact with raw or inadequately treated wastewater or environmental waters containing raw or inadequately treated wastewater.

In the project case, there are three potentially possible linear water management strategies based on the sources of 'new' water described in section 3.2 and on the application bases described in section 3.3. These strategies are as follows:

A. **Single-source linear water management strategy** (Figure 17A)
   1. **Seawater-based linear water management strategy**
      This strategy is based on the application of the Baltic Sea seawater as a raw potable water. The wastewater disposal of this strategy is executed through discharge of wastewater treatment effluent into the Baltic Sea.
   2. **Imported-water-based linear water management strategy**
      This strategy is based on the application of either raw, partially treated, or treated imported water for potable water production. The wastewater disposal is executed through discharge of wastewater treatment effluent into the Baltic Sea.

B. **Multiple-source linear water management strategy** (Figure 17B)
   1. **Seawater-and-imported-water-based linear water management strategy**
      This strategy is based on the simultaneous application of the seawater and imported water (raw, partially treated, or treated potable water) for potable water production. The wastewater disposal is executed through discharge of wastewater treatment effluent into the Baltic Sea.

3.5.1 Seawater-Based Linear Water Management Strategy

Seawater-based linear water management strategy utilizes the seawater of the Baltic Sea as a feedstock for drinking water production (Figure 18), thereby taking an advantage of an unlimited water source which is in the immediate vicinity of the island and is practically available on the permanent basis.

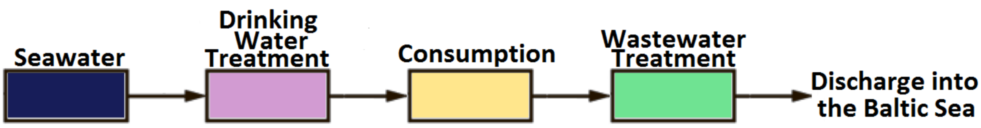

Figure 18. Seawater-based linear water management strategy

Drinking water treatment. From the standpoint of potable water production, this water management strategy will require an application of special submerged seawater intake system, which will not be adversely impacted by ice formation during winter, and specific treatment technologies which, along with other seawater constituents, will address dissolved solids contributing to a salinity of the brackish seawater. Drinking water production solely based on processing of the Baltic Sea seawater to a drinking water quality can be severely complicated by the source water quality issues (section 3.2.1), such as presumably poor initial quality of the seawater and possible fluctuations in the quality induced by natural and anthropogenic phenomena (e.g., algal bloom, oil spills (HELCOM, Norden, 2013, p. 12), etc.).

Wastewater disposal. From the standpoint of wastewater disposal, this strategy will require treatment equipment to process generated wastewater to a quality which will not cause a deterioration of ecological conditions of the Baltic Sea and will not cause adverse health implications for the island population. Also, wastewater treatment will require an application of specialized treatment processes and/or operations which specifically aim nutrients in order to prevent discharge of chemical substances required by the microorganisms for growth and reproduction.

The island is planned to be located in the environment which has been heavily and adversely impacted by a variety of human activities (section 3.2.1). Due to its poor quality, the ecological situation of the Baltic Sea is subjected to the attention of the European Union and several organisations (Lukaševičius, 2019; Alonderytė & BNS, 2020; BNS, 2020). Regardless of an implemented linear water management strategy, it can be anticipated that an island's wastewater treatment plant discharging treated effluent into the Baltic Sea will be initially subjected to a relatively high degree of regulatory discharge requirements that can necessitate high levels of wastewater treatment. Also, there is always a probability that regulatory requirements will become stricter in the future and will require even higher degree of wastewater treatment.

Public health protection. Even though this linear water management strategy is not incorporating planned reuse of wastewater, inadequate establishment of wastewater treatment effluent discharge system can possibly result in abstraction of certain amount of treated effluent discharged into the Baltic Sea by a seawater withdrawal system. Depending on constituents, abstraction of wastewater treatment effluent together with seawater may potentially adversely impact performance of drinking water treatment and/or drinking water quality and, hence, represent a risk for the inhabitants.

3.5.2 Imported-Water-Based Linear Water Management Strategy

Imported-water-based linear water management strategy utilizes raw, partially treated, or treated potable water imported from mainland Finland as a feedstock for drinking water production (Figure 19). Most probably, this strategy will utilize freshwater withdrawn from a surface water body and/or groundwater aquifer located in mainland Finland since importation of brackish waters requiring the same degree of drinking water treatment as the seawater will not be financially reasonable.

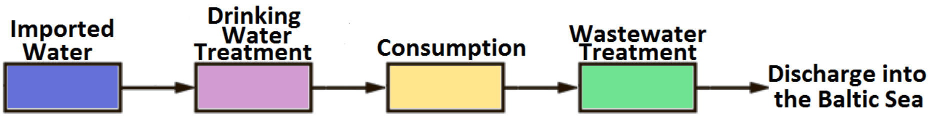

Figure 19. Imported-water-based linear water management strategy

Drinking water treatment. To be converted into potable water, imported freshwater will require less intense and extensive drinking water treatment than the brackish seawater due to a significant difference in their quality parameters. For instance, application of treatment technologies addressing dissolved solids (i.e., desalination) will unlikely be necessary since inland freshwater usually contains less dissolved solids than the brackish seawater. Other required drinking water treatment unit processes and operations will be dictated by the exact quality of imported water. To be converted into drinking water, raw imported water will require full drinking water treatment, partially treated imported water will require treatment provided by only certain drinking water treatment processes and/or operations, while treated imported water will require only disinfection to eliminate microorganisms which can grow within water distribution systems (e.g., *Legionella* species (WHO, 2017b, pp. 244-245), etc.).

In addition to the possible negative issues addressed in the section 3.2.2, drinking water production of this linear water management strategy may also be susceptible to 'external' negative impacts, since it will most probably apply a water source which is already used by another community, in order to take an advantage of an established water supply system and prevent expenses required for a development of new water supply system in mainland Finland. The city of Espoo will be the closest urban center with an already established water supply system and will be connected to the island by the tunnel (Figure 14), which brings the city into a possible consideration as the most probable water supplier in mainland Finland. (In the case of alternations in the project plan, the same principle can be applied to another urban area). Despite the already established and proven character of the Espoo water supply system, this single-source linear strategy, in short-term perspective, can make a water supply of the island more susceptible to sudden and unexpected disruptions caused, for example, by technical or operational failures of pumping systems or water treatment facilities. In the long-term perspective, this strategy can possibly create a 'competition' for available water between a water supply system of the island and the city water supply system which can be caused, for example, by a population growth and a consequent increase in water demand in the area of the water supplier.

An isolated case of the possible 'competition' between the city of Espoo and the island will also involve and impact water supply systems of other cities of the Greater Helsinki area because the cities of Espoo, Helsinki, Vantaa, Kauniainen, Hyvinkää, Järvenpää, Kerava, Kirkkonummi, Sipoo, and Tuusula are withdrawing potable water from the same source – Lake Päijänne – by means of the 120-km long Päijänne water tunnel (Janita, 2018). The possible 'competition' for available water can also occur in the case of population growth and increase in water demand in any of the mentioned cities.

Wastewater treatment. In this linear strategy, wastewater treatment and discharge of treated effluent will be subjected to the same requirements and will have the same characteristics as those described for the seawater-based linear water management strategy (section 3.5.1).

3.5.3 Multiple-Source Linear Water Management Strategy

There is only one possible linear water management strategy, which applies the sources of 'new' potable water described in the section 3.2 on the combined basis. This multiple-source linear water management strategy is based on the application of the seawater in combination with water imported from mainland Finland (Figure 20). In this strategy, imported water can also be either imported freshwater, partially treated imported freshwater, or treated imported freshwater.

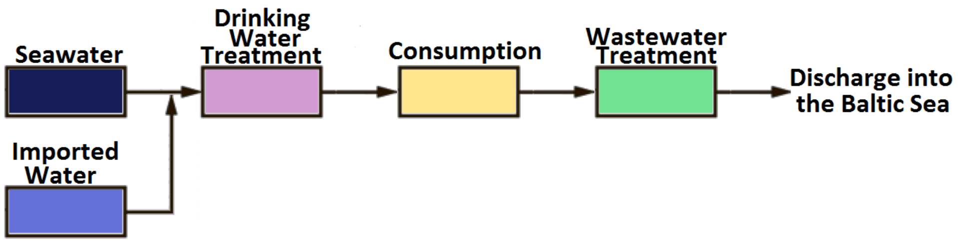

Figure 20. Multiple-source linear water management strategy based on the simultaneous application of the Baltic Sea seawater and imported freshwater

In comparison with the described single-source linear water management strategies – seawater-based and imported-water-based – this linear strategy possesses some advantageous characteristics derived from reduced volume of water to be imported from the mainland and water to be withdrawn from the sea. In other words, the implementation of this strategy can allow to mitigate some of the specific disadvantages of each of the applied sources (sections 3.2.1, 3.2.2, and 3.5.2) by achieving a lesser reliance on each of them.

By substituting certain amount of imported water for the seawater, this multiple-source linear water management strategy can reduce required dimensions of the water transfer pipeline, thereby diminishing its space requirements in the space-limited tunnel, which will ease an establishment and maintenance of the pipeline. The magnitude of impacts on an entire island's water supply system caused by sudden and unexpected disruptions in a water importation from the mainland will also be reduced. In the case of water importation from the city of Espoo, the possibility of occurrence of the 'competition' between the urban areas for available water will be minimized since the island will apply another source of raw potable water.

The diversification of water sources can also significantly reduce the risk of occurrence of conditions or situations, which can cause temporary shut-downs of an entire water supply system of the island (e.g., drinking water treatment underperformance caused by sudden source quality deterioration, transfer piping break, etc.), since there is a possibility to rely on a remaining source while supply is disrupted from another one.

Drinking water treatment. From the standpoint of drinking water production, the multiple-source linear water management strategy based on the simultaneous application of the seawater and imported water will require treatment technologies which must be able to process the waters into safe drinking water. Required treatment must include processes and/or operations, including desalination technologies, to process seawater into potable water and processes and/or operations to process imported water which can be either raw, partially treated, or treated, into potable water. Due to possible difference in qualities of the seawater and imported water, blending issues, as described in the section 2.2, can occur and, therefore, drinking water treatment should be calibrated to a resulting blend quality in order to provide an effective treatment.

Wastewater treatment. In this linear strategy, wastewater treatment and discharge of treated effluent will be subjected to the same requirements and will have the same characteristics as those described for the seawater-based linear water management strategy (section 3.5.1).

Public health protection. As in the seawater-based linear water management strategy, inadequate establishment of wastewater treatment effluent discharge system may result in abstraction of certain amount of wastewater by a seawater intake system.

3.5.4 Summary for the Linear Water Management Strategies

Water treatment requirements, wastewater treatment requirements, advantages, and disadvantages of the described linear water management strategies are summarized in Appendix 3.

3.6 **Closed-Cycle Water Management Strategies**

All closed-cycle water management strategies can be referred to as *water recycle* or *water reuse strategies* since their integral idea is to reprocess and reapply wastewater for beneficial non-potable and potable purposes. Closed-cycle water management strategies based on the application of wastewater for potable purposes are referred to as *planned potable reuse*. Planned potable reuse can be divided on the direct potable reuse (DPR) (Figure 21A) and indirect potable reuse (IPR) concept (Figure 21B).

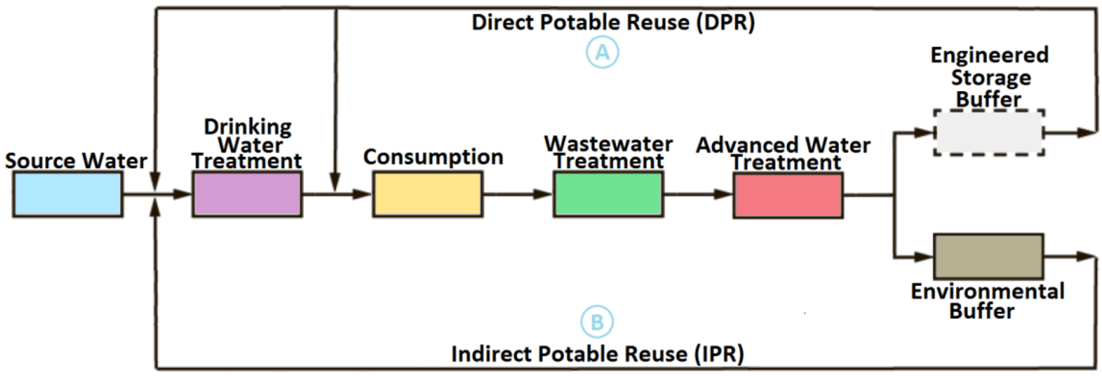

Figure 21. Closed-cycle water management strategies encompassing wastewater reuse for potable purposes (planned potable reuse): A) direct potable reuse and B) indirect potable reuse (NWRI, 2015a, pp. 5-8)

Planned potable reuse and its concepts (DPR and IPR) can all be defined as the planned and publicly acknowledged augmentation of water supply with treated wastewater. The main difference between the IPR and DPR models is that the IPR model utilizes an additional core element – an environmental buffer – instead of the optional ESB element (Figure 21B). Both forms of planned potable reuse are implemented on a worldwide scale (see Appendix 4 for the maps of the implemented projects).

The main advantage of any multiple-source linear water management strategy – mitigation of source-specific disadvantages (Section 3.5.3) – is also inherent to potable water recycling strategies since more than one source of water is applied. In addition to that, planned potable reuse is armed with several additional important advantages that make it a viable water management solution for the planned island, more beneficial than any other possible water management strategy (sections 3.5.1, 3.5.2, and 3.5.3), and that facilitate its increasing implementation on a worldwide scale (WHO, 2017c, p. 2). These advantages are discussed in relation to the project case, but they can also be used to characterize any other planned potable reuse strategy in any other location with an allowance for local specific features.

3.6.1 Advantages of Planned Potable Reuse

An inexhaustible source of raw potable water. In terms of a water amount available for withdrawal for drinking water production, closed-cycle water management strategies, whether the DPR or IPR concept, and the seawater-based linear water management strategy (Figure 18), are taking an advantage of practically inexhaustible sources of raw potable water. Despite the losses occurring during consumption and treatment (section **Ошибка! Источник ссылки не найден.**), wastewater will be constantly and continuously generated by the island population.

Reinforced autonomy and resilience of a water supply system. In terms of an assurance of prolonged application of water sources without any supply disruptions, water reuse strategies (regardless of an applied source of 'compensating' water) as well as the seawater-based linear water management strategy (Figure 18) can potentially reinforce an autonomy and independence of a water supply system of the proposed island. In this context, the terms *autonomy* and *independence* can be interpreted as a water supply self-sufficiency or, in other words, as a reduction of possibility of subjection to disruptions in water supply which can be occasionally caused by events occurring in other locations. Generated wastewater and the seawater can be regarded as raw potable waters directly pertaining to the island since their sources are located directly on the island (wastewater collection system) or in the immediate vicinity of it (the Baltic Sea); thereby, giving the island a practically full and standalone control over the water resources and diminishing short-term and long-term issues potentially caused by other users (as it can be the case in the imported-water-based linear water management strategy (section 3.5.2)).

Increased independence from climatic and environmental issues. All delineated linear water management strategies (sections 3.5.1, 3.5.2, and 3.5.3) are entirely relying on the natural sources of water (Table 1). Regardless of geographical location, morphology, and protective regulations, all environmental sources of water may be subjected to unforeseen events inducing deterioration of source water quality. The deterioration can be caused by a continuum of natural or anthropogenic reasons, from algal blooms to accidental spills or illegal discharges, and can severely impact drinking water treatment performance and/or produced drinking water quality. In most circumstances, detection of detrimental changes in source water quality and subsequent adverse changes in drinking water quality bears more ex-post character. Conversely, quality of raw potable water applied in potable water recycling strategies, despite its poor initial characteristics, is usually relatively stable and not subjected to significant qualitative and quantitative fluctuations in composition even on prolonged time periods. Reduced compositional fluctuations of wastewater quality are mostly achieved through the compulsory application of operational, managerial, and technical procedures specifically designed to predict and eliminate the variations (e.g., source control program). These procedures are applied in each of the fundamental elements of any planned potable reuse scheme (Figure 21) and enable the possibility to 'finely' adjust wastewater treatment to an exact quality of raw wastewater and advanced water treatment to an exact quality of treated effluent; thereby, assuring reliable and efficient conversion of raw potable water of poor but relatively stable quality into either ATW or finished water.

Meeting future regulations. In the project case, wastewater disposal of all possible linear water management strategies, including the described ones, is based on the discharge of treated effluent into the Baltic Sea, the aquatic environment of which has already been adversely and heavily impacted by a variety of human activities and is subjected to the attention of the European Union government and several other organisations. These factors can possibly initiate further tightening of regulatory discharge requirements which must be met by an island's wastewater treatment plant. The treatment plant, which will meet the discharge requirements of a moment of construction and commissioning, may not meet tightened requirements and may be forced to integrate new treatment processes and/or operations in an already established treatment train configuration. Mandatory reconfiguration of the treatment train will incur cost implications, which may be comparable to expenses required by initial design, and cause certain issues related to water supply management during a process of the reconfiguration. In the project case, suddenly required integration of new treatment elements may have especially detrimental impacts, since the necessitated reconfiguration may not be possible without an interim wastewater treatment plant establishment which can be particularly complicated on the island limited and densely-developed land area. Potable water recycling strategies are potentially able to simultaneously meet present and future regulatory requirements since an amount of discharged treated effluent can be significantly reduced and since these strategies employ advanced water treatment as one of their fundamental elements.

Single source located within the island urban area. Despite the obvious proximity of the Baltic Sea to the island, it, strictly speaking, cannot be characterized as a water source, which is located directly within the island urban area, since seawater intake system will require additional piping infrastructure to transfer the water to a drinking water treatment plant.

The piping infrastructure will likely be necessitated by a submerged intake system, the application of which will be necessitated due to a possible risk of ice formation during winter periods. An exact length of the piping will depend on a depth of submerged intake system establishment (elevation difference between a point of abstraction and drinking water treatment plant) and distance between the point and plant. Conversely, wastewater generated by the island population will be located directly within the planned urban area (within its collection and treatment system).

Reduced infrastructural requirements. All possible linear water management strategies will require their own specific and dedicated infrastructure to abstract and transfer water from applied sources (e.g., seawater intake system, etc.) and will also require infrastructure to manage wastewater flows. Potable water reuse strategy takes an advantage of wastewater collection and treatment system, which must be established regardless of an implemented water management strategy (linear or closed-cycle), as the main part of raw potable water transfer system, thereby diminishing infrastructural requirements of an entire water management strategy.

Abatement of wastewater-induced pollution. Through the compulsory incorporation of specific operational, managerial, and technical procedures aimed to maintain uniform raw and treated wastewater quality, planned potable reuse strategies enable greater control over qualitative and quantitative characteristics of generated and treated wastewater composition, thereby significantly reducing a wide range of potential constituents and creating an opportunity to restrict usage or disposal into sewer system and subsequent discharge into environment (if certain volume of wastewater is to be discharged) of specific recalcitrant contaminants. Also, pollution abatement is achieved through reduced volume of discharged wastewater since it is reprocessed and reapplied for beneficial purposes. Considering the ecological situation of the Baltic Sea and the fact that wastewater discharges are making a significant contribution to water pollution problems (WHO, 2017c, p. 2), pollution control and abatement are especially important in the project case since adverse environmental impacts induced by wastewater discharges can become an unacceptable condition for the island construction.

There are, at least, two additional advantageous features of planned potable reuse but their significance and relevance in the project setting require additional verification. These advantages are as follows:

1. Planned potable reuse is less expensive than seawater desalination (WHO, 2017c, p. 2). This advantage needs additional verification because the seawater of the Baltic Sea is brackish (Finnish Environment Institute, 2014a, p. 1), which means that it contains less total dissolved solids (TDS) than seawater of oceans or other seas. The brackish seawater of the Baltic Sea will still require desalination to be converted into potable water, but, in

comparison with desalination of ocean seawater, it should be less costly due to the lower salt content (NWRI, 2015a, pp. 14, 16).

2. Planned potable reuse is experiencing increasing public acceptance (WHO, 2017c, p. 2). This feature does not require additional verification since there are numerous already implemented projects on a worldwide scale (see Appendix 4 for the maps of the projects) but it requires assessment of public perception in the setting of Finland since there are no implemented projects incorporating planned potable reuse concepts.

Furthermore, several advantages, which facilitate the implementation of planned potable reuse on a global scale and which are related to global issues, such as the unprecedented growth of the world population, accelerated urbanization in coastal areas, the concept of sustainable development (the 17 sustainable development goals), water-energy nexus, and climate change impacts on water resources, are of less importance in the isolated case of the planned island and, therefore, are not considered here. More information related to the global issues can be found in the following sources:

– *Potable Reuse: Guidance for Producing Safe Drinking-Water* by the World Health Organisation (WHO);
– *The United Nations World Development Report 2017. Wastewater: The Untapped Resource* by the United Nations Educational, Scientific and Cultural Organisation (UNESCO); and
– *2012 Guidelines for Water Reuse* by the United States Environmental Protection Agency (EPA) and CDM Smith, Inc.

3.6.2 Challenges of Planned Potable Reuse

The main challenge of the production of potable water from wastewater is represented by an extremely poor quality of the source water (i.e., raw sewage) which stipulates compulsory involvement of a set of complex managerial procedures aimed to predict and prevent introduction of hazardous constituents into wastewater and the involvement of complex treatment measures required to convert the source water into safe drinking water. Also, possible negative connotations of the general public associated with the source water will require extensive educational and outreach programmes (WHO, 2017c, pp. 2-3).

3.6.3 IPR Water Management Strategies

As it was already mentioned in section 3.6, closed-cycle water management strategies based on the IPR model require the compulsory application of an environmental buffer (Figure 22). This fundamental component represents an artificial or natural water body which can be either surface water body or groundwater aquifer (U.S. EPA, CDM Smith, Inc., 2017c, p. 1). Reclaimed water is introduced in an environmental buffer, blended with environmental waters and remained in it for a specified time period, and then withdrawn as a raw potable water. An environmental buffer provides advantages of reduction of negative public connotations related to the potable reuse source water (i.e., wastewater) and, in some cases, additional contaminant attenuation processes (WHO, 2017c, p. 3; NRC, 2012a, pp. 79-86).

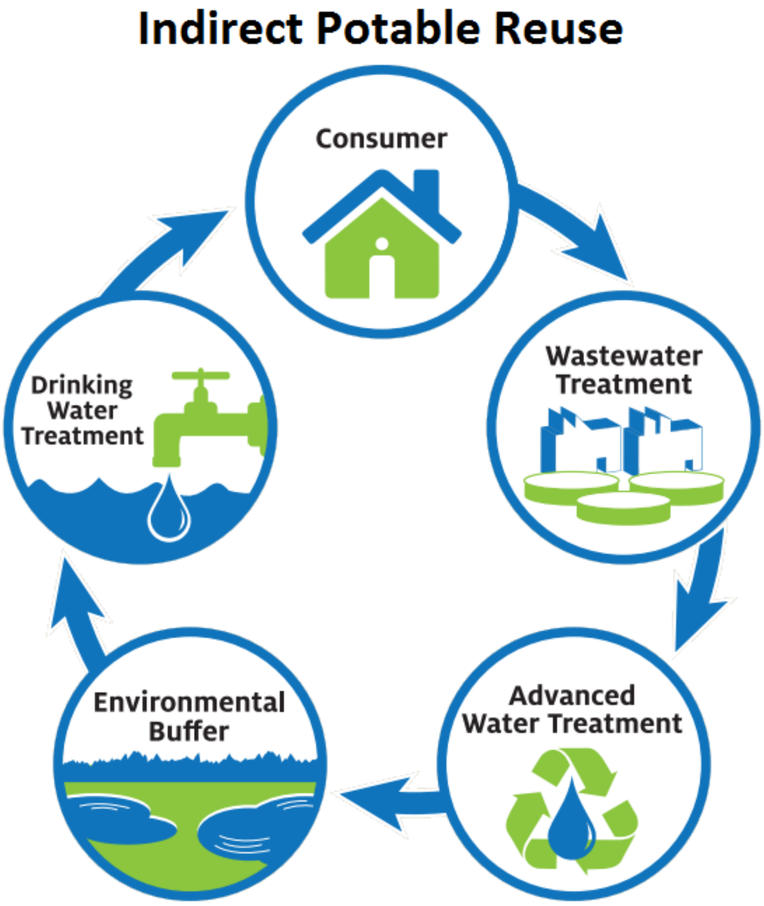

Figure 22. Graphical representation of IPR (Hummer & Eden, 2016, p. 3)

Volume of an environmental buffer, whether surface water body or groundwater aquifer, must meet certain storage and dilution requirements, otherwise an IPR scheme will become a DPR scheme (NWRI, 2015a, p. 7).

Due to the limited and highly-developed land area and the artificial character of the planned island (section 3.1), the presence or the opportunity to establish an environmental buffer, which meets the volumetric requirements, remain unlikely at the moment of writing. Therefore, a possible water management strategy based on the IPR model is not considered as a potential solution.

4 DPR WATER MANAGEMENT STRATEGIES

In addition to the main advantage of any multiple-source water management strategy – mitigation of disadvantages inherent to a particular water source (section 3.5.3) – and in addition to the advantages of planned potable reuse (section 3.6.1), there are, at least, three more advantageous factors which facilitate the suitability and reasonability of the DPR model in the project case. These factors include the following:

1. Modern advanced water treatment technologies can remove contaminants to exceptionally low levels, which will not cause any of known health risks, in an effective and reliable manner (Tchobanoglous, Leverenz, Nellor, & Crook, 2011b, p. 4; Leverenz, Tchobanoglous, & Asano, 2011, pp. 5, 6; U.S. EPA, CDM Smith, Inc., 2012a, p. 28).
2. The IPR model, which can be better recognized by the general public, requires specific hydrogeological or limnological conditions (for groundwater replenishment or surface water supplementation) to be established. The DPR model omits these compulsory conditions which are unlikely to be provided within the limited land area of the artificially constructed island. An environmental buffer, as any other water body, is also subjected to potential water quality issues caused by natural or anthropogenic reasons (e.g., algal blooms, contamination plumes, or illicit water discharges, etc.) – DPR effectively avoids these issues (Tchobanoglous, Leverenz, Nellor, & Crook, 2011b, p. 5).
3. Modern treatment and monitoring technologies are sufficient to replace an environmental buffer with and an ESB (Tchobanoglous, Leverenz, Nellor, & Crook, 2011b, p. 5; Leverenz, Tchobanoglous, & Asano, 2011, p. 6).

There are a variety of possible DPR water management strategies which can be potentially implemented in the project case and which will depend on a selected DPR scheme configuration (section 2.2), source of ‘compensating’ water (section 3.2), and application basis of water source(s) (section 3.3).

4.1 Seawater-Based DPR Water Management Strategies

Depending on the augmentation location, there are two possible DPR water management strategies based on the application of the Baltic Sea seawater as the single source of ‘compensating’ water:

1. Seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant (Figure 23A)
2. Seawater-based DPR water management strategy applying the augmentation of drinking water with finished water downstream of a drinking water treatment plant (Figure 23B)

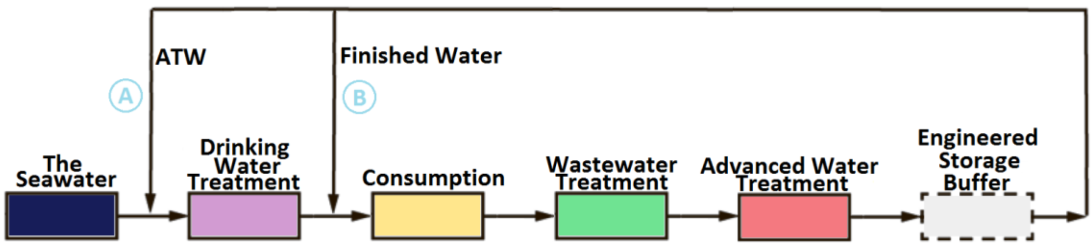

Figure 23. Seawater-based DPR water management strategies applying the A) augmentation of raw seawater with ATW upstream of a drinking water treatment plant and B) augmentation of drinking water with finished water downstream of a drinking water treatment plant

In addition to achieving the planned potable reuse benefits (section 3.6.1), such as abatement of wastewater-induced pollution, implementation of the seawater-based DPR strategies, in comparison with the seawater-based linear water management strategy (section 3.5.1), can achieve lesser reliance on the source water both qualitatively and quantitatively. This is especially the case in the DPR strategy applying the augmentation of raw seawater with ATW (Figure 23A) since reduced withdrawn volumes of the seawater of presumably poor quality (section 3.5.1) will be blended with ATW, thereby (depending on applied advanced water treatment technologies) reducing concentrations and loads of certain constituents in the seawater by dilution. In the case of the DPR strategy applying the augmentation of drinking water with finished water (Figure 23B), only lesser quantitative reliance on the Baltic Sea seawater can be achieved since drinking water and finished water are blended downstream of a drinking water treatment plant.

These DPR water management strategies utilize raw potable waters – the seawater and constantly generating wastewater – which are practically unlimited and will be available on the permanent basis in the immediate vicinity of and directly on the island.

4.1.1 Augmentation prior to Drinking Water Treatment

Public perception. From the standpoint of public perception, the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW (Figure 24) will represent suitable solution for the project case, since produced ATW will be blended with a ‘purely-environmental’ water (i.e., the Baltic Sea seawater) and subjected to the highest degree of drinking water treatment necessitated by the requirement to remove dissolved solids from the seawater (i.e., to reduce salinity of the brackish seawater and remove other dissolved constituents potentially present in the seawater).

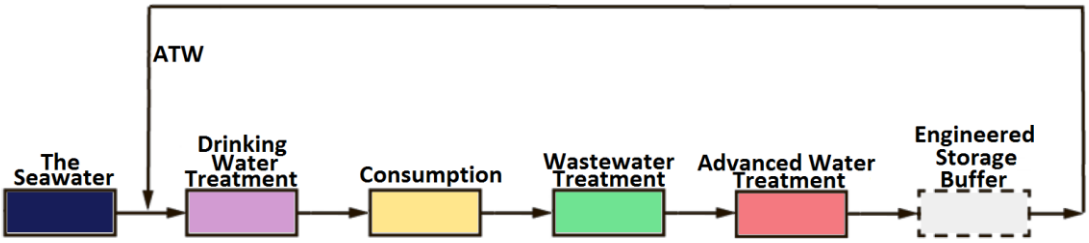

Figure 24. Seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant

Blending issues. In this DPR water management strategy, issues induced by blending of ATW and raw seawater will potentially arise since, depending on ATW quality achieved by advanced water treatment (section 2.2.1), a difference in qualities of the waters being blended may be significant. Therefore, drinking water treatment must be calibrated to an ATW and raw seawater blend quality in order to provide effective and reliable production of potable water (Figure 25).

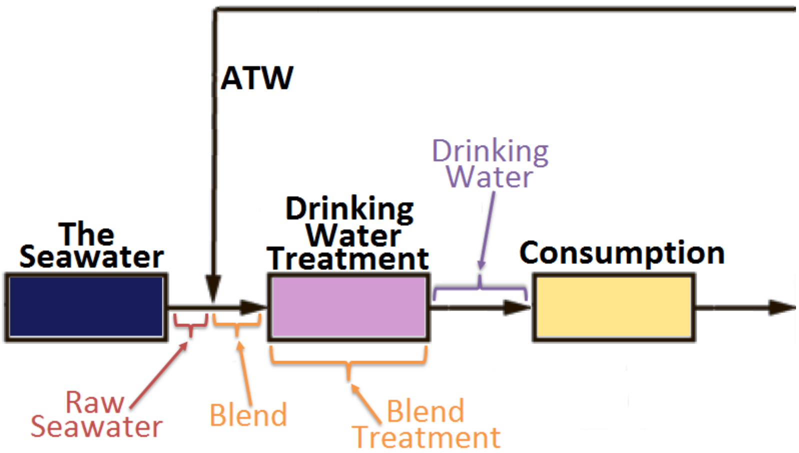

Figure 25. Blending of waters subjected to drinking water treatment in the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant

Drinking water treatment. As in the seawater-based linear water management strategy (section 3.5.1), drinking water treatment in this closed-cycle strategy must employ specific seawater intake system and, despite a dilution provided by ATW, treatment technologies which will address suspended and dissolved solids in withdrawn seawater. In the case if advanced water treatment is producing ATW of a quality lower than a drinking water quality or not utilizing extensive treatment of dissolved solids in wastewater treatment effluent, provisions must be made to ensure that drinking water treatment is capable to address all constituents of the ATW and raw seawater blend.

Advanced water treatment. Being an integral component of the considered potable water cycle, advanced water treatment must also provide treatment of dissolved solids and other constituents which remain in effluent of wastewater treatment. In the case when advanced water treatment must produce ATW of a drinking water quality, dissolved solids and certain other constituents will necessitate the integration of demineralization processes. In the case when advanced water treatment must produce ATW, the quality of which is not lower than a raw seawater quality but can be lower than a drinking water quality, there is no compulsory technical requirement to provide high-performance demineralization processes at an advanced water treatment plant since drinking water treatment will incorporate these processes.

Reallocation. Benefits brought about by a reallocation of certain treatment elements between drinking water treatment and advanced water treatment (Figure 26) are especially achievable in this water management strategy since the seawater and wastewater treatment effluent will require removal of dissolved solids to be converted into drinking water. In the case of demineralization, reallocation will be based on the fact that desalination processes are applied as final treatment steps since this treatment addresses the smallest constituents (i.e., dissolved solids) and requires water, which is free of larger constituents (e.g., suspended solids), to perform in an efficient and effective manner.

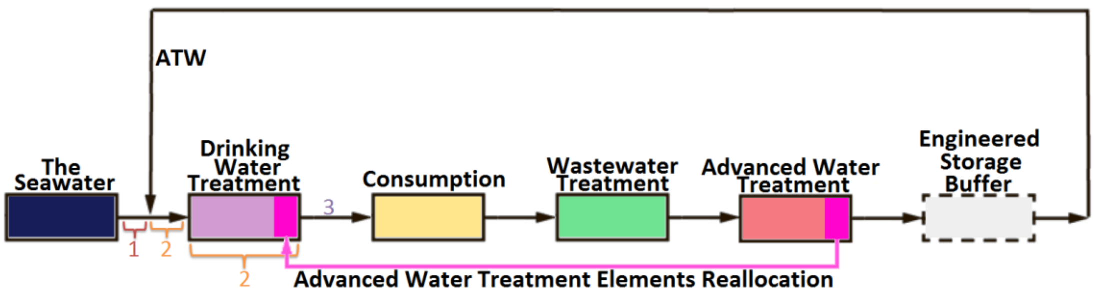

Figure 26. Possible reallocation of treatment elements between drinking water treatment and advanced water treatment in the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant [1 – raw seawater; 2 – blend of ATW and raw seawater; 3 – drinking water]

For instance, one of such demineralization technologies, which can provide a significant reduction of dissolved solids, is reverse osmosis (RO). This technology is likely to be applied in the project setting since it has reduced space requirements and the process of RO demineralization is employed by most of the implemented DPR schemes, including:

– The town of Beaufort West, South Africa (Khan, 2013c, p. 26; Khan, 2013d, pp. 47-48; Lahnsteiner, van Rensburg, & Esterhuizen, 2018, pp. 17-18; U.S. EPA, CDM Smith, Inc., 2017d, p. 9),
– The city of eMalahleni, South Africa (WHO, 2017d, p. 127),
– The city of Big Spring, Texas, United States (Tchobanoglous, Leverenz, Nellor, & Crook, 2011c, p. 29; U.S. EPA, CDM Smith, Inc., 2017e, pp. A.5-2-A.5-3; Lahnsteiner, van Rensburg, & Esterhuizen, 2018, pp. 17-18),
– The village of Cloudcroft, New Mexico, United States (Tchobanoglous, Leverenz, Nellor, & Crook, 2011c, p. 27; NRC, 2012c, pp. 40-41, 47; Khan, 2013d, p. 44).

As a process, which addresses dissolved constituents, RO is also utilized as one of the final steps of drinking water and advanced water treatment. In the project case, demineralization required to remove dissolved substances in the waters being treated can be provided by only one RO unit located at drinking water treatment plant (Figure 27A) instead of more conventional approach based on the compulsory incorporation of RO in an advanced water treatment train (Figure 27B).

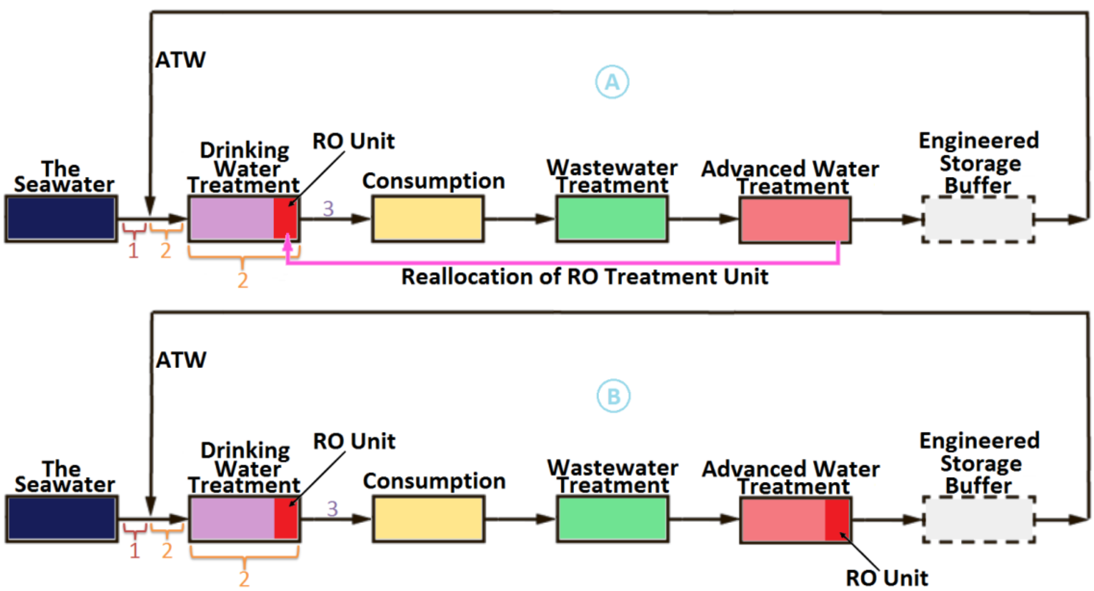

Figure 27. Reallocation of RO demineralization process between advanced water treatment and drinking water treatment in the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant: A) RO unit employed only as a component of drinking water treatment train and B) RO units employed as components of drinking water treatment and advanced water treatment train [1 – raw seawater; 2 – blend of ATW and raw seawater; 3 – drinking water]

The RO process reallocation will reduce energy consumption of the entire potable water cycle and expenses related to RO technical maintenance procedures, but ATW produced without RO will possess higher levels of dissolved solids which must be removed by drinking water treatment incorporating RO.

Wastewater treatment. From the standpoint of wastewater treatment, this DPR water management strategy must employ a range of treatment technologies which will produce effluent of the quality suitable for a reliable production of ATW. Applied wastewater treatment technologies will depend on a quality of raw wastewater generated by the community, applied advanced water treatment technologies, and targeted quality of ATW but, in general, must accomplish treatment steps described in section 2.1.4.

Public health protection. In the case of advanced water treatment and ESB monitoring failure, this DPR water management strategy will provide a high degree of public health protection by subjecting ATW to blending with raw seawater and to full drinking water treatment based on the compulsory application of treatment technologies addressing dissolved solids.

4.1.2 Drinking Water Augmentation

Public perception. From the standpoint of public perception, the seawater-based DPR water management strategy applying the augmentation of drinking water with finished (Figure 28) may incur relatively high public opposition since the blend of drinking water produced from the seawater and finished water (i.e., drinking water produced from wastewater treatment effluent) will not be subjected to any degree of drinking water treatment, regardless of the facts that advanced water treatment plant is permitted as drinking water treatment plant and finished water is compliant with all drinking water quality standards and criteria.

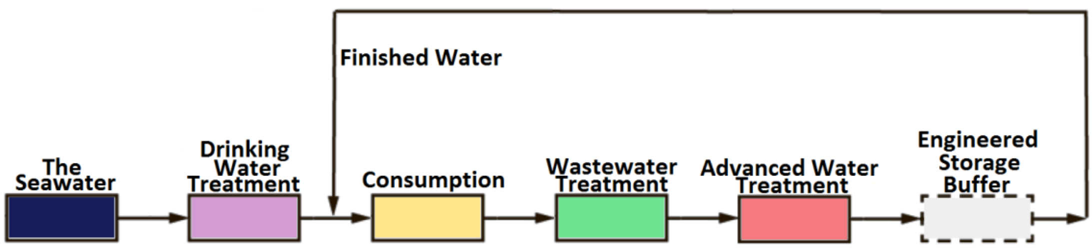

Figure 28. Seawater-based DPR water management strategy applying the augmentation of drinking water with finished water

Blending issues. Since drinking water derived from raw seawater and drinking water derived from wastewater treatment effluent are blended downstream of a drinking water treatment plant, there will be no blending issues adversely impacting drinking water treatment but possible aesthetic issues induced by temperature difference of blended waters will still be of concern (Figure 29).

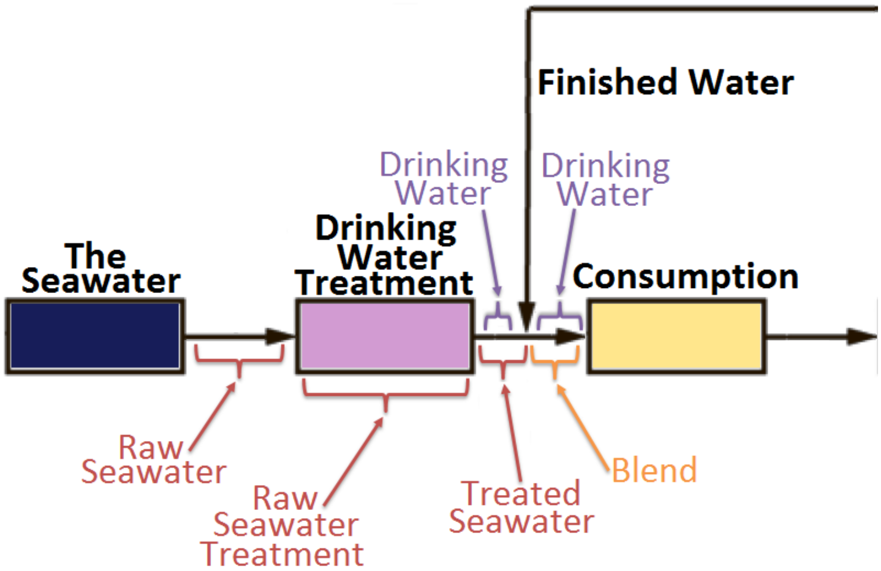

Figure 29. Only raw seawater is subjected to drinking water treatment in the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water

Drinking water treatment, advanced water treatment, and reallocation. Since the waters are blended downstream of a drinking water treatment plant or directly in a potable water distribution system, a drinking water treatment plant and an advanced water treatment plant must employ technologies, including demineralization processes, to reliably and continuously produce water compliant with all applicable drinking quality water standards (Figure 30). Due to this reason, reallocation of treatment elements between the treatment plants cannot be accomplished in this scheme.

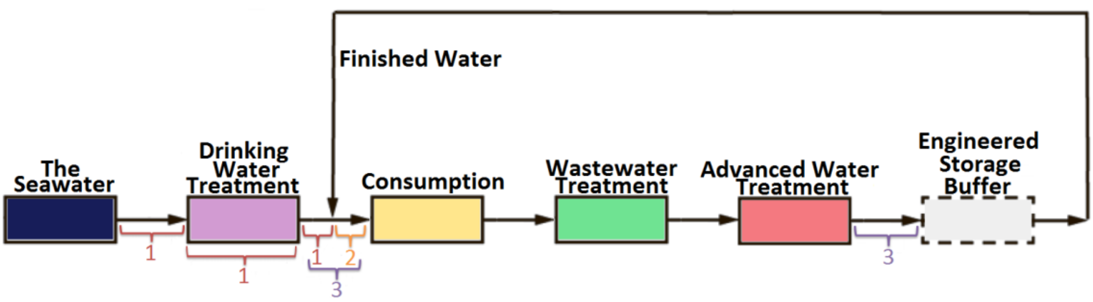

Figure 30. Waters in the seawater-based DPR water management strategy based on the augmentation of drinking water [1 – raw seawater; 2 – blend of drinking water and finished water; 3 – drinking water]

Wastewater treatment. Required wastewater treatment technologies will depend on applied advanced water treatment technologies and through accomplishment of the treatment steps described in section 2.1.4 must produce treated effluent which will be suitable for a reliable and continuous production of finished water by advanced water treatment.

Public health protection. In the case of advanced water treatment and ESB monitoring failure, there will be no additional treatment barriers to contaminants potentially present in inadequately treated finished water. Provisions must be made to ensure production of finished water which will be always compliant with all required drinking water quality standards.

4.2 Imported-Water-Based DPR Water Management Strategies

Depending on the augmentation location, there are two possible DPR water management strategies based on the application of raw, partially treated, or treated water imported from mainland Finland as the single source of 'compensating' water:

1. Imported-water-based DPR water management strategy applying the augmentation of source water (Figure 31A);
2. Imported-water-based DPR water management strategy applying the augmentation of treated drinking water (Figure 31B).

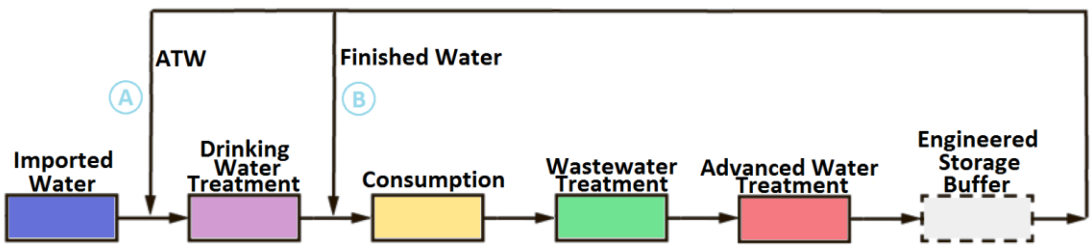

Figure 31. Imported-water-based DPR water management strategies applying the A) augmentation of raw, partially treated, or treated imported potable water with ATW upstream of drinking water treatment and B) augmentation of drinking water with finished water

In addition to achieving the planned potable reuse benefits (section 3.6.1), the implementation of the imported-water-based DPR water management strategies, in comparison with the imported-water-based linear water management strategy (section 3.5.2), can achieve lesser reliance on imported water both qualitatively and quantitatively. In these DPR water management strategies, qualitative benefits will play a minor role since raw, partially treated, or treated imported freshwater will most likely be of a relatively high quality but, in the case of severe contamination of a hypothetical inland freshwater source or drinking water treatment (if applied) underperformance, reclaimed water will provide a dilution of concentrations of hazardous constituents. The main advantage of the simultaneous application of wastewater and imported water is quantitative rather than qualitative since reduced amounts of water to be imported achieved by substitution for reclaimed water will require smaller water transfer pipeline, thereby reducing costs of pipeline components production, pipeline operation, and pipeline technical maintenance.

4.2.1 Augmentation prior to Drinking Water Treatment

Public perception. In a general case, the imported-water-based DPR water management strategy applying the augmentation of imported water with ATW prior to drinking water treatment (Figure 32) will be considered in the same way as any other DPR water management strategy applying the same augmentation location (section 2.2.1).

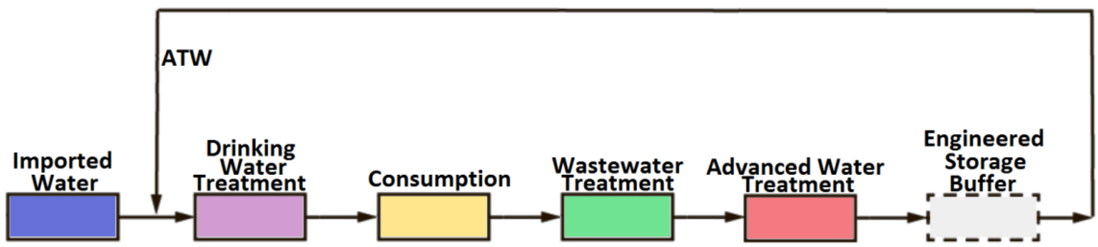

Figure 32. Imported-water-based DPR water management strategy based on the augmentation of raw, partially treated, or treated source water prior to drinking water treatment

Public perception of the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant (sections 4.1.1) and public perception of this DPR water management strategy may be different despite the fact that both of these strategies are based on the same augmentation location. The difference in perception will be governed by a potential existence of two possible opinions from which the prevailing one will determine the most popular solution.

In comparison with the seawater-based DPR water management strategy, negative perception of this imported-water-based strategy can occur due to the reason that blended ATW and imported water will receive a lower degree of drinking water treatment than in the seawater-based DPR strategy applying the augmentation of raw seawater (section 4.1.1) since, regardless of its quality, water imported from mainland Finland will, most probably, be derived from a freshwater body (surface water body and/or groundwater aquifer). Freshwater contains less dissolved substances and generally requires a lower degree of treatment to be converted into drinking water than the brackish seawater. Therefore, there is no technical requirement to employ treatment processes which remove dissolved substances (i.e., demineralization technologies).

On the other hand, public perception may lean towards a greater acceptance since any freshwater body in Finland applied as a water supply source contains water of better quality than the quality of the Baltic Sea seawater. Taking into consideration possible quality issues discussed in section 3.2.1 and their absence in a hypothetical freshwater body, an application of presumably cleaner water source can be more desirable by the island population.

It is also possible that public perception will gradually shift from acceptance to opposition with an application of raw, partially treated, or treated imported water since these waters will require different levels of drinking water treatment and, hence, a blend of ATW and raw, partially treated, or treated imported water will be subjected to different degrees of drinking water treatment.

Blending issues. To mitigate issues, which are induced by blending of ATW and imported water and which can adversely impact drinking water treatment performance, drinking water treatment must be adjusted to a quality of blend of ATW and raw, partially treated, or treated imported water (Figure 33).

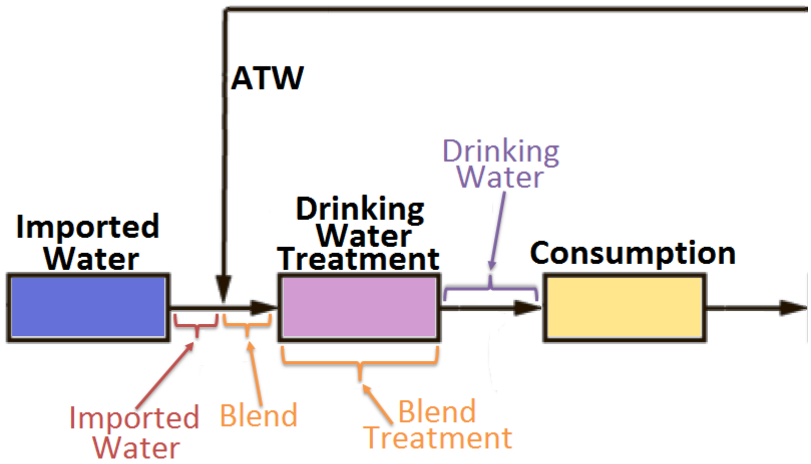

Figure 33. Blending of waters subjected to drinking water treatment in the imported-water-based DPR water management strategy applying the augmentation of raw, partially treated, or treated imported water with ATW prior to drinking water treatment

Drinking water treatment. In this closed-cycle water management strategy, application of certain drinking water treatment processes and operations will depend on the exact quality parameters of imported freshwater and degree of water treatment applied before exportation to the island. In a general case, required drinking water treatment will possess a more conventional character (i.e., drinking water treatment of surface water or groundwater usually required and applied in Finland) and consist of processes and operations mostly addressing suspended matter (e.g., filtration) and pathogenic microorganisms (e.g., disinfection). In theory, the application of desalination processes to remove dissolved solids will not be required since raw, partially treated, or treated imported freshwater should not contain excessive concentrations of dissolved matter.

Raw imported freshwater withdrawn from a surface water body and/or groundwater aquifer will require application of full conventional drinking water treatment. Partially treated imported freshwater will require application of only certain conventional drinking water treatment processes and operations to complete the conversion into potable water. In these cases, an exact arrangement of drinking water treatment train established on the island will be dictated by exact quality parameters of raw or partially treated imported water.

Treated imported freshwater will require only disinfection process to eliminate pathogenic microorganisms proliferating in the pipeline applied to importing the water to the island and generate a disinfection residual to prevent regrowth of the microorganisms and formation of biofilms in a drinking water distribution system of the island (e.g., disinfection by means of chlorination generates a chlorine residual). In this case, drinking water treatment train applied on the island can consist of a single disinfection step.

Advanced water treatment and reallocation. Even though, imported water can be not of a drinking water quality, production of ATW, the quality of which is lower than a drinking water quality but is not lower than a quality of applied imported water, will not be reasonable in the case of this DPR water management strategy since a quality difference of imported freshwater and wastewater treatment effluent will be significant both in a range of present constituents and in concentrations of constituents and, hence, drinking water treatment and advanced water treatment will incorporate distinct treatment processes and operations. Due to this reason, reallocation of certain treatment units between drinking water treatment and advanced water treatment will not be possible in this strategy.

Wastewater treatment. In this imported-water-based DPR water management strategy, wastewater treatment must incorporate a range of treatment technologies which by accomplishing the specific treatment steps described in section 2.1.4 will produce treated effluent, the quality of which will be suitable for a reliable production of ATW of drinking water quality.

Public health protection. In the case of advanced water treatment and ESB monitoring failure, drinking water treatment of imported freshwater can provide a barrier to microbiological contaminants since it will incorporate a disinfection process but will not provide protection from dissolved substances since it will not incorporate demineralization processes.

4.2.2 Drinking Water Augmentation

Public perception. As in the case of the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water (section 4.1.2), the imported-water-based DPR water management strategy applying the same augmentation location (Figure 34) may incur high public opposition since blended waters (drinking water produced from imported water and finished water produced from wastewater) will not be subjected to any degree of drinking water treatment, regardless of the facts that an advanced water treatment plant is permitted as drinking water treatment plant and finished water is compliant with all drinking water quality standards.

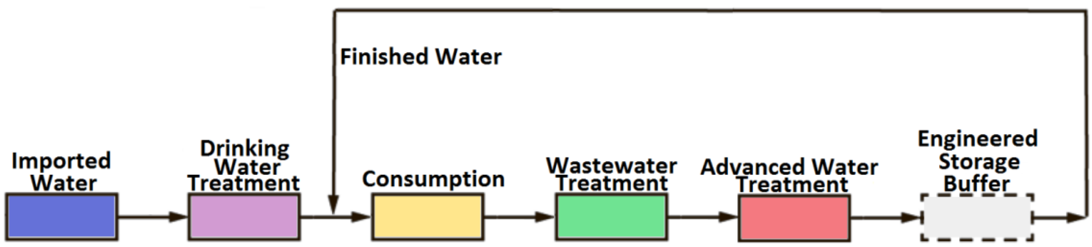

Figure 34. Imported-water-based DPR water management strategy applying the augmentation of drinking water with finished water

Blending issues. There will be no blending issues adversely impacting drinking water treatment performance since drinking water and finished water are blended downstream of a drinking water treatment plant. Aesthetic issues caused by a temperature difference of drinking water and finished water can be anticipated (Figure 35).

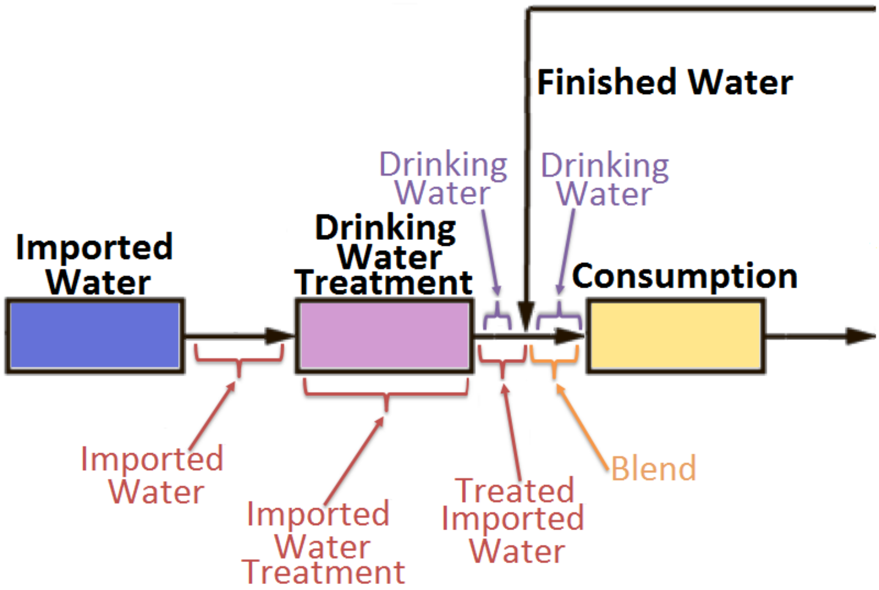

Figure 35. Only imported water is subjected to drinking water treatment in the imported-water-based DPR water management strategy applying the augmentation of drinking water with finished water

Drinking water treatment. In this DPR water management strategy, drinking water treatment must employ technologies to produce drinking water only from raw, partially treated, or treated imported freshwater. General factors influencing an exact arrangement of drinking water treatment train will be the same as those described for the previous imported-water-based DPR water management strategy.

Advanced water treatment and reallocation. Since drinking water and finished water are blended downstream of a drinking water treatment plant, advanced water treatment must employ treatment technologies, including those removing dissolved matter, to reliably produce finished water of drinking water quality. Due to the same reason, reallocation of certain treatment unit processes or operations is not possible.

Wastewater treatment. Wastewater treatment must employ a range of treatment technologies capable of producing treated effluent, the quality of which will be suitable for a reliable and continuous production of finished water, the quality of which, in its turn, will be compliant with all applicable drinking water quality standards. Wastewater treatment technologies must accomplish the specific treatment steps described in section 2.1.4.

Public health protection. In the case of advanced water treatment and ESB monitoring failure, there will be no additional treatment barriers to contaminants potentially present in inadequately treated finished water. Provisions must be made to ensure production of finished water which will be always compliant with all required drinking water quality standards.

4.3 Seawater-and-Imported-Water-Based DPR Water Management Strategies

There is also a possibility to combine the seawater and raw, partially treated, or treated imported water application and diversify a portfolio of 'compensating' water sources of any of the discussed DPR water management strategies.

Through the incorporation of all available waters for drinking water production, these DPR water management strategies will achieve a greater reduction of the disadvantages inherent to each of the water sources. For instance, the simultaneous application of the seawater, generated wastewater, and imported water will require a water transfer pipeline which will have the smallest space requirements among all water management strategies involving the importation of water from mainland Finland (sections 3.5.2, 4.2.1, and 4.2.2). Also, these DPR strategies can achieve more reduced qualitative and quantitative reliance on the seawater because reduced amounts of withdrawn seawater will be blended with both reclaimed water and imported water.

Since there are two possible augmentation locations and two possible qualities of imported water requiring different degrees of drinking water treatment, a possible DPR water management strategy based on the simultaneous application of the seawater and imported water can be represented by a variety of DPR scheme configurations.

Taking into consideration the disadvantages of water importation from mainland Finland (section 3.2.2) and possible issues, which can be caused by an application of potable water source that is already used by another community (section 3.5.2), as well as the fact that the Baltic Sea seawater requires a higher degree of treatment to be converted into drinking water, imported freshwater will be considered only as a supplemental source of 'compensating' water.

Possible DPR water management strategies incorporating simultaneous application of the seawater and imported water as 'compensating' waters will vary in the location of augmentation with reclaimed water (Figure 36A and B) and in the location of supplementation with imported freshwater (Figure 36C and D).

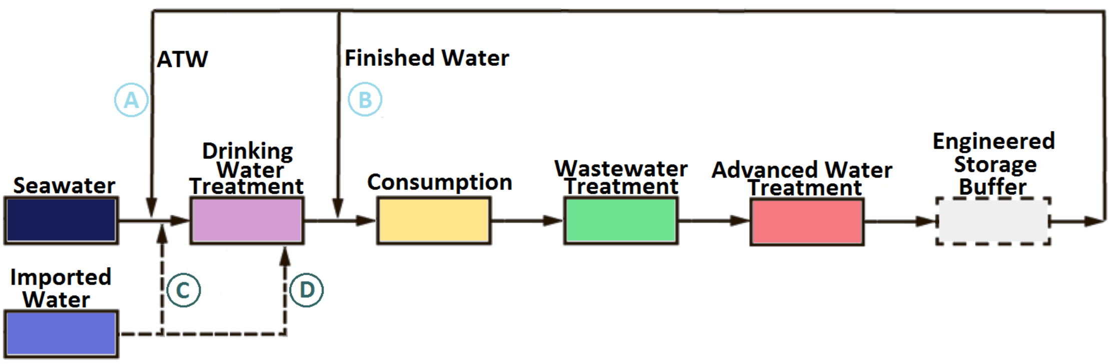

Figure 36. Seawater-based DPR water management strategies applying the augmentation with reclaimed water A) upstream or B) downstream of a drinking water treatment plant and supplementation with raw, partially treated, or treated imported C) upstream of a drinking water treatment plant or D) prior to drinking water disinfection

Supplementation with imported freshwater prior to drinking water disinfection can be implemented only with treated imported freshwater.

4.3.1 Augmentation prior to Drinking Water Treatment

Public perception. Regardless of the location of supplementation with imported freshwater, increased 'loss of identity' of ATW which will be brought about by the application of more 'new' water sources than in other DPR water management strategies will favour greater public acceptance of this DPR strategy in general and in comparison with the discussed DPR strategies applying on the same augmentation location (sections 4.1.1 and 4.2.1). The high degree of drinking water treatment necessitated by the seawater dissolved solids will also facilitate greater public acceptance.

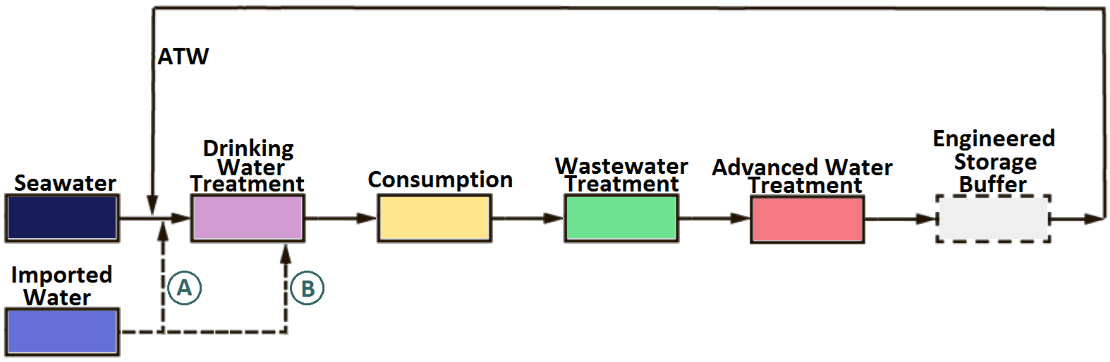

Figure 37. Seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW and supplementation with raw, partially treated, or treated imported water A) upstream of a drinking water treatment plant or B) prior to disinfection of drinking water (only treated imported water)

Blending issues. Possible problems induced by blending of raw seawater, ATW, imported water, and, depending on the supplementation location, blends will be of great concern in this DPR water management strategy since quality parameters of waters being blended can be substantially different. Therefore, certain drinking water treatment processes and operations must be calibrated to certain quality parameters of waters to be treated by these processes and operations.

Supplementation of ATW and raw seawater blend with raw, partially treated, or treated imported water (Figure 38) will necessitate adjustment of all drinking water treatment processes and operations to a quality of blend of all waters.

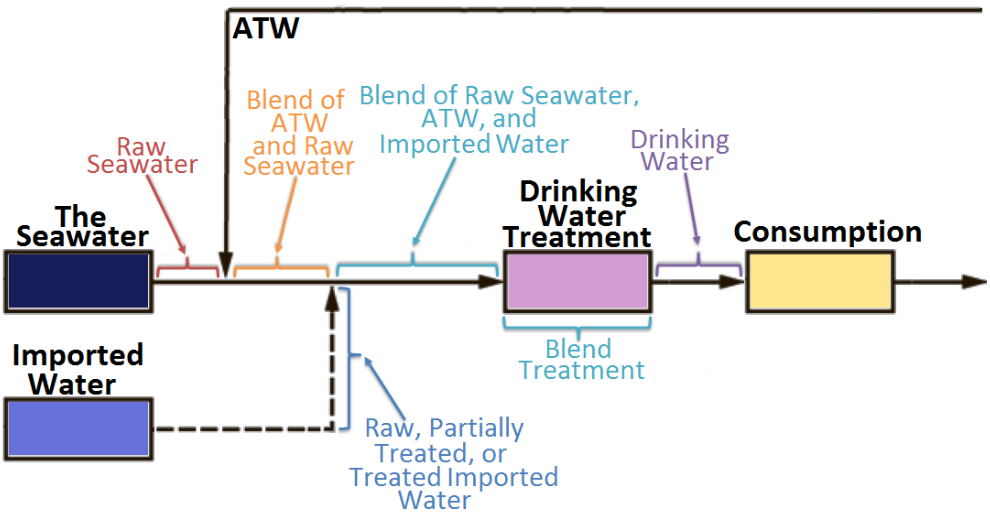

Figure 38. Blending of waters subjected to drinking water treatment in the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW and supplementation of ATW and raw seawater blend with raw, partially treated, or treated imported water

Supplementation of treated ATW and raw sweater blend with treated imported water prior to disinfection (Figure 39) will require calibration of certain drinking water treatment processes and operations to a quality of ATW and raw seawater blend, while final disinfection process must be calibrated to a quality of blend of all waters.

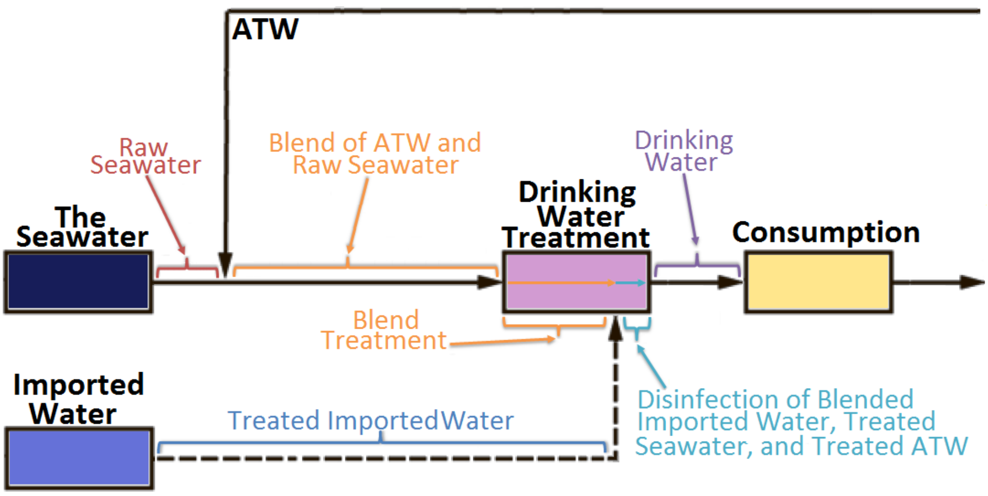

Figure 39. Blending of waters subjected to drinking water treatment in the seawater-based DPR water management strategy

applying the augmentation of raw seawater with ATW and supplementation with treated imported water prior to disinfection of drinking water

Drinking water treatment. Despite a dilution of raw seawater with ATW and imported water, general requirements applied to drinking water treatment will be the same as in the seawater-based DPR water management strategy applying the augmentation of raw sweater with ATW (section 4.1.1).

Advanced water treatment, reallocation, and wastewater treatment. Requirements applied to advanced water and wastewater treatment as well as opportunities of treatment processes and operations reallocation between drinking water and advanced water treatment will be the same as those described for the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW.

Public health protection. In the case of advanced water treatment and ESB monitoring failure, this DPR water management strategy will provide the highest degree of public health protection by subjecting ATW to blending with raw seawater and to full drinking water treatment based on the compulsory application of treatment technologies addressing dissolved solids. In this DPR strategy, when treated imported water is supplementing treated blend of ATW and raw seawater prior to disinfection of drinking water, provisions must be undertaken to ensure that imported water is free of contaminants which cannot be removed by disinfection.

4.3.2 Drinking Water Augmentation

Public perception. As in other DPR water management strategies based on the same augmentation location (sections 4.1.2 and 4.2.2), in the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water and the supplementation with imported water (Figure 40) public perception will lean towards opposition since reclaimed water (i.e., finished water) will not be subjected to any additional degree of treatment.

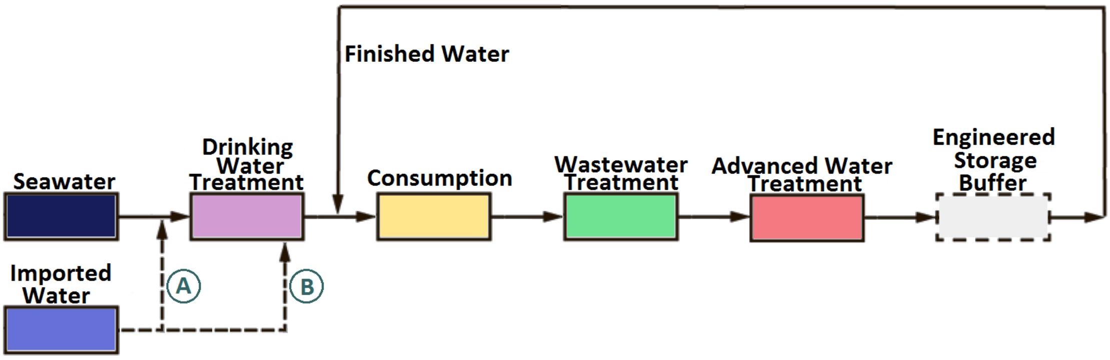

Figure 40. Seawater-based DPR water management strategy applying the augmentation of drinking water with finished water and the supplementation with raw, partially treated, treated imported water A) upstream of a drinking water treatment plant and B) prior to disinfection of drinking water

Blending issues. Supplementation of raw seawater with raw, partially treated, or treated imported water (Figure 41) will necessitate calibration of all drinking water treatment processes and operations to a quality of raw seawater and imported water blend.

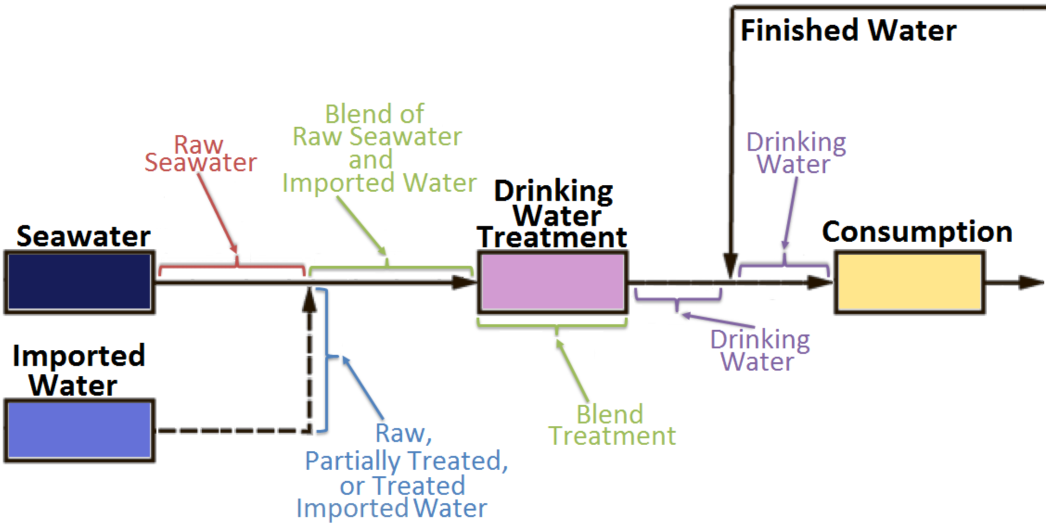

Figure 41. Blending of waters subjected to drinking water treatment in the seawater-based DPR water management strategy applying the supplementation of raw seawater with imported water and the augmentation of drinking water with finished water

Supplementation of treated seawater with treated imported water prior to disinfection of drinking water (Figure 42) will require calibration of only disinfection process to a quality of blend of treated seawater and treated imported water.

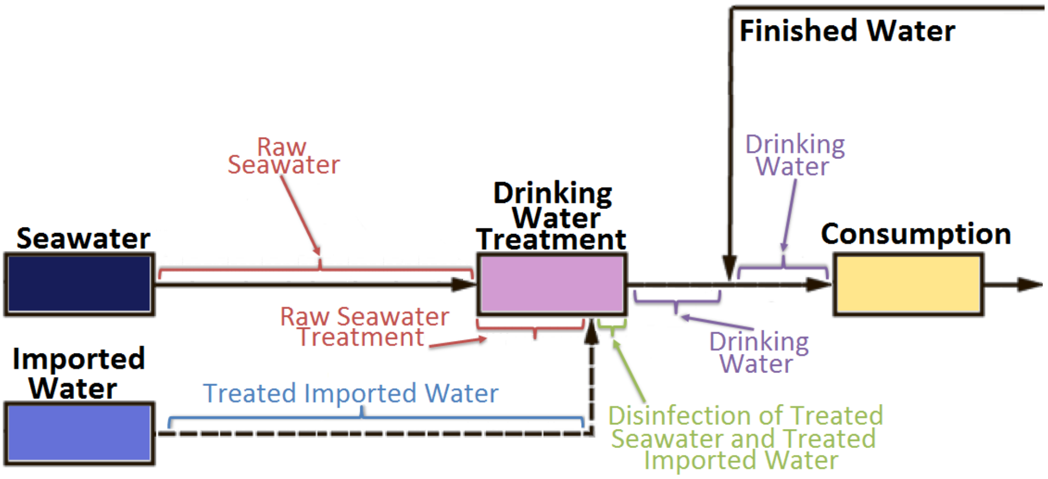

Figure 42. Blending of waters subjected to drinking water treatment in the seawater-based DPR water management strategy applying the supplementation of treated seawater with treated imported water prior to disinfection of drinking water and the augmentation of drinking water with finished water

Drinking water treatment. In this DPR strategy, drinking water treatment will be subjected to the same requirements as in the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water (section 4.1.2).

Advanced water treatment, reallocation, and wastewater treatment. Requirements applied to advanced water and wastewater treatment as well as opportunities of treatment processes and operations reallocation between drinking water and advanced water treatment will be the same as those described for the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water.

Public health protection. As in other DPR water management strategies based on the same augmentation location (sections 4.1.2 and 4.2.2), there will be no protection in the case of advanced water treatment and ESB monitoring failure.

4.4 Project DPR Water Management Strategy

4.4.1 Necessity of an ESB Application

Despite the optional character of ESB application, this element of a DPR scheme will be required in the project setting due to the reason that there are no DPR projects in operation in Finland and in Europe (see Appendix 4 for the DPR projects locations on a worldwide scale) and redundant monitoring of certain constituents established in an ESB will help to cover some theoretical knowledge and operational experience gaps. An ESB will also provide a technical capability to prevent introduction of water which is not meeting quality standards and regulations. From the standpoint of public perception, the ESB application will increase public confidence in the water treatment reliability and supplied drinking water safety.

4.4.2 Selection of 'Compensating' Water Source

Imported water. Since any DPR water management strategy is based on the application of multiple waters for drinking water production, it will achieve a certain degree of mitigation of the disadvantages inherent to each of the described water sources (section 3.2). Even though the disadvantages inherent to the water importation from mainland Finland will be reduced by combined application of imported water and reclaimed water (i.e., ATW or finished water), the DPR water management strategies solely based on the application of imported water (section 4.2) will still be susceptible to disruptions in water supply which can be potentially caused by events occurring outside of the island (i.e., in an area of water supplier or water source). Any disruption in the importation of water will force a drinking water authority of the planned island to resort to two possible potable water supply options:

- To supply reclaimed water, which can be treated (section 4.2.1) or not treated by drinking water treatment (section 4.2.2), as drinking water, or
- To suspended drinking water supply of the entire island until the importation will be resumed.

In the worst-case scenario, resolution of possible technical issues, such as pipe break or pump failure, can take days, thereby prolonging the supply of only reclaimed water as potable water or suspension of the entire drinking water supply. Also, these DPR water management strategies do not eliminate the risk of tunnel flooding in the case of water transfer pipe break.

The Baltic Sea seawater. The DPR water management strategies based on the seawater application as the 'compensating' water (section 4.1) may be susceptible to only water supply disruptions caused by sudden changes in quality parameters of the Baltic Sea seawater (section 3.2.1) but establishment of a submerged seawater intake system, dilution with reclaimed water, especially in the case of the augmentation of raw seawater with ATW (section **Ошибка! Источник ссылки не найден.**), and the compulsory application of technologies addressing dissolved matter should mitigate all issues related to sudden changes in a source water quality. Also, implementation of any of the seawater-based DPR strategies will not require establishment of a 15-km long water transfer pipeline (section 3.2.2), pump stations, and, in the case of partially treated or treated imported freshwater, drinking water treatment facilities, required to import water from mainland Finland.

Imported water and the seawater. In exchange for additional infrastructure (i.e., water transfer pipeline), the DPR water management strategies based on the simultaneous application of the seawater and imported water (section 4.3) can mitigate qualitative issues of the seawater and technical issues of imported water by establishing a lesser reliance on both of these waters. In the case of technical failures preventing supplementation with imported water, the island can maintain its potable water supply on remaining reclaimed water and the seawater. In the case of qualitative issues preventing abstraction of the Baltic Sea seawater, the island can rely on reclaimed water and imported water but, taking into consideration submerged seawater intake system, dilution provided by reclaimed water, and high degree of required drinking water treatment, qualitative issues related to the Baltic Sea seawater should play a minor role.

Possible unacceptable conditions of prolonged supply of reclaimed water as potable water or suspension of potable water supply, which can occur in the DPR water management strategies solely based on the application of imported water, and reduced infrastructural requirements of the DPR strategies solely based on the application of the seawater (in comparison with the described imported-water-based and seawater-and-imported-water-based DPR water management strategies) are favouring the selection of the latter one as the most suitable DPR water management strategy for the planned island.

4.4.3 DPR Scheme Configuration

As it was described in section 4.1, there are two possible seawater-based DPR scheme configurations which differ in the location of augmentation with reclaimed water (Figure 23 p. 35). Since both of the described seawater-based DPR scheme configurations can be theoretically and technically implemented on the island, the determination and selection of the most suitable configuration will be mainly based on:

- Public perception,
- Public health protection in the case of advanced water treatment and ESB monitoring failure, and
- Reallocation benefits.

The seawater-based DPR scheme configuration applying the augmentation of drinking water (derived from raw seawater) with finished water (section 4.1.2) is not providing any benefits of reallocation of certain treatment unit processes or operations between a drinking water treatment plant and advanced water treatment plant. In this strategy, reclaimed water (i.e., finished water) is not subjected to any additional degree of treatment (Figure 28 and Figure 29, pp. 39-40), thereby putting public health in the greatest jeopardy in the case of advanced water treatment and ESB monitoring failure. In comparison with the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW, this strategy will, most probably, incur a greater public opposition, despite the facts that an advanced water treatment plant will be permitted as a drinking water treatment plant and produced finished water will be compliant with all applicable drinking water quality standards. For these reasons, the seawater-based DPR scheme configuration applying the augmentation of drinking water with finished water will not be a suitable water management solution for the planned island.

The seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW (section 4.1.1) will incur a lower public opposition than the seawater-based DPR water management strategy applying the augmentation of drinking water with finished water since ATW will be blended with and diluted by raw seawater and the blend will be subjected to full drinking water treatment (Figure 24 and Figure 25 p. 36) incorporating treatment technologies addressing dissolved substances. Applied full drinking water treatment will provide the highest degree of public health protection in the case of advanced water treatment and ESB monitoring failure. Also, since both the seawater and wastewater treatment effluent require removal of dissolved solids, which can be provided by demineralization technologies, this DPR scheme configuration can employ only one high-performance demineralization unit located at drinking water treatment plant (Figure 26, p. 37), thereby reducing energy consumption of the entire scheme and expenses related to technical maintenance of demineralization processes.

For the reason that there are no operating DPR projects in Finland and the DPR concept will be relatively new, every factor increasing or decreasing public confidence in safety of potable water derived from wastewater must be considered very carefully. Subjection of ATW to blending with raw seawater and subsequent full drinking water treatment incorporating demineralization technologies will give more ground to public to be confident that potable water is safe to drink, wash, and cook. Therefore, the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW will be the most suitable DPR scheme configuration in the project setting.

5 SUMMARY

5.1 DPR and Linear Water Management Strategies

In comparison with all possible linear water management strategies, whether seawater-based, imported-water-based, or based on the simultaneous application of the seawater and imported water, which will be accepted by the general public without any issues since they represent a more traditional approach to potable water production and wastewater disposal, seawater-based DPR water management strategy offers the advantages which can help to easily overcome the impediments hampering implementation of the traditional linear water management strategies in the project setting. Such impediments are for example source water quality and its variation induced by natural or anthropogenic phenomena, establishment of unsustainable infrastructure with possible large carbon footprint, and increasing pressure of legislation related to discharge of wastewater treatment effluent.

As a water management solution, DPR will also be beneficial in the project setting since generated wastewater will most probably require a relatively high degree of treatment in order to prevent adverse impacts deteriorating the already impaired aquatic environment of the Baltic Sea. Therefore, discharge of effluent processed to a relatively high quality can be considered as a wastage of water.

The characteristics of the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant are as follows:

– Reduced withdrawal of the seawater,
– Application of the water remaining on the island,

- The program overseeing discharges of certain difficult-to-treat constituents into wastewater collection system,
- Enhanced wastewater treatment aimed to produce as 'clear' as possible effluent, and
- Advanced water treatment producing safe reclaimed to be reliably treated by drinking water treatment

These make the seawater-based DPR water management strategy superior to any linear water management strategy in terms of environmental issues.

5.2 DPR and IPR

IPR water management strategies will require the compulsory application of an environmental buffer (e.g., surface water body or groundwater aquifer) which must possess certain volumetric characteristics to provide dilution of reclaimed water with environmental waters and its retention in the buffer for a specified time period. The establishment of the buffer possessing such characteristics is unlikely in the project setting since the island is planned to have a relatively small land area and dense urban development. Conversely, the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW will only require the application of an ESB which can be incorporated within the treatment plants or in a variety of recreational objects. Also, as a water body, environmental buffer will require a certain degree of protection from contamination (possibly caused by littering or wild birds) which is not required for an ESB.

The limited land area and high-density development of the planned island will favour implementation of the DPR concept rather than the IPR concept.

5.3 In the Issuance

Island's potable water production and wastewater disposal opportunities are limited by the geographical and urban characteristics of the island, the qualitative characteristics of the aquatic environment surrounding the island, and the qualitative, quantitative, and geographical characteristics of the available water sources. These limitations make the concept of DPR and the seawater-based DPR water management strategy applying the augmentation of raw seawater with ATW upstream of a drinking water treatment plant a perfect water and wastewater management solution for the planned island.

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Comparison of the DPR scheme configurations described in the section 2.2

Augmented water (augmentation location)	**Section Figure**	**Degree of public acceptance**	**Degree of public health protection in the case of AWT and ESB failure**[1]	**Magnitude of blending impacts on DWT**[2]	**Reallocation of treatment elements between AWTP and DWTP**	**Required quality of produced reclaimed water**
Raw potable water (upstream of a drinking water treatment plant)	Section 2.2.1 Figure 10	High	High	High	Possible (Figure 11)	ATW (drinking water or raw potable water)
Treated drinking water (downstream of a drinking water treatment plant)	Section 2.2.2 Figure 12	Low	Low	None*	Not possible	Finished water (drinking water)

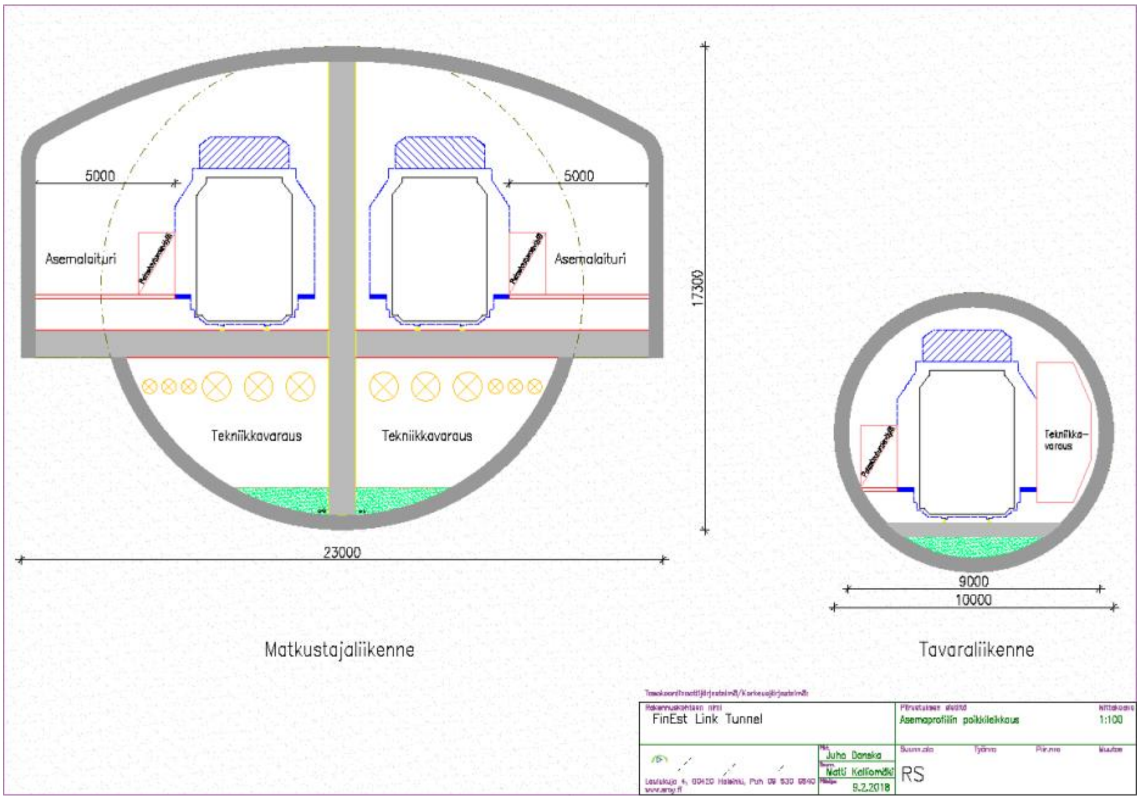
AWT – advanced water treatment, ESB – engineered storage buffer (monitoring), DWT – drinking water treatment, AWTP – advanced water treatment plant, DWTP – drinking water treatment plant, ATW – advanced treated water

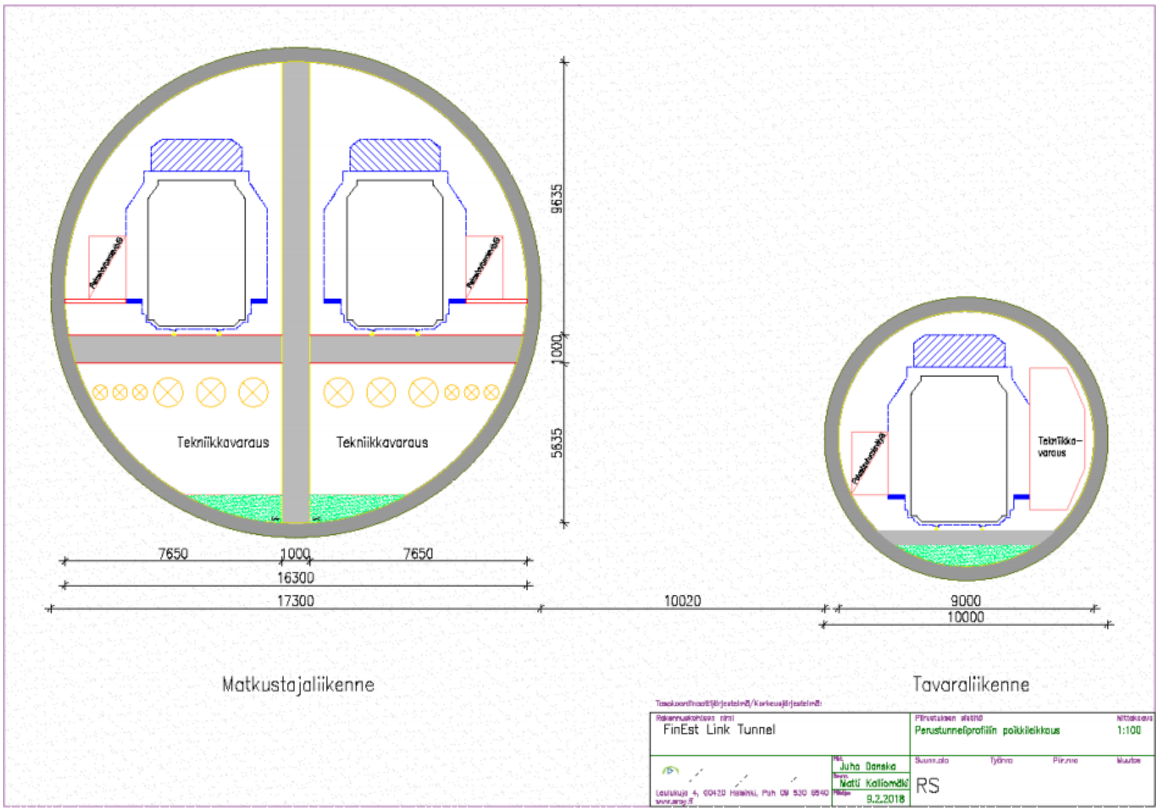
[1]Drinking water treatment is calibrated to a resultant blend quality and employs similar technologies as advanced water treatment. Otherwise, drinking water treatment may not have any effect.

[2]Drinking water treatment is only calibrated to a source water quality and not calibrated to a quality of reclaimed water and source water blend.

*Aesthetics issues induced by temperature difference can still be anticipated.

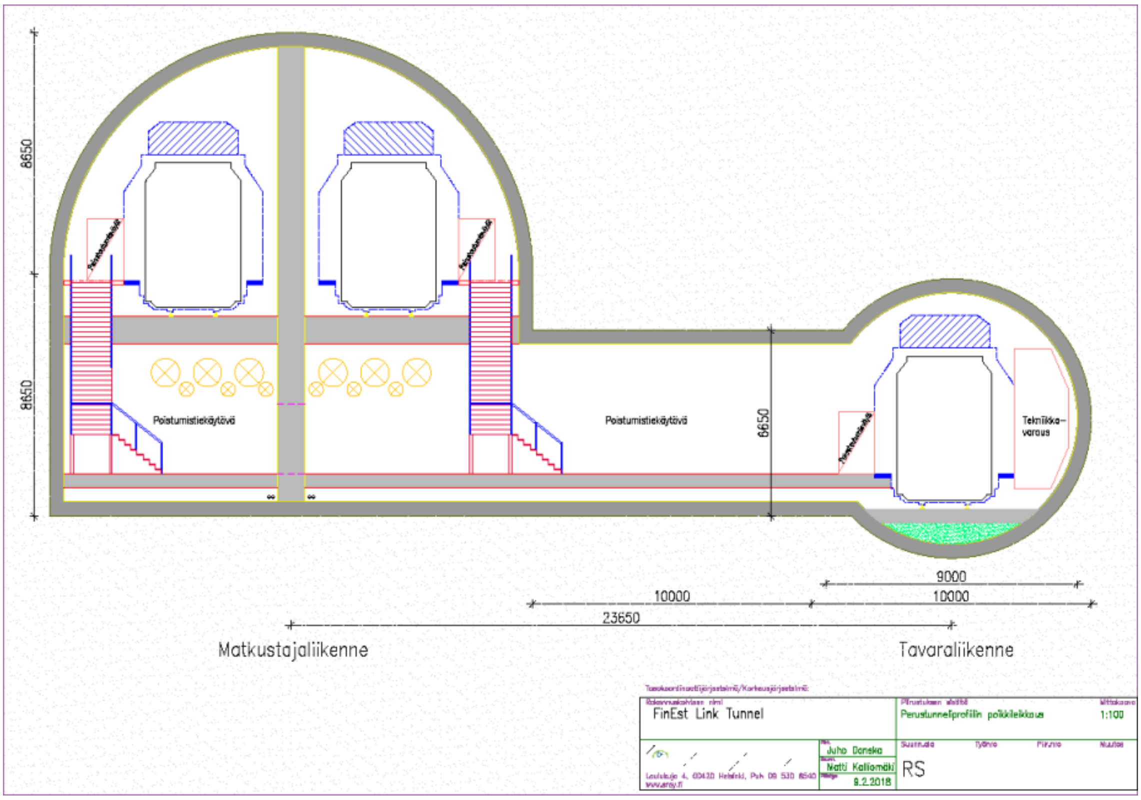
SCHEMATICS OF THE CONNECTING TUNNEL WITH POSSIBLE DIMENSIONS (Vesterbacka & Valtonen, 2018, p. 18) Appendix 2/1 (page 1)





SCHEMATIC DRAWINGS OF THE CONNECTING TUNNEL WITH POSSIBLE DIMENSIONS
(Vesterbacka & Valtonen, 2018, p. 18)

Appendix 2/2 (page 2)



SUMMARY: DESCRIBED LINEAR WATER MANAGEMENT STRATEGIES

Appendix 3

Summary for the linear water management strategies described in section 3.5

Linear water management strategy	**Section and figure**	**Drinking water treatment**	**Wastewater treatment**	**Advantages**	**Disadvantages**
Seawater-based	Section 3.5.1 and Figure 18	Desalination will be a compulsory requirement. Other treatment technologies will depend on exact quality parameters of the seawater.	Wastewater treatment effluent must possess quality which is protective of the Baltic Sea impaired aquatic environment and public health. Extensive nutrient and organic carbon removal will be a compulsory requirement. Most probably, requirements applied to wastewater treatment will necessitate relatively high degree of wastewater processing (up to tertiary treatment).	– Inexhaustible water source available on the permanent basis	– Poor quality of the source water – Possible quality fluctuations – Possible future quality deterioration
Imported-water-based	Section 3.5.2 and Figure 19	Will depend on exact quality parameters of imported water. – Raw imported freshwater will require full drinking water treatment. – Partially treated imported freshwater will require only certain treatment process(es) and/or operation(s). – Treated imported freshwater will require only disinfection.		– Source water quality can better than a quality of the seawater	– Susceptibility to disruptions caused by technical or operational failures – Possible 'competition' with other urban areas for available water – Water importation technical issues (pipeline maintenance, pumping) – Risk of tunnel flooding
Seawater-and-imported-water-based	Section 3.5.3 and Figure 20	Desalination will be a compulsory requirement. Other treatment technologies will depend on exact quality parameters of the seawater, imported water, or their blend.		– Mitigation of the disadvantages of the single-source strategies	– Same as those described for the single-source strategies but in a lesser extent

MAPS OF THE LOCATIONS OF DPR AND IPR PROJECTS AS OF 2017 (U.S. EPA, CDM Smith, Inc., 2017d, pp. 5, 7)

Appendix 4