Conceptual Upgrade Considerations for the Bridgetown Sewerage Treatment Plant

Consultancy to Produce Requisite Design, Studies and Plans – The 3R's for Climate Resilience Wastewater Systems in Barbados (3R Crew Barbados) Preparation Project

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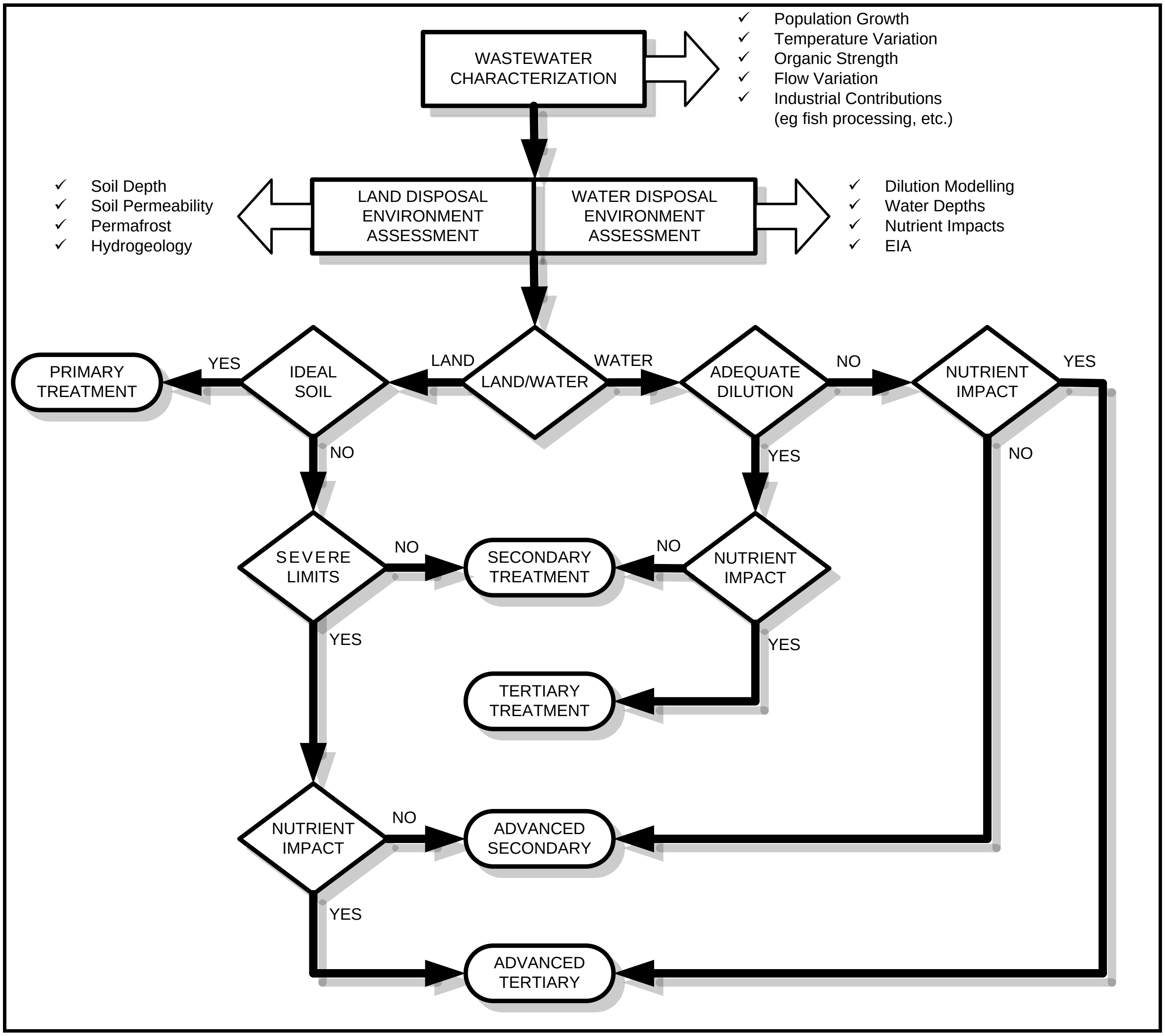
WASTEWATER CHARACTERIZATION
Population Growth
Temperature Variation
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WATER
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NO
NUTRIENT IMPACT
YES
NO
YES
NO
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NO
SECONDARY TREATMENT
NO
NUTRIENT IMPACT
YES
YES
TERTIARY TREATMENT
NUTRIENT IMPACT
NO
ADVANCED SECONDARY
YES
ADVANCED TERTIARY

DEFINITIONS

De facto reuse: Condition where the wastewater is unintentionally being reused (e.g., wastewater discharged to ground that becomes groundwater extracted for a drinking water supply).

Direct potable reuse (DPR): The use of reclaimed water as a raw water source for drinking water.

Indirect potable reuse (IPR): Intentional augmentation of a drinking water source by releasing reclaimed water with an environmental buffer between the discharge and drinking water extraction.

Non-potable reuse: All water reuse applications used to satisfy water demands that do not require potable water quality.

Potable reuse: Planned augmentation of a drinking water supply using reclaimed water.

Reclaimed water: Municipal wastewater that has been treated so that it can be beneficially reused to satisfy a wide range of specific water demands.

1 RESOURCE RECOVERY

Conventionally wastewater is treated and then discharged to the environment in a manner that "will do no harm". However, wastewater is more than 99.9 percent pure water, meaning it has value particularly in areas of the world impacted by climate change and drought. Reclaimed water can benefit agricultural production, reduce energy consumption, increase the availability and reduce the cost of potable water. It can also be a significant source of recovered nutrients and renewable energy. The drivers for reuse centre around three categories: 1) reducing the impact of urbanization on diminishing water supplies, 2) increasing the efficiency of resource utilization, and 3) protecting the environment and public health.

Wastewater management and reuse projects must factor in climate change and extremes that can affect water supply and make it inappropriate to use water only once and then dispose of it. Reuse practices will become increasingly common as the world's population continues to become increasingly urbanized and concentrated near coastlines, and climate change creates lengthy or intermittent periods of drought or impacts on wastewater collection systems from extreme precipitation events that overwhelm wastewater collection and treatment infrastructure. Water and energy are mutually dependent with energy production requiring large volumes of water, and water infrastructure requires large amounts of energy. A sustainable water management strategy is one where water resource management meets the needs of present and future generations. Water reuse reduces energy use by eliminating additional potable water treatment and associated water conveyance costs. Although additional energy is required to treat wastewater for reclamation, the amount of energy required for treatment and transport of potable water is generally much greater.

Climate change, resulting in increased high-intensity and duration surface runoff, can also create negative impacts from nutrient release into coastal waters, making nutrient reductions in wastewater effluent discharged to the ocean increasingly important. By eliminating effluent discharges through water reuse, the need for costly nutrient removal treatment processes can be reduced or minimized while protecting sensitive marine ecosystems.

Implementing water reuse programs can pose financial, technical, and institutional challenges in comparison to the conventional wastewater management approach to collect, treat, and discharge wastewater. An extremely wide range of advanced water treatment technologies have been developed over the past 50 years enabling any level of water quality to be achieved that is required for the beneficial use of reclaimed water, including addressing contemporary water quality issues related to emerging pathogens and trace organic and inorganic chemicals. As illustrated in Figure A, water treatment technologies offer a ladder of increasing water quality, and the choice of the level of treatment is dictated by the end application of the reclaimed water taking into consideration social, economic, and environmental sustainability dimensions. Choosing the right water quality level depends on the intended use, public health and the potential for public contact, and environmental factors – also referred to as a recognition of the "Fit for Purpose" framework to determine the most cost-effective level of treatment that is best suited for the intended reuse application(s).

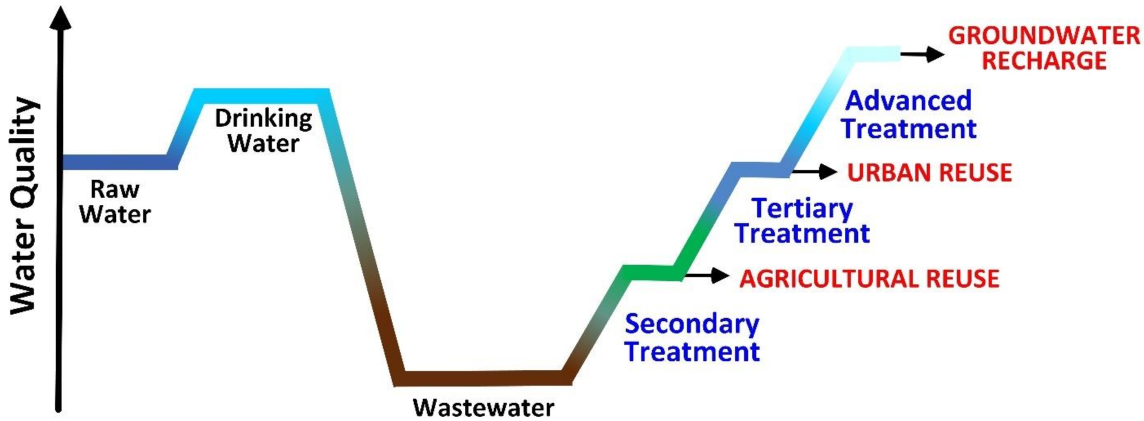


Figure A. Treatment technologies to achieve increased reuse water quality

Advances in wastewater treatment technologies now enable a wide range of resources to be recoverable from wastewater as illustrated in Figure B. The term sewer mining, pumping wastewater from sewers to serve as a source of water to meet non-potable water needs, has become so common that an internet search results in 31,500 hits.

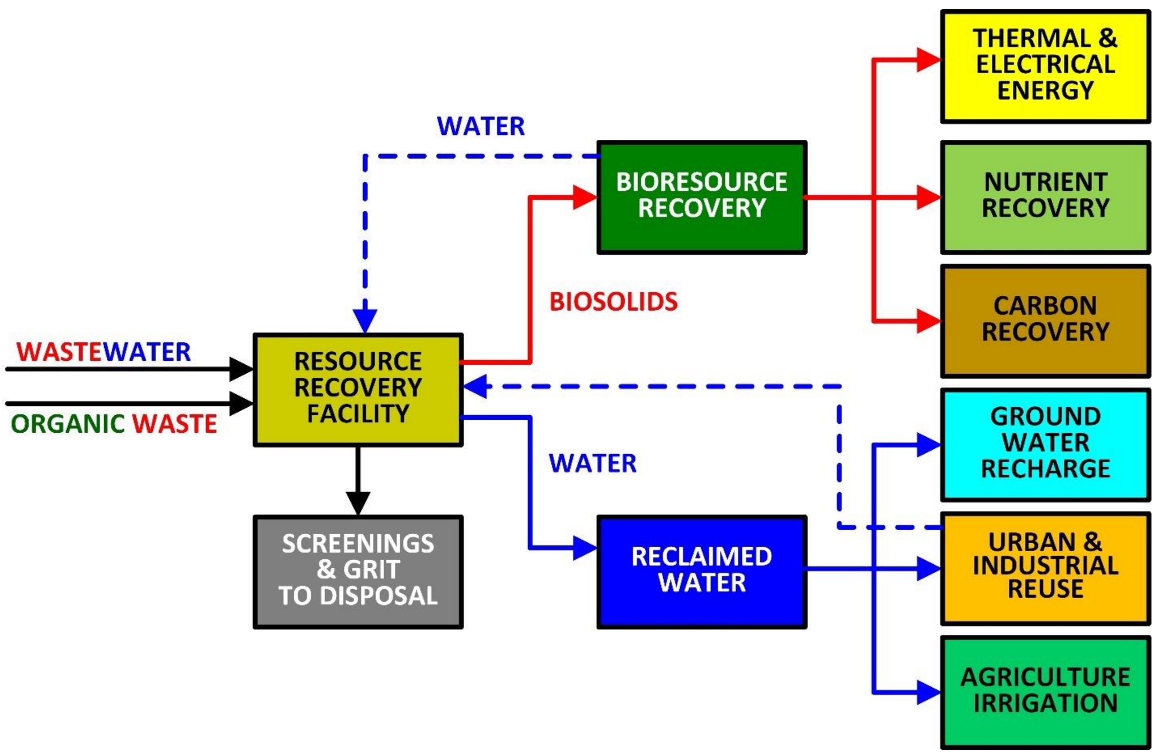


Figure B. Wastewater Resource Recovery Example Alternatives

2 RECLAIMED WATER

2.1 Public Education and Acceptance

What does a citizen in Windhoek, Namibia, a resident of Big Spring, TX, and the astronauts on the International Space Station have in common? They all reclaim their wastewater and use it for direct potable reuse (drinking water).

While the use of reclaimed wastewater to produce drinking water is quite uncommon, the technology to treat the water reliably to protect public health has existed for over half a century (Windhoek has been recycling wastewater into drinking water since 1968). The barrier to this "extreme" reuse application is not technology; it is public acceptance. The experience of US states who actively promote water reuse, as well as Australia, Singapore and Namibia, is that water reuse projects are only successful when citizens are genuinely included in the decision-making process. This includes public opinion regarding the water utility or other agency who is promoting the reuse project, and early public outreach to build trust in the community, with the dissemination of factual information beginning at the highest levels in the community. By engaging the support of key stakeholders, they can be later called upon to provide endorsements of water reuse.

Stakeholder engagement also includes the dissemination of information and public education. In some communities the water utility develops programs to provide educational support materials for teachers and participate in the delivery of public education programs and associated events that serve to educate students and increase general knowledge within the community about water, so they are able to make informed decisions, starting with the water cycle and basic facts about water use and measures in place to protect public safety before addressing water reuse. Australia has established an interactive Water Education Program for schools, including the development of manuals for teachers to use, that explores the connections between water and the environment including how pollution affects the health of community creeks, and an understanding of the intrinsic and utility (resource) values of water to society, with guidance on conducting inquiry-based learning opportunities.

2.2 Water Reuse Opportunities & Quality

Table A presents a description of the water reuse categories and applications that are typically considered or accepted in a broad manner internationally. The US and Australia have been leaders in advancing standards and regulations for water reclamation and reuse that protect both the environment and public health. Supported by public health risk assessment studies, the specific water quality criteria used for each category may vary slightly between jurisdictions; however, based on the committee work done by the ISO TC282 Water Reuse standards development committee since 2013, there is general consensus regarding acceptable applications and water quality parameter categories. For example, while different jurisdictions may use a different indicator microorganism to assess pathogen risk (e.g. total or faecal coliforms, and E. coli), reuse water applications with unrestricted public access are expected to be at a non-detect level.

Table A. Water reuse application categories (US EPA, 2012)

Water Reuse Category		Description
Urban Reuse	Unrestricted Public Access	The use of reclaimed water for non-potable applications in municipal settings where public access is not restricted.
	Restricted Public Access	The use of reclaimed water for non-potable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction.
Agricultural Reuse	Food Crops	The use of reclaimed water to irrigate food crops that are intended for human consumption
	Processed Food Crops and Non-food Crops	The use of reclaimed water to irrigate crops that are either processed before human consumption or not consumed by humans.
Impoundments	Unrestricted Public Access	The use of reclaimed water in an impoundment in which no limitations are imposed on body-contact water recreation activities.
	Restricted Public Access	The use of reclaimed water in an impoundment where body contact is restricted.
Environmental Reuse		The use of reclaimed water to create, enhance, sustain, or augment water bodies including wetlands, aquatic habitats, or stream flow.
Industrial Reuse		The use of reclaimed water in industrial applications and facilities, power production, and extraction of fossil fuels.
Groundwater Recharge – Non-Potable Reuse		The use of reclaimed water to recharge groundwater aquifers that are not used as a potable water source.
Potable Reuse	Indirect Potable Reuse (IPR)	Augmentation of a drinking water source (surface or groundwater) with reclaimed water followed by an environmental buffer that precedes normal drinking water treatment.
	Direct Potable Reuse (DPR)	The introduction of reclaimed water (with or without retention in an engineered storage buffer) directly into a water treatment plant, either collocated or remote from the advanced wastewater treatment system.

2.3 Wastewater Resource Recovery

As illustrated in Figure B, wastewater and "waste" in general contains valuable resources for which technology exists to extract and recovery for beneficial use. The figure considers two waste streams entering a resource recovery facility, wastewater and organic solid waste, both of which contain carbon-energy and nutrient (nitrogen and phosphorus) components that have recycle value. The resource recovery model could be expanded to include other community streams, but for the purpose of this document we'll focus on just these two and begin with the reclaimed water stream.

The three reclaimed water applications noted in Figure B, each have unique water quality requirements that represent the spectrum of what secondary, tertiary, and advanced water treatment technologies can achieve as illustrated in Figure A.

2.3.1 Agricultural Water Reuse

Agricultural water reuse reduces demands on fresh water sources, is a means of nutrient management and recovery, and results in a greater crop production reliability due to constant yields. However, wastewater needs to be adequately treated to be used for agricultural irrigation, especially for food crop irrigation, which is currently not allowed in Barbados, due to potential health risks.

Agriculture water demands have been met using secondary treated wastewater for over 100 years with great success, taking primary advantage of the water and nutrient content for seasonal plant growth that characteristically occurs during dry periods with diminished natural precipitation. While the state of Washington's 1992 Reclaimed Water Act formally established the state's commitment for the treatment and management of wastewater as a renewable water supply to replace drinking water for non-drinking (non-potable) purposes, the importance of wastewater to agriculture was legally established through a 1927 court-ordered water rights agreement that obligated the city of Walla Walla to provide reclaimed water to the agriculture irrigation districts. Currently, 42 US states have regulations and guidelines in place to permit reuse water to be used for non-food/processing crops and 28 states permit reuse water for food crop irrigation. Very few jurisdictions include chemical constituents in their agricultural water reuse standards.

Dissolved salts present in wastewater have the potential to affect the structure and ability of the upper soil layer to retain water and can have negative environmental effects on crops by increasing the soil water pressure and requiring more energy for plants to take up water from the soil. There are no inexpensive ways to remove the salts from the treated wastewater and in arid countries, such as Israel where the main contributor to the salinity in wastewater is the water-softening process used for the meat koshering process, measures have been developed to address salinity and facilitate the ability to reuse the wastewater for irrigation. In climates with high levels of seasonal precipitation, such as Barbados (and Walla Walla, Washington), the dissolved salt concentration in wastewater is generally not an issue.

Long a leader in water reuse (Title 22, 1918) California has established a Recycled Water Policy for irrigation applications that does not specify a water quality criteria but, rather, includes salt and nutrient management planning to help address the potential for recycled water use to impact groundwater quality and to promote salt and nutrient management planning (SNMP) only on those basins identified as "priority basins" by the United States Geological Survey (USGS) as part of their 2003 study of monitoring and assessment of California groundwater. The program components include a predominant element that is consistently applied in all basins, and a secondary element that may be applied in specific basins where local conditions warrant attention and is developed through a stakeholder driven process.

Where irrigation practices may result in salt accumulation in the topsoil, it is appropriate to address the salt and associated sodium adsorption ration (SAR) concerns through periodic flushing of the salt to below the root zone by a combination of rainfall and irrigation. Because of this, very few jurisdictions include total dissolved solids (TDS) in their irrigation reuse water quality requirements. None of the U.S. states include Electroconductivity (EC) or TDS thresholds in their agricultural water reuse regulations.

The government of Barbados is proposing to use a TDS requirement for irrigation of < 450 mg/L. This value is also referenced within the FAO User's Manual for Irrigation with Treated Wastewater, as summarized in Table B.

Table B. Irrigation TDS Restrictions (FAO, 1985)

Parameter	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
TDS	mg/L	< 450	450 – 2,000	> 2,000

The TDS values in Table B can be traced back to a single 8-page Technical Memo published by the University of California Committee of Consultants in 1974 regarding an irrigation study done in California, and subsequently adapted by R.S. Ayers and D.W. Westcot in their report titled "Water quality for agriculture" (1985).

The irrigation table produced by Ayers and Westcot in 1985 has since been referenced and re-referenced so many times that it has become a defacto standard used throughout the world, but none of those references relate back to the original paper or the *Water quality for agriculture* guidance document. What Table B means is that regardless of the nature of the soil or application, a TDS of less than 450 mg/L is inconsequential, and TDS concentrations of up to 2000 mg/L may have a slight to moderate impact on soil that can be managed or addressed. The authors provide this note on the potential use of the values shown in their table:

> *"The water quality guidelines in Table 1 are intended to cover the wide range of conditions encountered in irrigated agriculture. Several basic assumptions have been used to define their range of usability. If the water is used under greatly different conditions, the guidelines may need to be adjusted. Wide deviations from the assumptions might result in wrong judgements on the usability of a particular water supply, especially if it is a borderline case. Where sufficient experience, field trials, research or observations are available, the guidelines may be modified to fit local conditions more closely."*

Regarding the assumed site conditions applicable to the values in their table, Ayers and Westcot offer the following advice in the notes to Table 1 in their document:

> *"In a monsoon climate or areas where precipitation is high for part or all of the year, the* ***guideline restrictions are too severe****. Under the higher rainfall situations,*

infiltrated water from rainfall is effective in meeting all or part of the leaching requirement."

In other words, the TDS value used for irrigation should be based on location and site-specific considerations, including flushing by rainfall, and the proposed TDS limit of 450 mg/L is too low, and attempting to meet that value for irrigation purposes using RO is not a sustainable decision.

2.3.2 Urban and Industrial Water Reuse

The water quality requirements for reclaimed water for use in an urban environment for domestic, commercial, or industrial use under circumstances and reuse applications with a high probability of public contact are greater than required for agricultural irrigation practices and requires tertiary treatment. Tertiary treatment can produce a water quality that is safe for unrestricted public contact and typically has a very broad range of non-potable water uses including unrestricted urban irrigation of playgrounds and landscaped areas accessible to the public, toilet and urinal flushing, vehicle, and road surface washing, building cooling, etc. While tertiary treatment can include nutrient removal, it does require tertiary filtration to remove colloidal particles that cause turbidity and can interfere with disinfection efficiencies. As a consequence, chemical coagulation and media filtration, or the equivalent, has become the accepted sole technology requirement for urban water reuse treatment requirements, with the other requirements based on water quality limits as illustrated in Table C. In general, reuse water quality meeting the criteria noted in Table C can also be used agricultural food crops, including food crops consumed raw (ISO, 2015)

Table C. Unrestricted Public Access Urban Reuse Water Quality Standard

Parameter	Units	Reuse Water Quality Criteria
BOD & TSS	mg/L	$\leq$ 10 (average); $\leq$ 15 (Maximum)*
Turbidity	NTU	$\leq$ 2 (average); $\leq$ 5 (Maximum)
Indicator Bacteria	CFU/100 mL	< 1 (median); $\leq$14 (Maximum)
pH	-	6 - 9

2.3.3 Indirect Potable Reuse & Groundwater Recharge

Where there is a high expectation for the reuse water to become an indirect source of potable water, such as when the reclaimed water is discharged into a watershed used as a source of drinking water (e.g. Singapore), or used to replenish groundwater that is used as a source of potable water, advanced water treatment is carried out after secondary or tertiary treatment for the intent of remove contaminants of concern necessary to achieve a water quality suitable for potable water source augmentation or for direct potable reuse. Advanced treatment technologies include reverse osmosis (RO) membrane filtration and advanced oxidation processes, or the two technologies combined and referred to as Full Advanced Treatment (FAT). The difference between indirect potable reuse and direct potable reuse is the former involves having an environmental buffer (e.g. an aquifer, wetland, river, or reservoir) between the point of reuse water discharge and potable water extraction.

2.4 Nutrient Recovery

2.4.1 General

Additional treatment beyond secondary is referred to as tertiary treatment and is generally required if a discharge is into a receiving environment or an environmental control zone that can be impacted by either nitrogen or phosphorus. Nitrogen and phosphorus discharged into a fresh-water or marine receiving environment can cause excess nuisance weed and algae, and in extreme cases can result in fish mortality. Nitrogen discharged to ground can contribute to the build-up of nitrate in ground water, which can be a public health concern under certain circumstances.

Nitrogen and phosphorus removal can be achieved in a number of ways including biological and chemical treatment.

- Biological treatment is generally carried out using an activated sludge (suspended growth) treatment process, which has been compartmentalized into "environmental" zones, and in which bacteria can be conditioned to remove nitrogen or phosphorus, as illustrated in Figure C.

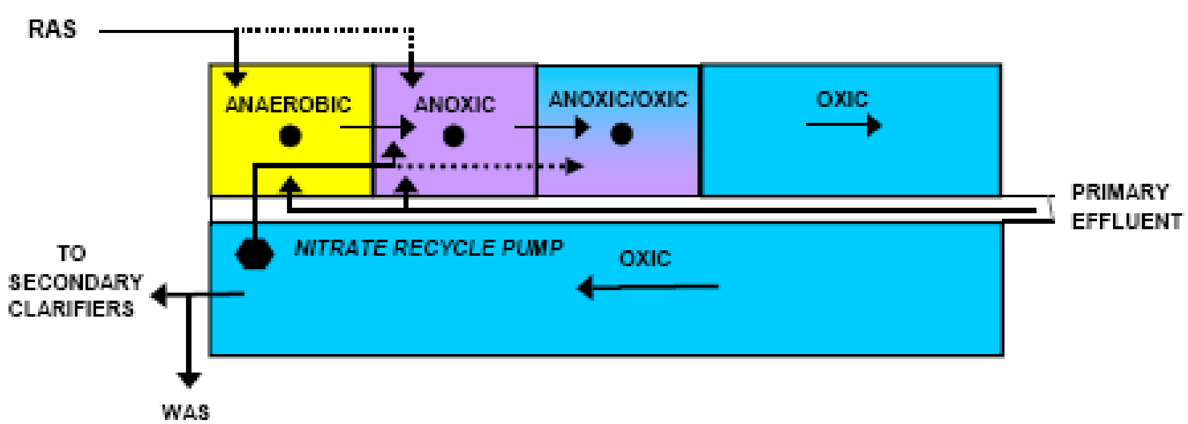


Figure C. Example Biological Nutrient Removal Process

- Chemical treatment is possible for phosphorus and ammonia removal. Phosphorus can be precipitated-out by adding specific chemicals to the wastewater, or by adsorption through a special filter. Ammonia can be removed with ion-exchange resins, or with zeolite. Chemical addition is not generally considered practical for small wastewater treatment applications.

There are three general environmental conditions that can be incorporated within a tertiary treatment process to determine the degree of nitrogen and phosphorus removal that can be achieved: 1) aerobic; 2) anoxic; and 3) anaerobic.

Aerobic conditions have a high oxygen content, result in the greatest rate of BOD5 reduction, and are essential to efficient biological treatment. Generally, oxygen is supplied as part of the atmospheric air that is bubbled into the bioreactor through an aeration device, but in some cases the oxygen can be provided through the use of pure oxygen, or by submerging the bacteria in the wastewater and then exposing them to atmospheric air (e.g. Rotating Biological Contactor).

Anoxic conditions have no dissolved oxygen present, but generally have other sources of oxygen (electron acceptors) available such as nitrate. Bacterial growth and BOD5 reduction is slower under anoxic conditions than under aerobic conditions, but the condition can be strategically incorporated into a bioreactor design for the purpose of removing nitrogen, as the nitrate present in solution is converted by bacteria to nitrogen gas, which is released to atmosphere.

Anaerobic conditions have no oxygen or nitrate present and are most commonly used to extract energy from biosolids by bacteria that can convert organic compounds into methane gas through anaerobic digestion. It takes much longer under anaerobic conditions for bioreactions to take place than for anoxic or aerobic conditions, so normally anaerobic conditions would be considered undesirable. However, about 50 years ago it was discovered that certain biochemical processes could be triggered by exposing bacteria to alternating aerobic and anoxic/anaerobic conditions including the biological removal of phosphorus and the growth inhibition of undesirable filamentous bacteria (excess filamentous bacteria can adversely affect secondary solids separation).

2.4.2 Biological Nitrogen Removal

Biological nitrogen removal can be simplistically described as a two-step bacterial process. First ammonia is converted by bacteria to nitrite (NO_2) and then nitrate (NO_3), under aerobic conditions, through a process called nitrification. Then a second group of bacteria convert the nitrate (NO_3) back to nitrite (NO_2) and then to nitrogen gas (N_2) under anaerobic or anoxic conditions (without oxygen), through a process called denitrification. The nitrogen gas is then released to the atmosphere. In fact, there are bacteria that can complete the full nitrification process, others that can compete the full denitrification process, and still other that can bypass most of the nitrogen conversion and combine ammonia and nitrite to form nitrogen gas. Needless to say, it is a complicated process that characteristically requires a high degree of operator knowledge and training.

Nitrification is accomplished by a group of aerobic bacteria that use carbon dioxide as a carbon source (i.e. they do not need organic matter as measured by BOD_5), and which perform best under conditions of high dissolved oxygen. They do not compete well with bacteria that aerobically consume BOD_5. Consequently, efficient nitrification occurs under low BOD_5 conditions (generally less than 15 mg/L), and any aerobic advanced secondary treatment process (i.e. achieving a BOD_5 of less than 10 mg/L) would be expected to have a high degree of nitrification with up to 95 percent of the ammonia being converted to nitrate.

Denitrification is accomplished by another group of facultative bacteria that require an organic carbon source (BOD5), but do not require oxygen for growth. This group of bacteria (actually two groups) can use nitrate (NO3) and nitrite (NO2) as an electron source instead of oxygen. From a process perspective, this is usually accomplished by recirculating treated nitrified wastewater back to the front of the plant into a tank that has no oxygen source and is fed raw wastewater. In small package plants the recirculated wastewater may be returned to the septic tank, or a non-aerated tank following the septic tank.

Because of the need for flexible operation and control, most nitrifying and denitrifying tertiary treatment plants are based on multi-chambered suspended growth (e.g. activated sludge, SBR, etc.).or hybrid (e.g. MBBR) process technologies.

Alternatively, a post-denitrification process configuration could be used to convert nitrate to nitrogen gas. This requires applying an external source of carbon (such as methanol) to the treated (nitrified) effluent under carefully controlled conditions with minimal (ideally no) dissolved oxygen levels. The need for chemical addition, control, online monitoring, and operator attention makes such systems unsuitable for individual onsite or small decentralized application. If excess carbon source is added, the process can also result in failing the effluent BOD_5 criteria.

Although it is possible to reduce the total nitrogen concentration in effluent to less than 3 mg-N/L, this requires a significant degree of operator attention and optimization. A more practical expectation for individual onsite and small decentralized systems is a total nitrogen effluent concentration of 10 mg-N/L.

2.4.3 Biological Phosphorus Removal

Biological phosphorus removal requires a similar process configuration and conditions as biological nitrogen removal. Although it can be accomplished with only a two stage (tank) process (anoxic/oxic), generally multiple reactors and recirculation lines are required for optimal removal efficiencies. Like biological nitrogen removal, biological phosphorus removal is typically accomplished using suspended growth treatment processes. This is because the bacteria responsible for enhanced biological removal (i.e. in excess of growth requirements) need to be subjected to alternating anaerobic and aerobic environments, and be readily removed from the process along with the consumed phosphorus. Even if attached growth bacteria could be conditioned to remove excess phosphorus, it would not be practical to remove the attached bacteria from the process. However, some process configurations have been proposed and tested, with some degree of success, which incorporate fixed film and suspended growth processes. However, the fixed film process component is not responsible for biological phosphorus removal.

Although it is possible to reduce the total phosphorus concentration in effluent to less than 0.2 mg-P/L in large treatment plants, this requires a significant degree of process complexity, operator attention, control sophistication and solids handling capacity, and may require the supplemental addition of chemicals. Consequently, it is not practical to expect an individual household system or small decentralized system to efficiently and or consistently remove phosphorus biologically.

2.5 Sustainable Energy Recovery

Biosolids produced by wastewater treatment processes represent a valuable source of renewable energy. Biosolids include primary wastewater organic solids and the secondary bacteria that are grown and produced within the biological treatment process. Climate change concerns combined with fuel cost spikes and increased public awareness for the value of renewable energy sources. Numerous technologies exist that can be used to reduce a wastewater utility's net energy consumption and recover energy by using biosolids as well as through co-digestion of organic animal and food waste. Through anaerobic digestion, these organic materials can be converted to biogas comprised of methane and carbon dioxide (CO2), and the methane can be collected and combusted for use in process heating as well as other benefits when coupled with CHP systems. This displaces the need for fossil-fuels and increases power reliability. Biosolids typically contain about 8,000 British thermal units per pound (Btu/lb) on a dry weight basis (2.3 kWh/lb) - similar to the energy content of low-grade coal. Energy can be realized through two pathways: biodegradation (biological conversion of organic matter to methane); and 2) thermal conversion (including incineration, gasification, and pyrolysis).

Biodegradation to recover energy involves anaerobic digestion in which biodegradable portion of the volatile solids is converted to methane (60-65 percent) and CO_2 (35-40 percent). Biogas can be collected and converted to electricity using onsite power generation equipment (engine generators, turbines, or fuel cells). Residual heat from power generation can also be collected and used to increase the digestion temperature overall efficiency of the process. Biogas production can be increased through co-digestion with other organic biodegradable feedstocks such as fats, oils and grease wastes from restaurants and waste food.

2.5.1 Nutrient (Fertilizer) Recovery

The development over the past 60 years of biological nutrient removal (BNR) processes that can remove large quantities of phosphorus from wastewater that is far greater than that required for cell growth has created opportunities to recover nitrogen and phosphorus as a fertilizer product, generally in the form of struvite crystals. When the waste bacteria from these processes are digested, high concentrations of phosphorus and ammonia are released from the cells during dewatering processes and can result in the formation of precipitates within the treatment system that can cause damage to the process equipment and block pipes. The uncontrolled discharge of high concentrations of nutrients into receiving waters can cause a serious deterioration in water quality.

A successful approach to address this problem is to add magnesium to the filtrate to form magnesium-ammonium-phosphate (struvite). These crystals can also form and grow rapidly in the kidneys (kidney stones) of humans and animals. However, in a controlled environment they can be precipitated in a relatively pure form and harvested, producing a valuable multi-nutrient slow-release fertilizer for agriculture use, and it is estimated that approximately 15,000 tons of struvite are produced annually in Europe from wastewater (Huygens, et al, 2019),

3 TECHNOLOGY SELECTION

There are a wide and full spectrum of water treatment technologies that can be considered for any level of treatment or water reuse application. The selection depends on social, financial, environmental and technology sustainability dimension considerations and stakeholder values. One method of technology selection is to consider the following factors:

3.1 Land Availability (2 Extremes)

3.1.1 Large Area of Land Available

As a general rule, the greater the amount of land required to implement a technology, the more robust its performance and the simpler it is to operate. A classic example of a large treatment process is a lagoon or wetland system. Treatment is carried out through natural biological and physical/chemical processes over a very long period of time (months to years). Lagoons require little to no operator involvement and are very insensitive to changes or variation in influent wastewater flows or chemical concentrations but, on the other hand, there is little to nothing an operator can do to adjust or optimize the lagoon treatment performance.

3.1.2 Small Area of Land Available

Limited land availability generally means a more complex plant process and equally complex operating requirements. As municipal wastewater treatment is fundamentally based on biological processes, the primary objective for treatment is to maximize the amount of bacteria present in the treatment process to do as much treatment as possible in the limited space. This generally means selecting a technology that can "house" large amounts of bacteria (e.g. moving bed biofilm reactor – MBBR) or retain and increase the concentration of suspended bacterial cultures (e.g. membrane bioreactor – MBR). The two technologies can achieve a similar level of treatment using the same amount of land, but they have distinctly different operating characteristics. Because the MBBR process is an attached growth process, there is much less an operator can do to optimize the process performance other than to add or subtract the amount of media available for bacterial growth. On the other hand, the suspended growth nature of the MBR process provides a high degree of operations flexibility to adapt to changing wastewater characteristics but cleaning (anti-fouling) the membranes adds to the operational complexity, and the energy and chemical cleaning requirements for the MBR process are much greater than for the MBBR process. MBR process can provide a superior degree of turbidity removal, but also have a disadvantage of having a very narrow range of hydraulic flexibility.

3.2 Reuse Water Quality (3 Representative Non-Potable Water Applications)

3.2.1 Agricultural Irrigation and Environment Dispersal (Secondary Treatment)

As noted above, agricultural irrigation is generally accepted to only require secondary (biological) treatment and modest levels of disinfection if the agricultural crop being irrigated is reasonably remote from urban areas and homes. While the interim proposed irrigation TDS concentration criteria of < 450 mg/L can't be met with secondary treatment, as noted in the discussion above that represents an irrigation TDS condition which has "no" agricultural consequence or concern, and the value, in being borrowed and echoed repeatedly over the years since it was first postulated fifty years ago, has been taken out of context. TDS concentrations of up to 2,000 mg/L have only a slight to moderate risk of damaging soil over many years "if" the salts are expected to accumulate. However, the high precipitation events that occur from September through December are expected to flush the salts from the root zone and prevent accumulation within the soil.

3.2.2 Urban Unrestricted Public Access Water Reuse (Tertiary Treatment)

In combination with agricultural irrigation applications, urban water use presents a wide range of year-round non-potable water use applications and can have a significant impact on conserving potable groundwater resources. A major drawback, however, is the cost of distributing the reclaimed water into the community for non-potable use, and the complete lack of dual plumbing systems to be able to safely distribute and use the reclaimed water within buildings. This challenge can be overcome by considering a decentralized approach to expanding wastewater services in Barbados. Decentralized treatment technologies exist to treat and reclaim wastewater from groups of buildings and even individual homes, thereby significantly reducing or eliminating the need to construct non-potable water distribution systems. This is similar in concept to the current reclaimed water treatment systems currently deployed by some hotels in Barbados, which reclaim the water and reuse it within the hotel complex or golf courses. An urban water reuse strategy could be developed for an optimal combination of decentralized, cluster and centralized water reclamation and reuse applications, with the centralized reclaimed water being transmitted and used for agricultural irrigation or industrial use (i.e. lower cost of reclaimed water transmission).

3.2.3 Indirect Potable Water Reuse & Groundwater Recharge (Advanced Treatment)

Whether advanced treatment is required for water that is to be discharged to ground depends on the proximity of the discharge to potable wells, and the amount of advanced treatment or renovation expected as the water moves through the aquifer. If the treatment facility is able to achieve a water quality suitable for urban water reuse applications and is not discharged in the immediate vicinity of potable water wells, then there may be no need for advanced water treatment. However, if indirect potable water quality considerations are warranted, it is recommended that reverse osmosis (RO) membrane treatment be avoided, and advanced oxidation technologies be considered instead. The RO process only serves to separate and partition contaminants of concern from the product water and generates a large quantity of reject water (typically from 25 - 40 percent of the water treated), or brine, containing the impurities that requires disposal. Advanced oxidation, on the other hand, is expected to oxidize and destroy complex organic compounds, destroy pathogens, and oxidize and precipitate inorganic compounds (e.g. metals). An advantage of discharging to ground is that a marine discharge is avoided, and the natural processes within the soil can attenuate residual contaminants.

3.3 Wastewater Technology Considerations (3+ Processes)

3.3.1 General

Wastewater treatment essentially mimics natural biological treatment in a manner that maximizes and optimizes the rate of contaminant remediation that would occur in the environment so that it can be addressed in a much smaller area and can be controlled. The primary target of municipal wastewater treatment is the biodegradable organic content that, if released to the environment, could overwhelm the natural attenuation capacity and create unacceptable impacts such as dissolved oxygen depletion within the aquatic environment. This organic material also interferes with the ability to disinfect the water and remove or decrease the health risk associated with pathogenic (disease causing) parasites, bacteria and viruses.

The second-tier target for municipal wastewater treatment is the removal of nutrients (nitrogen and phosphorus) that are present in high concentrations in wastewater and could promote excess biological growth in aquatic systems, including the proliferation of algae and weeds. The excessive growth of algae and weeds is often noted by the general public and related to pollution as a nuisance, but it also has a significant potential to overload the ability for natural attenuation of decaying organic matter resulting from the inevitable death and decay of the algae and plants. Excess nutrients can also stimulate undesirable changes in the receiving environment ecosystem resulting in, for example, the destruction of coral reefs. Caribbean waters are particularly sensitive to nutrient loading.

While phosphorus can be removed through chemical precipitation, nitrogen is removed biologically through a series of biochemical reactions involving a wide range of bacteria and environmental growth conditions. Over the past 50 years there have been great advances in the biological removal of both nitrogen and phosphorus, and in the ability to recover these nutrients to produce fertilizers that can be collected and used for plant propagation either as a by-product of the treatment process or through land-application of nutrient-rich dewatered bacteria that are grown in the treatment process (biosolids) and applied to land.

As a consequence, municipal wastewater treatment processes are based on establishing optimal growth conditions for bacteria under specific environments conducive to removing organic matter and/or nutrients. Aerobic bio-oxidation respiration is the most rapid means of organic matter reduction and results in converting the organic matter into a by-product of bacterial cells (biosolids) which then must be removed and digested to reduce the quantity of biosolids and potentially recovery energy and nutrient by-products through a separate biosolids management process.

To be able to treat organic waste in a small area requires a process that can concentrate the bacteria available to achieve a faster rate of treatment than would be achieved in the environment with much fewer bacteria.

There are two primary types of biological treatment, classified by the manner in which the bacteria present come into contact with wastewater and are retained within the process: 1) suspended-growth; and 2) attached-growth.

In suspended-growth systems the bacteria that are retained within the bioreactor for treatment are kept in suspension by the mixing energy applied to the bioreactor, either through aeration or mechanical mixing. A secondary clarifier, dissolved air flotation unit or membrane is used to retain the bacteria within the system, and the bacteria are then returned to the bioreactor. This type of system is called an Activated Sludge process, because the bacteria returned to the bioreactor have been without food for some time and are "activated" (hungry).

In attached-growth systems the bacteria are retained within the bioreactor as clusters attached to the surface of material retained in the bioreactor. One such attached growth process is the Moving Bed Bofilm Reactor (MBBR) process, an attached growth process in which the bacteria grow attached to small plastic media that is mixed and kept in suspension by aeration. Because the mass of bacteria attached to the MBBR media is much greater than is possible to be retained in a suspended growth process, there is no need to return bacteria to the bioreactor. Other forms of attached growth processes include trickling filters, recirculating biofilters and rotating biological contactors.

Both approaches have unique advantages and disadvantages that are highlighted in the following sections, primarily related to the technology used to build up and maintain the bacterial population, the ability for operators to modify the technology dynamically to adapt to variable wastewater characteristics, the amount of energy required, and the ability to customize the process to maximize nutrient removal and/or energy recovery.

A third technology is considered in the following process description sections that is essentially a hybrid process, combining both suspended and attached biofilm growth properties, and is referred to as a granular activated sludge process.

Lastly, there are a number of treatment processes which have been developed based on the concept that natural treatment or attenuation involves a number of adaptive and complex natural ecosystems, and that a plant-based treatment process that emulates a natural treatment process can provide a better more comprehensive level of wastewater treatment. While there is no doubt that the natural environment provides better and more comprehensive treatment than a mechanical process can achieve, natural systems require a much longer period of time to achieve the same level of organic contaminant reduction than an aerobic biological treatment process. Examples of such natural treatment processes include natural and artificial (aerated) lagoons and wetland treatment systems; however, this report provides a description of a plant-based system housed in an aesthetically pleasing green-house structure that is combined with a suspended growth process and membrane filtration technology that is being applied to meet unrestricted-access reuse water quality standards in Sechelt, British Columbia, Canada.

3.3.2 Suspended Growth Processes

Suspended growth wastewater treatment processes involve growing bacteria in a completely mixed tank to prevent them from settling out while they are treating the wastewater, and then separating the bacteria from the treated liquid, and recycle the bacteria back to the bioreactor to build up the bacterial population and maximize the amount of treatment that can be achieved. This type of process that recirculates or returns bacteria is called an activated sludge process. Conventional activated sludge processes use gravity clarification to separate the bacteria from the treated effluent, like the current treatment process in Bridgetown. The limitation of the process is related to the effectiveness of the clarification process, as the system reaches a condition or bacterial population that interferes with the clarification efficiency.

Over the past forty years an alternative method to separate the bacteria from the treated effluent has evolved referred to as a Membrane Bioreactor Process (MBR). The MBR process eliminates the clarifier and replaces it with a series of membranes that let water though but hold back bacteria. This allows the process to retain more than double the amount of bacteria than a conventional activated sludge process, and enables the plant size to be reduced while also achieving a highly filtered effluent. Because MBR processes retain more than twice the number of bacteria that conventional activated sludge processes retain, MBR systems typically require twice the amount of electricity or power in comparison to conventional wastewater treatment processes. Overall energy costs in in the order of $0.6 kWh/m3 for an MBR process.

While a MBR process typically produces a higher quality effluent than a conventional activated sludge process with respect to biochemical oxygen demand, suspended solids, and turbidity concentrations; it also has a higher capital and operating cost and inherently limits the maximum wastewater flows to the capacity of the membrane filters to filter water.

Because the ultrafiltration membrane is capable of rejecting ultra-fine colloidal particles, the head loss across the membrane is fairly high and suction (negative pressure) is required to draw water through the membrane. The rate at which water can be drawn per unit of membrane surface area is referred to as the membrane flux and is the limiting factor in determining the quantity of water that can be filtered,

As water is drawn through the membrane, bacteria and other solids accumulate on the surface, impeding flow or flux, and increasing the head loss through the membrane. The increasing surface solids reduces permeability and greater pressure, or vacuum is required to maintain the flow rate. In order to clear the surface of the membrane of solids and reduce the head loss across the membrane, the pressure across the membranes is reversed, or back pulsed, at regular intervals as shown in Figure D. The membranes require vigorous aeration to keep the membranes from fouling and remove solids from within the group of membranes, requiring a significant amount of energy.

However, permeability isn't fully recovered following the back-pulse due to a gradual increase in precipitates that form within the membrane, and eventually the membrane requires chemical cleaning to restore permeability. At small facilities membranes are cleaned at least every six months using sodium hypochlorite (bleach). The membranes may have to be lifted, inspected, washed, and then placed in the dip tank for 24 hours, and damaged membranes repaired or tied-off. Alternatively, the membranes may be cleaned in place, depending on the manufacturer. The membranes are also periodically cleaned with citric acid. The high membrane-fouling environment results in low membrane flux rates and the need for large membrane surface areas and a very low peak flow tolerance. As a consequence, a large equalization volume is required to maintain uniform membrane flux rates under variable flow conditions, and a large amount of energy is required to provide a sufficient air flow past the membranes to keep them clear of solids. The high bacterial concentrations also impacts and reduces the oxygen transfer efficiency within the bioreactor, increasing the amount of energy required to maintain required dissolved oxygen conditions.

While chemical cleaning can recover most of the head loss through the membrane, the amount recovered by chemical cleaning gradually reduces as a result of irreversible fouling. After many cycles, and typically about 7 to 10 years, the irreversible fouling is so great that the membranes need to be replaced.

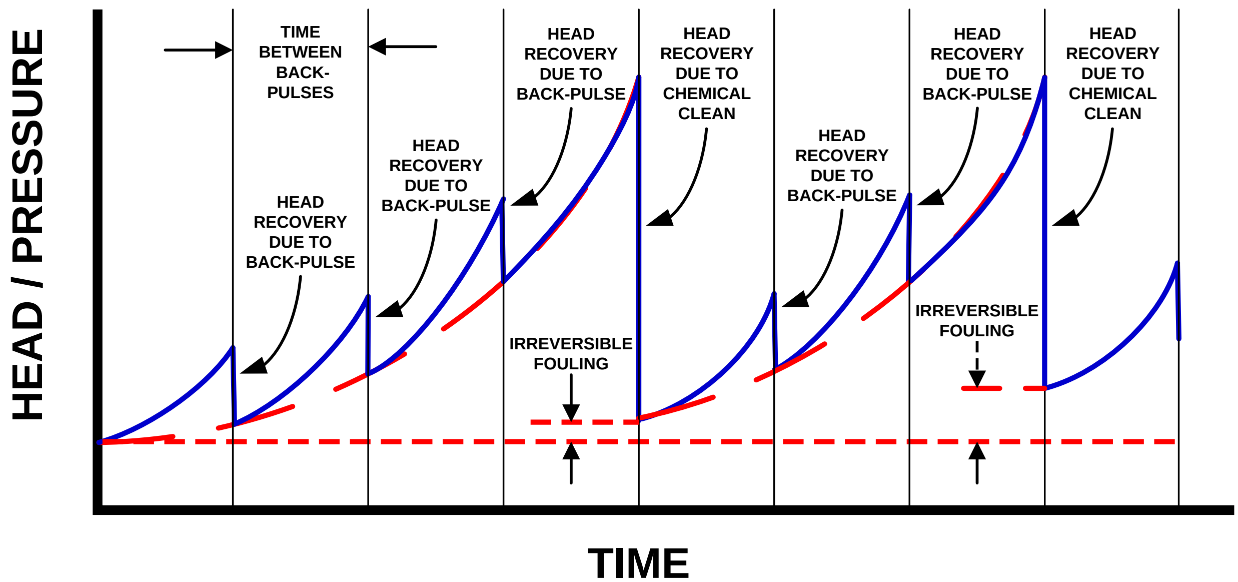


Figure D. Effects of Back-Pulsing and Chemical Cleaning on Membrane Recovery and Fouling

Membrane bioreactors also require a high degree of preliminary treatment including fine screening that also ends up removing a substantial amount of untreated organic waste solids that must be disposed of and is more expensive than the screening required for a more conventional, suspended growth treatment process. Membrane systems also require high efficiency pre-treatment to prevent debris such as plastics, rags, wire, fibrous materials, sand, and grit from entering the bioreactor and getting tangled in the membranes. This material is not only an operational challenge with respect to having to clean the membranes, but the debris and grit can tear and abrade the membranes, damaging them and reducing their life-expectancy. Hollow-fibre membranes are particularly sensitive to damage as a result of the entanglement of the debris. The debris in the fine hollow-fibre membranes can be forced through the membrane when they become entangled and are dragged by the air moving through the membrane, and the membranes can also be damaged by attempts to clean the debris from the membranes.

3.3.3 Attached Growth Processes

The attached growth process that is being considered is referred to as a Moving Bed Biofilm Reactor (MBBR) process. The support media in an MBBR process creates a higher percentage of protected surface area for microorganisms to adhere to and propagate. This feature results in increased levels of overall biomass concentrations inside the reactor and the reduction of the reactor's volume required for the biodegradation of organic matter in the influent. MBBR processes are typically very easy to operate and do not have solids separation problems nor do they have to incorporate membrane technology to achieve a clear effluent. Daily operation is less complicated than for a MBR activated sludge suspended growth process and can be more readily automatically controlled and executed by the operator through a PLC.

Polyethylene carriers such as the media shown in Figure E, are used to a maximum fill of 60 percent of the reactor volume. The process includes the installation of screens at the discharge end of the bioreactors to prevent the suspended carriers from being washed out of the bioreactor and supplying air lances to assist in breaking up media should it become locked. Provision may also be required to be able to add or extract media from the bioreactor tanks to adjust for seasonal loading conditions. It is expected that additional aeration will be required to keep the media mixed than would be required to maintain suspended growth mixing conditions. Accordingly, additional aeration capacity may be required.

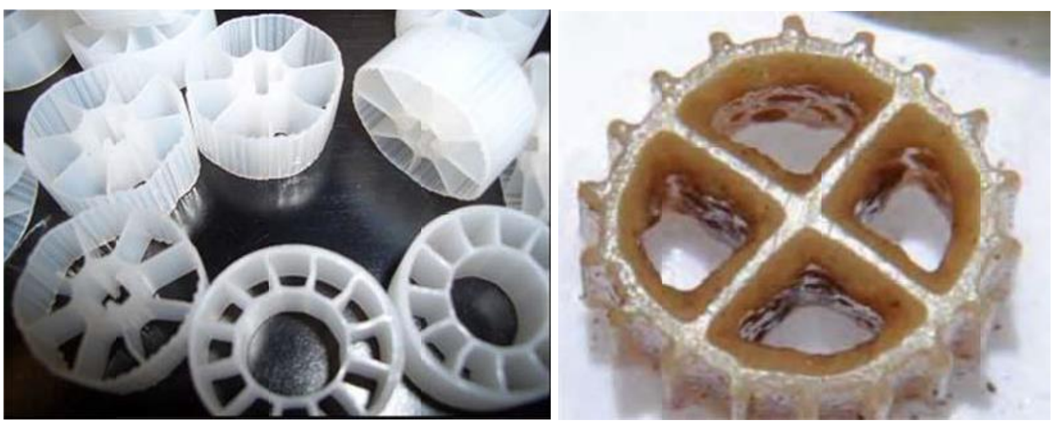


Figure E. MBBR Media Examples - New Media (left photo) and with Biofil Growth (right photo)

3.3.4 Hybrid Process – Granular Activated Sludge

The granular activated sludge process is a form of activated-sludge suspended-growth process that is able to retain a large sludge mass similar to that achieved by an MBBR process but without the need for support media and while being able to achieve both total phosphorus and total nitrogen removal (including low effluent ammonia concentrations) and increase the overall capacity of the plant to remove BOD. The granules result in a biomass that settles rapidly (SVI ~ 20) and enables the existing bioreactors to carry up to 10 times the MLSS biomass (up to 35,000 mg/L) while eliminating the need for secondary clarification – as the bioreactors operate as sequencing bioreactors. The concept of a sequencing batch reactor is illustrated in Figure D, which illustrates how a single tank serves as both a bioreactor and clarifier.

The granular nature of the biomass not only enables settling to occur rapidly, but also facilitates simultaneous nitrogen and phosphorus removal within an aerobic bioreactor.

Laboratory studies indicate a potential to grow stable aerobic granules under a feast/famine regime at high dissolved oxygen concentrations (Beun et al., 1999, 2000; Etterer and Wilderer, 2001; Tay et al., 2002). However, maintaining high oxygen concentrations requires a high energy input and may be economically unfeasible. Moreover, the design of a compact installation is based on the possibility of simultaneous nitrification/denitrification (SND) within the granules (Beun et al., 2001; De Bruin et al., 2004), which can occur at moderate oxygen concentrations.

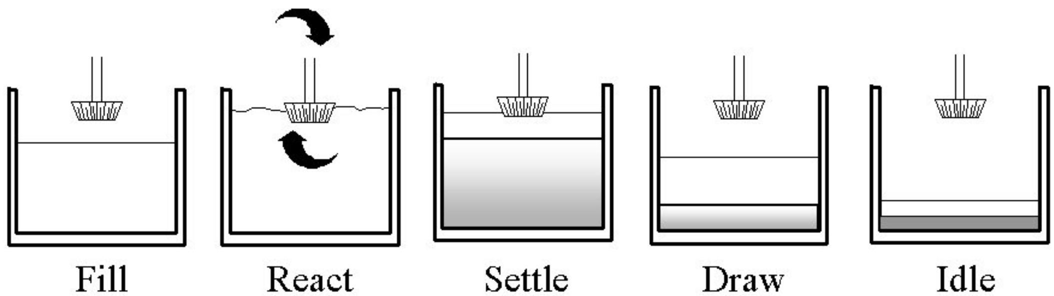


Figure F. Sequence of Reactions in a Single Sequencing Batch Reactor

3.3.5 Plant-Based (Aesthetics & Education)

The idea of wastewater treatment facilities could look like greenhouses typically captures the imagination of the average person. Often a treatment facility has very little aesthetic appeal, consisting of concrete tanks filled with bubbling brown coloured liquid. In contrast, there are a number of wastewater treatment process technologies that have considerably greater visual appeal and aesthetics, appearing to be greenhouses. While their underlying treatment technologies are based on very conventional bacteria-based treatment processes, the plants and greenhouse structure above the conventional infrastructure convey a considerably superior impression to visitors and nearby property owners.

Figure G. Water Resources Centre in Sechelt, Canada

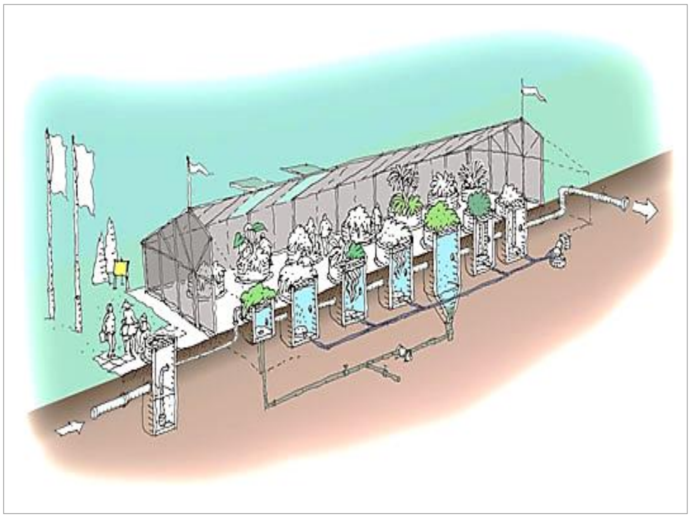


Figure H. Greenhouse Structure over an Activated Sludge Process

This impression is evidenced by the photo shown in Figure A of the Sechelt "Water Resources Centre", demonstrating that conventional ugly-looking sewage treatment plants can be presented in such a manner as to have the neighbouring residences across the street feel their property values have increased. Treatment is achieved using a conventional suspended growth sequencing-batch-reactor (SBR) enclosed within an appealing greenhouse environment. In addition to meeting the most stringent reclaimed water standards in the province, the treatment process also incorporates ultrafiltration membrane and granulated activated carbon filters that remove pharmaceuticals, endocrine disruptive compounds, and other unregulated contaminants that are of emerging concern, and recovers thermal energy from the treated water before being released from the treatment facility. The visual appeal is such that the District of Sechelt, the municipal authority that operates the treatment facility, received numerous requests for groups to have receptions in the building's conference area that overlooks the greenhouse area. What visitors are unaware of is that the plant roots dangle into tanks containing wastewater that is undergoing bacterial treatment.

The concept of a "greenhouse" or "plant-based" treatment process began with Dr. John Todd who started two companies based on his hypothesis that treatment carried out by diverse ecosystems would improve the quality of treatment. Despite the general

perception and advertising claims that these wastewater treatment processes result in a higher quality effluent due to their ecologically superior characteristics to conventional treatment systems, they are all fundamentally conventional activated sludge treatment systems that rely on bacteria for treatment. However, they can be designed to even higher standards. While there is some evidence that wetlands and marshes retain complex contaminants, allowing more time for bacteria to degrade them, the plants in commercially available greenhouse-style treatment processes are not in contact with the wastewater undergoing bacterial treatment long enough to have a measurable effect on water quality, other than to extract some nutrients for plant growth. However, in addition to being more acceptable to neighbouring property owners, these systems can have a significant educational impact as the community is visually reminded that chemicals and other materials they may waste to sewer through toilets and sink drains could have an impact on the plants, representing the environment. These greenhouse-style wastewater treatment systems can play an important and critical sustainable role in changing public behaviour with respect to preventing waste materials from being discharged to sewer.

Figure I. Sechelt Water Resources Centre Interior

As noted there are several greenhouse style treatment technologies commercially available including: 1) Solar Aquatics; 2) Living Machines; and 3) Organica. The Solar Aquatics and Living Machines systems have been constructed in educational settings. A

Solar Aquatics treatment plant was installed within a glassed-wall area at the entrance to the Center for Interactive Research on Sustainability (CIRS) building at the University of British Columbia where it reclaims wastewater generated within the building, as well as wastewater extracted from the campus sewer, and reuses the water for toilet and urinal flushing within the building as well as landscape and green-roof irrigation. A Living Machines treatment system serves the Islandwood Centre outdoor school located on Bainbridge Island, where it is used as part of the educational program to illustrate how wastewater is renovated in the environment. A Living Machines treatment system is also the focal point of the lobby at the entrance of the Missouri Department of Conservation Anita B Gorman Conservation Discovery building in Kansas City where it treats the wastewater generated within the building before releasing it to the natural wetlands surrounding the building and eventually the nearby watercourse. The Sechelt Water Resource Centre was designed to achieve an extremely high-quality reclaimed water and incorporates a number of advanced treatment components including: tertiary filtration using ultra-filtration membranes; activated carbon filters to remove endocrine disrupting compounds, pharmaceuticals and other emerging contaminants; and effluent thermal heat recovery. Rather than building a conventional wastewater treatment plant, the community has constructed a Water Resource Centre that provides the community with a source of high-quality source of water that can be used to off-set limited potable water demands – of particular importance now that the community is routinely facing severe drought conditions during the summer.

Figure J. Anita B. Gorman Conservation Discovery Center - Kansas City Missouri

Figure K. Illustration of Plants Growing above Bacterial Bioreactor Tanks in a Solar Aquatics System

All of the installations described in this section have an impact on waste management behaviour, enabling visitors and building occupants to better understand the relationship between their waste discharge habits and potential impacts on the environment. Although the greenhouse structures are placed above or surrounding the mechanical bacterial-mediated treatment systems, aside from the visual aesthetic advantage of covering over the ugly mechanical processes, the greenhouse structure could be constructed adjacent to the mechanical plant, and the plants could still take advantage of the nutrients hydroponically, or a greenhouse growing environment could be incorporated into virtually any conventional treatment process, including an oxidation ditch (with some creativity).

The ability to have a greenhouse facility in either direct or indirect association with a mechanical treatment process, and the ability to grow a wide range of attractive plants within a greenhouse environment brought forth the concept of that environment being a botanical garden that could have tourism value. For example, the water quality achieved by the Sechelt facility meets the most stringent EPA Class A reuse standard, as well as removing micro-pollutants that most treatment plants are incapable of effectively removing. This quality of reclaimed water would be well suited to a botanical garden environment that was open to the general public. The Sechelt experience demonstrates such a facility can meet stringent performance specifications included meeting zero odour and zero noise impacts on the surrounding residential area, and that a treatment facility can be constructed within a residential neighbourhood with minimal impact and in an economical, and sustainable manner.

3.4 Process Evaluation Factors

In general, the factors for consideration include:

1. Land Area Requirement (Large → Small)
2. Operator Skill Level Requirement (Simple → Complex)

3. Technology Adaptability (Low → High)
4. Capital Cost (Low → High)
5. Operating Labour Cost (Low → High)
6. Energy Requirement (Low → High)
7. Process Robustness (Low → High) {ability to accommodate wastewater variability}
8. Water Quality Achieved (Secondary → Advanced)
9. Water Reuse Applications (Low → High)

Treatment technologies for consideration that can achieve the indicated water quality categories (note in all cases we will assume pre-treatment and ultraviolet light disinfection will be also deployed)

Secondary Treatment

- Suspended Growth (Extended Aeration Activated Sludge) + Clarification
- Attached Growth (Moving Bed Biofilm Reactor) + Clarification
- Granular Activated Sludge + Disc Filtration

Tertiary Treatment

- Suspended Growth (Membrane Bioreactor)
- Attached Growth (MBBR) + Clarification + Disc Filtration
- Granular Activated Sludge + Disc Filtration

Advanced Treatment

- Suspended Growth (Membrane Bioreactor)
  - + Advanced Oxidation
  - + Reverse Osmosis
- Attached Growth (MBBR) + Clarification + Disc Filtration
  - + Advanced Oxidation
  - + Reverse Osmosis

Nutrient Recovery Options

- Modified UCT Process
- MBR BNR Process
- Granular Activated Sludge

Energy/Carbon Recovery Options

- Conventional Anaerobic Digester
- Thermophilic Anaerobic Digester

Table D. Wastewater Treatment Process Categories

Process Category	Process Description	Pros & Cons
Fixed Film Growth	▪ Moving Bed Biofilm Reactor (MBBR) (activated sludge combined with suspended plastic or polyethylene fixed-film-growth media);	▪ less flexible operation ▪ low operator skill ▪ lower energy demands ▪ greater biosolids generation ▪ limited or no nutrient removal capacity
Hybrid	▪ moving bed biofilm reactors (MBBR) ▪ with a MBR	▪ moderate to low operational flexibility ▪ moderate operator skill ▪ chemical nutrient removal ▪ small footprint ▪ moderate energy demands
Suspended Growth	▪ membrane bioreactor (MBR)	▪ flexible operation ▪ biological phosphorus removal ▪ high operator skill ▪ may be designed to achieve efficient chemical or biological nutrient removal ▪ high energy demand

General Direction of Increasing Cost & Operating Skills

Table E. [Table Name]

Characteristic	Septic Tank	Fixed Film	Greenhouse	Hybrid	Conventional Activated Sludge	Membrane
Effluent Quality	1	4	4	4	4	5
Load Adaptability	3	2	3	3	4	4
Land Required	1	3	2	3	3	2
Operator Skill Level	5	3	2	2	2	1
Heat Loss Resistance	3	4	4	4	4	4
Biosolids Generation	1	2	4	4	3	3
Power Requirement	5	3	2	3	2	1
Nutrient Removal (* seasonal)	0	1	4	4	5	5
Educational Value & Aesthetics	0	2	5	2	2	4
Capital Cost	5	2	1	2	2	1
Operating Cost	2	3	1	2	2	1
TOTAL SCORE	26	29	32	33	33	31

INTEGRATED SUSTAINABILITY

INTEGRATED SUSTAINABILITY

Appendix 1 – Treatment Selection Matrix

Criteria	SECONDARY			TERTIARY - REUSE		TERTIARY – REUSE & PHOS		INDIRECT POTABLE REUSE		ENERGY RECOVERY	
	MBBR-S	MBR-S	GAS-S	MBBR-TR	MBR-TR	MBR-TRP	GAS-TRP	+AO	+RO	CAD	TAD
Land Area Required	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑
Operator Skill Required	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑	☑☑☑	☑☑	☑☑☑☑	☑☑☑☑
Technology Reliability	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑
Technology Adaptability	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑
Capital Cost	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑
Operating Cost	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑	☑☑☑	☑☑	☑☑☑☑☑	☑☑☑☑
Electrical Consumption	☑☑☑☑	☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑☑	☑☑☑	☑☑	☑☑☑☑☑	☑☑☑☑
Robust Performance	☑☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑
Environmental Impact	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑☑
Aesthetics	☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑	☑☑☑	☑☑☑☑	☑☑☑☑
RESOURCE RECOVERY											
Agricultural Irrigation	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑		
Urban Water Reuse				☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑	☑☑☑☑	☑☑☑☑☑	☑☑☑☑☑		
Indirect Potable Reuse								☑☑☑☑☑	☑☑☑☑☑		
Nutrient Recovery						☑☑☑☑☑	☑☑☑☑				

INTEGRATED SUSTAINABILITY

Energy Recovery										☑☑☑☑	☑☑☑☑☑

Legend:

SECONDARY TREATMENT (AGRICULTURAL IRRIGATION)

MBR-S MBR Treatment – Secondary Water Quality

MBBR-S MBBR Treatment – Secondary Water Quality

GAS-S Granular Activated Sludge – Secondary Water Quality

TERTIARY TREATMENT (UNRESTRICTED URBAN NON-POTABLE WATER REUSE)

MBBR-TR MBBR Treatment – Tertiary Water Quality for Urban Reuse

MBR-TR MBR Treatment – Tertiary Water Quality for Urban Reuse

TERTIARY TREATMENT (UNRESTRICTED URBAN NON-POTABLE WATER REUSE WITH NUTRIENT RECOVERY)

MBR-TRP MBR Treatment – Tertiary Water Quality for Urban Reuse with Biological Phosphorus Removal

GAS-TRP Granular Activated Sludge - Tertiary Water Quality for Urban Reuse with Biological Phosphorus Removal

ADVANCED TREATMENT (INDIRECT POTABLE REUSE – AQUIFER RECHARGE)

+AO Plus Advanced Oxidation

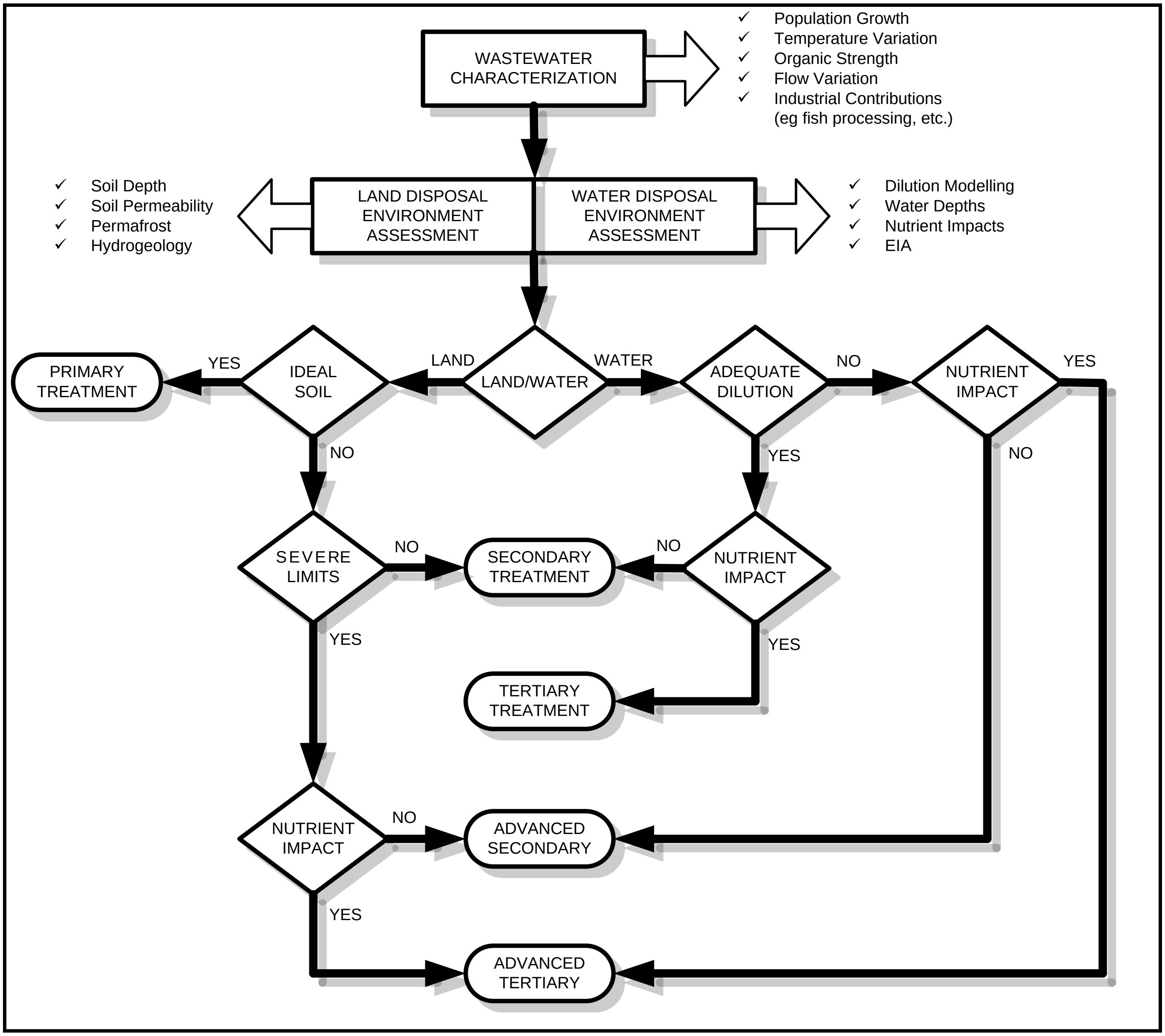
+RO Plus Reverse Osmosis

ANAEROBIC CO-DIGESTION (ENERGY RECOVERY_

CAD Conventional Anaerobic Digestion

TAD Thermophilic Anaerobic Digestion

APPENDIX 2 – DECISION TREES FOR WASTEWATER TECHNOLOGY SELECTION



INTEGRATED SUSTAINABILITY