Chapter 2

Uncertainty in wastewater treatment – current practice

2.1 INTRODUCTION

The wastewater treatment industry has evolved towards increasingly sophisticated, capital-intensive engineered systems. Decisions on plant design and operation often depend on the estimation of risk. As discussed in Chapter 1, risk is intrinsically related to uncertainty. By reducing, where possible, uncertainty, the probability of failure can be more accurately assessed and in turn optimal designs can be proposed. To understand risk, we must therefore explore uncertainty.

This chapter covers how risk and uncertainty are currently handled in engineering practice and focuses on the risk of non-compliance. The approaches described in the following sections will be familiar to engineers across the world, however, the chapter focuses on current practice in North America. Examples of design practices in other jurisdictions have been included in Appendix D.

2.2 GENERAL APPROACHES FOR ADDRESSING UNCERTAINTY IN WASTEWATER TREATMENT

2.2.1 Design guidelines

2.2.1.1 Overview

Uncertainty and risk of non-compliance is frequently handled in wastewater treatment practice through the use of design guidelines. Historically, process design criteria have been based on regulatory requirements, industry-accepted design standards or state-specific regulations (industry standards, adapted to specific state conditions with additional requirements). Some examples of these design standards include:

- Theory, Design and Operation of Nutrient Removal Activated Sludge Processes (Ekama *et al.*, 1984);
- Water Environment Federation Manual of Practice 8 (WEF MOP-8, 2017);

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- Wastewater Engineering: Treatment and Resource Recovery 5th Edition (Metcalf & Eddy Inc. *et al.*, 2013);
- Great Lakes Upper Mississippi River Board, Recommended Standards for Wastewater Treatment Facilities (Ten State Standards) (GLUMRB, 2014);
- ATV Guidelines (ATV, 2000);
- USEPA Nitrogen Control Manual (USEPA, 1993);
- USEPA Phosphorus Removal Design Manual (USEPA, 1987a);
- Biological Wastewater Treatment (Grady *et al.*, 2011);
- WERF/CRTC Methodologies for Evaluating Secondary Clarifier Performance (Wahlberg, 2004);
- Virginia's Sewage Collection and Treatment Regulations (Virginia DEQ, 2008);
- Biological Nutrient Removal (BNR) Operation in Wastewater Treatment Plants (WEF MOP 29, 2005).

Design guideline documents typically provide design targets such as surface overflow rates for average and peak hour flows. These standards tend to address risk by using relatively conservative design criteria and forcing the designer/engineer to look at multiple scenarios. What these design criteria generally do not do, is address plant-specific conditions or provide methods for determining design flows and loads that are both 'real' and statistically rigorous. Frequently, how the criteria are to be applied is open to interpretation from the designer/engineer and/or regulator. For instance, often these standards do not directly address covariance (correlation) of flows and loads, the interaction between unit processes, or reliability. None of the guidance documents provide specific criteria for managing risk in process design, however using the design standards generally results in a conservative design with relatively low probability of failure.

Because the criteria are frequently open to interpretation, engineers tend to evaluate several scenarios that include combinations of critical design parameters. This approach can result in conservative and expensive designs without necessarily providing a worthwhile benefit (Doby, 2004). Russell (2019) states that most municipal wastewater treatment plants are 30–50% overdesigned based on municipal codes and, after safety factors are used by consultants, can be overdesigned by 100% or more (Box 2.1).

2.2.1.2 Design criteria

In certain jurisdictions, permit writers need to review engineering design reports and contract documents during the permit application process in order to issue construction permits.

For example, in the USA, the listing of specific design criteria for unit processes varies depending on the State. Texas and Virginia, for example, provide design requirements as part of state law for various methods of activated sludge treatment, clarification, and biosolids treatment. The risk for the permit writer is mitigated because the state law mandates criteria that does not leave room for interpretation. Other states, such as Florida, do not list specific design criteria for unit processes in State Code. In this case, the permit writer is dependent on the guidance from other documents such as the Ten States Standards (GLUMRB, 2014) for reviewing design criteria. In Florida, as design criteria are not mandated in the Florida Administrative Code (Fla. Admin. Code, 2013), it is the responsibility of the engineer-of-record signing and sealing the engineering report and/or contract documents to address risk in the design. In this case, risk is shifted from the regulator to the engineer-of record.

2.2.1.3 Safety factors

Historically, safety factors have been the most common approach for mitigating risk for multiple reasons. With early wastewater treatment plants design, safety factors could easily be used to account for a great deal of uncertainty in all of the factors that control process performance.

Lawrence and McCarty (1970) derived a formula for the minimum sludge age to avoid washout. The safety factor was defined as the ratio of the design sludge age to the minimum sludge age (Lawrence, 1971a; Lawrence & McCarty, 1970). German design standards (ATV, 2000) recommend safety factors for determining the aerobic sludge age for nitrification and nitrification/denitrification facilities.

Box 2.1 shows how multiple safety factors may work together to affect the target design concentration.

BOX 2.1 COMPOUNDING OF SAFETY FACTORS

In wastewater treatment infrastructure, safety can be introduced in various ways. A regulator can introduce safety by lowering the discharge permit limit. Similarly, a design engineer can choose to design for an effluent target concentration lower than the permit. Figure 2.1 shows how multiple safety factors may work together to affect the target design concentration. The development of the effluent permit in the regulatory stage includes safety factors to reduce the probability of negatively impacting the ecosystem whereas the WRRF planning and design stages introduce safety to increase the probability of not surpassing this permit. As a result, compounding of safety factors occurs.

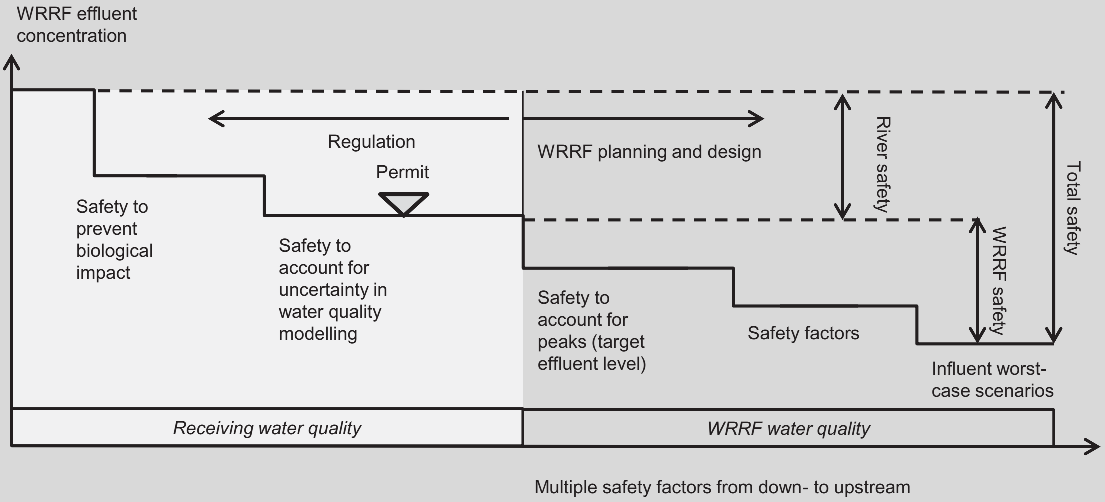

Figure 2.1 Multiple safety factors introduced at different locations reduce the target design effluent concentration.

As our knowledge of the wastewater treatment process has progressed, more sophisticated methods for design (such as modelling) have evolved which give practitioners the means to evaluate reducing safety factors. Models can also be used in combination with safety factors to reduce the number of scenarios that need to be analysed or modelled. For instance, a model can be run for a maximum month condition, with safety factors that are built in to account for daily or diurnal fluctuations in flows and loads.

2.2.1.4 *Reliability and redundancy standards*

Reliability and redundancy standards are used to reduce the risk of failure due to individual unit processes being out of service either due to mechanical failure or maintenance. Guidelines where available are, by necessity, somewhat vague because they must deal with a wide range of conditions. The real degree of reliability and redundancy is developed by the designer/engineer in conjunction with the owner. These requirements are often difficult to specify as they often rely on the relationships between the equipment at various locations within a facility.

Design guidelines for adding redundant or backup components to a system design have been developed to ensure that critical components retain redundant configurations in the event of failure (Palmer *et al.*, 2003). A definition of redundancy and its links to uncertainty and reliability can be found in Appendix A.

In North America, redundant design practices began with fault-tolerant requirements under the directive of water quality regulatory compliance and safety (USEPA, 2000). The justification for including redundant equipment in treatment facilities began with the need to continuously operate treatment processes during equipment failure and while performing preventative maintenance that required equipment to be taken out of service. This assured that a treatment facility's continuous treatment operations would meet federal and state regulatory requirements that protect the environment and public health and safety.

The U.S. Environmental Protection Agency (EPA) and several states have developed standards for equipment redundancy considerations. These standards tend to address risk by using relatively conservative design criteria. Typical redundancy requirements for treatment facility's unit processes are presented in Table 2.1. A comprehensive list of federal and state redundancy requirements for U.S. and Canada are presented by Palmer *et al.* (2003).

2.2.1.5 *Development of tight contract documents*

Well-developed plans and specifications that have been reviewed and approved by the owner should decrease risk during construction. Development of these items will prevent errors and/or omissions and will also minimise loopholes for change orders in the event the design intent is not clear. Consideration should be given to both the appropriate equipment manufacturers and the selection of proper materials for construction. Change order mitigation can be addressed by providing flexibility in the bid form to include allowances for unforeseen conditions in the field.

Well-developed drawings and specifications provide the means to develop a recommended sequence of construction and a list of construction constraints which will keep the facility operating in a manner that ensures adequate treatment during construction and start-up. Sequencing provides the designer/engineer with an estimate of project duration in the event that liquidated damages are included as part of the contract. Finally, well-developed plans and specifications provide an accurate construction cost estimate. This estimate will be used by the owner for financing the project.

2.2.1.6 *Staffing and monitoring*

In certain jurisdictions, under conditions where there may be concern over meeting effluent permit limits, regulators have the flexibility to require additional staffing and/or monitoring known as 'reasonable assurance'. The addition of staff or the requirement for additional monitoring offsets risk and uncertainty that the permit writer may believe is evident during review of the engineering reports and/or contract documents during the permit application process.

Table 2.1 Example of regulatory redundancy/reliability requirements for wastewater treatment facilities.

Unit Process	**USEPA (1974)**	**Great Lakes Upper Mississippi River Board (Ten State Standards) (2014)**
Mechanically cleaned screens	One backup screen	Minimum of two screens, with capability to treat design flow with one unit out of service
Pumping systems	One backup pump for each system performing the same function	One backup pump for each system performing the same function
Grit removal	Not specified	Minimum of two units with ability to bypass. No redundant tankage required
Primary sedimentation basins	Must be able to process 50% of plant flow with one (largest) unit out of service	Requires multiple units capable of independent operation for plants with flows higher than 0.1 MGD, but no redundant unit required
Secondary sedimentation basins	Must have 75% of rated capacity with one (largest) unit of service	Requires multiple units capable of independent operation for plants with flows higher than 0.1 MGD, but no redundant unit required
Activated sludge – Aeration basins	Must have at least two basins for processing full plant flow. No standby tankage required	Must have at least two parallel basins.
Activated sludge – Aeration blowers	Must have sufficient capacity to meet oxygen demands with largest blower out of service	Must have sufficient capacity to meet oxygen demands with largest blower out of service
Activated sludge – Air diffusers	Air diffusion system must be designed so that largest section can be isolated without measurably impacting oxygen transfer capability	Plants with less than four independent aeration basins shall be designed with removable diffusers that can be serviced without draining the tank
Ultraviolet disinfection	Must be able to process 50% of plant flow with one (largest) unit out of service	Must have a minimum of two lamp banks per channel to facilitate cleaning or service while maintaining capacity
Aerobic and anaerobic digestion	At least two tanks required, but no standby tank required	Requires multiple units or alternative method of sludge processing/disposal, but no standby tank required
Sludge dewatering equipment	Centrifuges require backup unit, which can be uninstalled. No other redundancy listed for alternative dewatering systems	Not specified

N/A: Not specified

2.2.2 Statistical methodologies

Although there are many federal and state guidelines providing statistical methodologies for calculating the risks associated with wastewater effluent or potential pollution sources on the environment, there is little guidance for applying statistical methods to the wastewater process design itself.

In process design, various statistical methods are used to calculate design flows and loads. Design criteria from most of the standard texts dictate that 'maximum month' or 'peak' flows or loads be used. These are usually defined using a period of 5−10 years and are usually selected by calculating a percentile based on several years of data. Rigorous statistical methods are not typically applied to data screening or sample size collection.

Frequently, flows are analysed in more detail than loads, simply because there is often more data to work with. Multivariate regression analysis can be used to estimate collection system response to rainfall and soil conditions. This enables estimates of flow based on long-term rainfall event data as well as estimates of soil conditions based on time of year, frequency of serial rainfall events, and temperature.

2.2.3 Scenario analysis

An established method of accounting for variability and uncertainty is to run a steady state or dynamic model under several conditions. This one at a time type of scenario analysis tries to capture how the plant will operate under multiple conditions including conditions such as:

- High and low temperatures;
- High and low flows or loads;
- Seasonal permitting requirements; and
- Combinations of units in or out of service.

Additionally, in the preliminary design stage, multiple scenarios may need to be addressed that account for:

- Multiple population growth scenarios; and
- Multiple future permitting requirements.

The designer/engineer may choose to analyse the effect of other uncertainties that affect the design such as kinetic variables or wastewater characteristics that have not been well defined. The number of scenarios analysed is usually limited by the budget for planning and design and typically is focused on the most realistic or critical scenarios.

2.2.4 Mathematical modelling

The use of models to support the decision-making process has become common practice. The results obtained from modelling efforts must, however, be used judiciously, given the fact that plant design and operation remain vulnerable to imperfect data and to imperfect predictability of the system behaviour. When implementing models for design, the engineer must select plant-specific inputs to the model including detailed wastewater characteristics and biokinetic parameters. The operational envelope of the model-based design under evaluation can be tested by varying the values of the model parameters and influent characteristics.

With the development of sophisticated whole plant computer models, the standard design criteria can be challenged if the designer/engineer can convince regulators that the models reasonably predict plant performance. This will require detailed wastewater characterisation and/or pilot testing. In such a case, the engineer's and the regulator's judgement are generally used to determine the acceptable risk of applying modified criteria.

Model application for design typically requires that the designer/engineer identifies the most critical inputs and the most appropriate values for those inputs. The less critical model inputs can be fixed at a default value set by a knowledgeable model developer. The designer/engineer must select an appropriate methodology for determining flows, loads, and other model inputs that when combined do not result in an overly conservative design or a critically under-designed system. The designer/engineer must also be able to communicate the level of risk of critical design decisions to decision makers.

As computer processing power and speed has increased, interest in using Monte Carlo techniques has also increased. The Monte Carlo approach is attractive to treatment process design for several reasons including:

- The number of variables that can affect a design is high;
- The Monte Carlo method can account for covariance between variables;
- Sophisticated whole plant simulators are available that account for the interaction of multiple processes;
- Different unit processes may be affected in opposite ways by certain assumptions and the Monte Carlo method can test many assumption combinations;
- The Monte Carlo method enables the determination of peak, average, and minimum design requirements; and
- The Monte Carlo method enables the use of computing power to analyse multiple scenarios.

In academia, sophisticated statistical analyses are sometimes used for model calibration and process design. However, most of these methodologies have not been used outside of academia because they require significant compute resources, detailed data needs, as well as time and expertise to complete the analyses.

Chapter 3 discusses in detail the potential of incorporating mathematical models and statistical techniques for process design.

2.3 ADDRESSING SPECIFIC SOURCES OF UNCERTAINTY AND VARIABILITY IN CURRENT DESIGN PRACTICE

Even though not explicitly stated, design guidelines identify areas of uncertainty – in this STR called **sources of uncertainty** or **variability** (for definitions see Chapter 1, Box 1.2) – and assign safety factors to each one. The objective is to determine which of these sources of uncertainty are most important, and which have the biggest role in the decisions that need to be taken. As the project progresses and decisions are made, fewer sources of uncertainty need to be considered and the degrees of freedom in the design process are reduced.

2.3.1 Addressing sources of variability and uncertainty in flow and load determination

2.3.1.1 Use of historical information to develop design flows and loads

Good design practice is to use historical information as a component of the design basis for the facility. This includes actual facility data (e.g., raw influent flow and concentration data), population growth and projections, current and future zoning of the service area, past, present, and future capital improvement projects (e.g., infiltration and inflow improvements). For new facilities, data collected in nearby plants or in plants situated in similar catchments can be used.

Population growth projections are generally looked at in several different ways including, historical straight-line projections, traffic analysis zoning, and census projections. The evaluations are independently evaluated to determine future growth for flow projections. As with any analysis, the use of multiple data sets reduces the uncertainty in the evaluation. In most cases, the risk and uncertainty at this level is generally accepted by the owning entity.

Zoning changes and capital improvement projects in the service area can significantly impact the flow and characteristics of the wastewater conveyed to the treatment facility. Standard design practice is to consult the owning entity on future plans for the service area and to address changes expected during the planning life of the treatment facility during the preliminary design. This is typically done by adjusting historical facility data to account for these changes. In most cases, the risk and uncertainty regarding zoning changes is accepted by the owner.

Engineers will typically use peaking factors to account for the variability in flows and wastewater concentrations. These peaking factors can be developed by evaluation of historical data from flow meters or from empirical equations such as those provided in the 2014 edition of Ten States Standards (GLUMRB, 2014) that relate population to the hourly flow peaking factor.

Flow peaking factors are used to verify that facilities will perform at peak flow conditions as well as to confirm loading rates on unit processes such as clarifiers and tertiary filters. Mass loading peaking factors are commonly used to ensure performance and permit compliance.

It is the designer/engineer's responsibility to assign risks to the various peaking factors to size components such as bioreactor volumes, oxygen-delivery systems, clarifiers and filter surface area requirements, as well as chemical feed system requirements.

Risk and uncertainty in the use of facility data are associated with sample collection and analysis. Verifying the data quality procedures followed by the owning entity will reduce the uncertainty of the data sets. The designer/engineer further mitigates risk and uncertainty by evaluating the data and, for example, removing outliers. After the historic data set is modified, the design basis is modified further for the other factors described below. This is, of course, limited only to facilities already in service.

2.3.1.2 Use of per capita flows and loads

For existing facilities, the use of industry accepted per capita flows and loads, supplemented with population projections, can provide verification for facility design criteria. Significant discrepancies found in this verification step can warn of insufficient conservatism in the design. The designer/engineer needs to examine the cause of the discrepancy and should re-evaluate the design criteria if the discrepancies cannot be explained by a change in the service area or future capital improvements.

2.3.1.3 Screening of influent wastewater data

Analysis of the historical data is used to understand the influent wastewater characterisation. The designer will be more certain in his/her design if he/she is certain that the available influent data represent the true wastewater characteristics. Data evaluation techniques include data plotting, screening, flow- and mass balances, correlations, and the calculation of peak flow and mass loading factors. The specific methods used to evaluate the data vary widely as there is currently no commonly accepted best practice to do this evaluation.

2.3.1.4 Wastewater characteristics when data are not available

If wastewater characterisation data are not available, designers must make assumptions regarding the wastewater characteristics and loading patterns. These assumptions are often based on a combination of published information, information from surrounding facilities, and engineering judgement. The design then normally includes some safety factors because of the larger degree of uncertainty.

Wastewater characterisation also changes over time introducing uncertainty to the future plant performance. These changes can be attributed to the gain (or loss) of population, water consumption patterns, and industry. Wastewater characteristic changes should be estimated during design, especially when considering nutrient removal.

2.3.2 Addressing sources of uncertainty in unit process design

The following sections focus on how current practice addresses uncertainty in the design of unit processes. The continuous activated sludge system is used as an example.

2.3.2.1 Selection of design aerobic solids retention time

Perhaps the most common example of addressing uncertainty and variability in WRRF design practice today is the use of a safety factor when determining the aerobic solids retention time (SRT) for a nitrifying system. There are many variables related to both influent wastewater quality as well as operations that determine the system SRT needed to assure sufficient ammonia removal. These include parameters related to the growth rate of autotrophic organisms such as temperature and pH along with operational parameters such as the dissolved oxygen concentration and the ammonia concentration in the bioreactor. Other operational parameters, such as clarifier performance (solids leaving the plant) as well as waste activated sludge quantities, also impact SRT.

For example, in the ATV-DVWK-A 131 (2000) guidelines, the equation used for the calculation of the SRT includes a safety factor which takes into account: (a) potential variations of the maximum growth rate caused by certain substances in the wastewater, short-term variations and/or pH shifts, and (b) the variations of ammonium load. The guidelines suggest that the safety factor should be in the range of 1.4−1.8 (lower safety factors for higher population equivalents). Similar safety factors are included in most guidelines such as Metcalf and Eddy (Metcalf & Eddy Inc. *et al.*, 2014) and WRC (Ekama *et al.*, 1984) among others.

Due to the variability and uncertainty in both bacterial growth and plant operations, safety factors are used to ensure that washout of autotrophic organisms does not occur. The designer/engineer may also employ the use of a longer SRT to ensure that a target effluent ammonia concentration is met although increasing SRT does mitigate risks associated with nitrifier washout and high effluent ammonia concentrations, it does present additional challenges. Long SRT systems can be prone to filamentous bulking as well as high capital and operating costs, as a result of requiring more oxygen and larger tank volumes.

2.3.2.2 Selection of design sludge volume index

State-point analysis is commonly used to determine the horizontal surface area needed for secondary clarifiers and to determine underflow rates. Uncertainty in state point analysis outputs stems from uncertainty in the gravity flux curve and the Vesilind parameters. Additional limitations of the state-point analysis can be found in Henze *et al.* (2008).

Uncertainty relating to solids settling in secondary clarifiers typically results in a design sludge volume index (SVI) that is rather high. In order to mitigate the risk caused by the uncertainty of varying SVIs and operating conditions, the secondary clarifier is typically evaluated using multiple state-point analyses at varying design conditions to determine the performance of the clarifier under those different conditions (Henze *et al.*, 2008).

Empirical relationships between SVI and initial settling velocity (ISV) have been developed to be able to generate solids-flux curves based on SVI and mixed liquor suspended solids concentrations (Daigger, 1995).

This helps the designer/engineer to quickly evaluate clarifier conditions without knowing facility specifics. To mitigate the risk associated with these empirical relationships, column testing can be performed using the facility's mixed liquor to develop the solids-flux curve for that individual system, but allowances will still be needed for varying conditions.

The WRC guidelines (Ekama *et al.*, 1984) include an explicit safety factor that is used to multiply the estimated area of the secondary settling tank. The area of the secondary clarifier is estimated as a function of peak wet weather flow, mixed liquor suspended solids concentration, the recycle ratio, and $SSVI_{3.5}$ using an empirical equation that has been derived based on flux settling parameters measured at 30 plants in the UK. The calculated area is then multiplied by a safety factor of 1.25.

2.3.2.3 Selection of design denitrification rates

Uncertainty relating to the denitrification rate in nitrogen removal facilities is a function of several items: temperature, pH, dissolved oxygen carry-over from aerated zones, use of light aeration in anoxic zones to maintain solids in suspension, availability of readily biodegradable (fermentable) COD (S_B) in the anoxic zone feed and hydrolysis of particulate biodegradable COD (X_B) to S_B. The designer/engineer can account for variations in temperature by determining minimum temperature requirements and sizing the reactor accordingly. Alkalinity balances can be performed to determine if pH is impacted and, if needed, alkalinity feed systems can be added. The impact of dissolved oxygen can be accounted for during design by providing tapered aeration, real-time aeration control and/or de-oxygenation zones for mixed liquor internal recycles.

Uncertainty relating to the denitrification rate in nitrogen removal facilities is typically handled by the appropriate sizing of the anoxic zone. For example, in the ATV-DVWK-A 131E (2000) design guidelines, the size of the anoxic tanks has to satisfy the recommended ratio of the anoxic to total volume of the bioreactor. Ratios of less than 0.2 or greater than 0.5 are not recommended.

In the WRC guidelines, the anoxic tank volume is derived from the aerated section volume. The volume of the aerated sections of the bioreactor is calculated as a function of SRT and the maximum specific growth rate of the nitrifying organisms. The recommended values for the un-aerated to the total bioreactor volume are presented graphically and indicate that the ratio should not be larger than 60%.

Historically, the equations used for the sizing of the anoxic zones have been proven to be conservative, alleviating the risk involved in meeting effluent total nitrogen concentrations. In the event that the design engineers feel that the risk has not been adequately addressed, they often choose to add tertiary treatment.

Variations in readily biodegradable COD (S_B) in the influent wastewater cannot be mitigated by the designer/engineer or operations staff. The uncertainty in this parameter is exacerbated by the fact that most treatment facilities do not perform S_B measurements, which require either respirometry or a combination of physical chemical analyses (Choubert *et al.*, 2013; Melcer *et al.*, 2003). This component of the influent waste stream is vital for both biological phosphorus removal and denitrification.

The uncertainty related to S_B for denitrifying systems is generally accounted for in two ways. The designer/engineer might rely on either empirical equations (or use an uncalibrated process model) to calculate a denitrification rate, or might use a value of the hydraulic retention time based on a rule of thumb to directly calculate anoxic volume.

Several empirical equations and curves have been developed to determine denitrification rates for pre- and post-anoxic zones. The most prevalent equation for pre-anoxic zone sizing was published by Burdick *et al.* (1982), which relates the F/M ratio to the denitrification rate.

In addition to empirical relationships, the size of the anoxic zones is frequently determined with a simulator.

2.3.2.4 *Selection of dissolved oxygen concentration in bioreactors*

Designers typically will select design dissolved oxygen concentrations for varying design conditions (average day, maximum day, etc.) to ensure that there is adequate oxygen available for oxidation of carbonaceous and nitrogenous matter. Historically, activated sludge plants have been designed to operate at a dissolved oxygen (DO) concentration of 2 mg/L as a means to account for uncertainty in aeration demand due to variability in wastewater strength and temperature.

2.3.2.5 *Selection of design oxygen transfer efficiency*

The designer/engineer often assumes several key parameters that have large impacts on the sizing of air delivery systems in wastewater treatment. These include the alpha value, diffuser fouling factor, the standard oxygen transfer efficiency (SOTE) for diffused air systems and the standard aeration efficiency (SAE) for mechanical surface aeration systems.

Alpha values are typically prescribed in industry-accepted literature based on the method of aeration being employed. Field testing can also be done to determine this number. The standard oxygen transfer efficiency is the percentage of the oxygen transferred into the mixed liquor from the overall amount of oxygen delivered at standard conditions. This number varies based on the diffused air method used, as well as the depth of the diffusers. The standard aeration efficiency (measured in kg/kw-hr or lb/hp-hr) is generally provided by the surface aerator manufacturer, and is often found to be unrealistic in actual applications. These values have been scrutinised over the years and found to be overly aggressive. Field testing done by third parties has indicated SAE values lower than the typical claims of the manufacturer.

The oversizing of air systems can be problematic from both a capital investment standpoint as well as from an operational standpoint. Providing too much air will impact the biology of the mixed liquor potentially causing poor settling. For facilities employing nutrient removal, high dissolved oxygen concentrations in recycle flows can impact the performance of fermentation and anoxic zones.

These risks are typically addressed by sizing air systems with adequate turndown through the use of multiple units and/or use of variable frequency drives to ensure that sufficient air is provided at both the minimum and maximum design condition. Automatic control systems to control the speed on blowers can also be employed to ensure that the proper amount of oxygen is provided to the system. Risk can further be mitigated through field oxygen transfer testing to determine actual field transfer conditions.

2.3.3 Addressing uncertainty via effluent permit selection

The following sections discuss how uncertainty in WRRF performance can be taken into account by selecting more conservative effluent permits both as a permit writer as well as a design engineer. To illustrate the point, an example for the USA legal framework has been included.

2.3.3.1 *Effluent limits*

In the United States, the Environmental Protection Agency (USEPA) Clean Water Act (USEPA, 1987b) requires that any point source discharge to a navigable water body be permitted through the USEPA or a State with delegated authority under the National Pollution Discharge Elimination System (NPDES) programme. The Clean Water Act specifies limitations using ‘best available current technology’ to issue technology-based effluent limits.

Permitting authorities are required to add more stringent water-quality-based standards for impaired waters. The total maximum daily load (TMDL) programme was instituted as part of the Clean Water Act to identify and determine point and non-point source reductions to impaired water bodies with the intent that the water met the applicable designated uses.

The Florida Administrative Code (Fla. Admin. Code, 2013) explicitly lists effluent limits for discharge to ocean outfall, deep well injection, reclaimed water, and for surface and groundwater discharges that do not have water-quality-based standards. This removes all issues of dealing with risk and uncertainty from the wastewater permit writer.

The requirement for water-quality-based standards indicates that the surface water is impaired and has an approved TMDL. The TMDL is developed through water quality modelling done by those other than the wastewater permit writer. The data used in the water quality modelling is either real or generated by the water quality modeller (water quality modellers use only a margin of safety factor to account for uncertainty). When multiple discharges occur within a discharge segment the permit writer must consider the waste load allocation (WLA). Non-points and natural sources are included as a load allocation (LA). The modeller uses the following formula to develop a TDML for a specific parameter; $\text{TDML} = \text{WLA} + \text{LA} + \text{MOS}$. Stakeholders (those contributing to the impaired water body) can provide public input and data to assist in the development of the TMDL.

Once the TMDL is established and approved by the USEPA, the wastewater permit writer incorporates it into the permit. The wastewater or stormwater permit writer does not take on any risk in issuing this numerical limit as it has been established and approved by others. When multiple discharges occur within a discharge segment the permit writer must consider the WLA as it was utilized during the modelling process.

2.3.3.2 *Selection of effluent design criteria*

Facility design is based upon meeting a numerical effluent limit in order to meet a permit requirement.

The designer/engineer normally employs a lower target effluent concentration in the process design, as compared to the permit limit, to account for uncertainty. For high rate (non-nitrifying) facilities requiring only BOD and TSS removal, assuming lower BOD and TSS values in the effluent do not significantly impact facility sizing if guidelines, such as selection of SRT to washout nitrifiers and clarifier loading rates, are followed.

Larger impacts are common where nutrient removal is required and the designer/engineer accounts for uncertainty by utilizing a design effluent ammonia, nitrate, or total phosphorus value lower than the effluent limit. Modelling with Monod kinetics has shown that lower substrate concentrations decrease the growth rate of the organism. For nitrifying bacteria, use of a lower than required substrate concentration will result in a larger bioreactor. This relationship is not linear and, therefore, a slightly modified effluent target concentration can significantly impact a modelled growth rate and bioreactor size.

Risk mitigation options depend on the effluent compliance period of the facility. For example, if the plant has a very low phosphorus limit over a short averaging period (e.g., 7-day average or monthly average), significant risk mitigation methods may be warranted to address the issue of even a ‘small’ excursion causing a permit violation.

Risks over meeting total phosphorus limits are sometimes mitigated by the designer/engineer using a lower effluent total phosphorus value, which often requires the use of increased metal salts during operation. This may ensure compliance with effluent phosphorus limits at the cost of additional operational costs for the metal salt, a significant increase in solids production, and potentially detrimental effects on the pH in the process.

2.3.4 Summary of uncertainty analysis methods in current practice

Table 2.2 summarises the methods used in practice during design to address key sources of uncertainty and variability. Most of the engineering decisions are made during this phase and thus it is important to be able to quantify the associated uncertainty.

Table 2.2 Summary of methods used in practice to address key sources of uncertainty and variability.

Source of Uncertainty	Uncertainty or Variability	Risk	How Practice Addresses Risk
Influent flows and mass loads	Rate of increase of flow and concentration Peak flow and loading events Correlation between flow and load Variability of historical flows and loads Data accuracy	Underestimating flows and loads Overestimating flows and loads Ignoring correlations or lack of correlations between flows, loads temperature, and discharge requirements. Changes in flows and loads due to changes in population or service area make-up	Use of historical information to determine population growth rates and peaking factors Verification of historical data by using per capita mass loads and flows Screening of data and omission of outliers Use of flow and load peaking factors for design of hydraulic elements and unit processes
Characterisation of the wastewater components	Consistency of fractionation over project planning period Lack of long-term historical data to measure COD fractionation	Overestimation of nutrient removal and/or sludge quantity Underestimation of nutrient removal and/or sludge quantity	Sensitivity analysis Practical checks of process models vs. traditional design criteria
Aerobic SRT	pH and DO control Variability and correlation of pH, temperature Nitrification rate Plant operations	Washout of autotrophic organisms Effluent ammonia concentrations exceeded Bulking sludge	Washout SRT safety factor
Design SVI	Plant upsets Plant operations	Poor settling mixed liquor Clarifier failure	Use of selectors Clarifier safety factors Percentile evaluation on historical SVI

(*Continued*)

Table 2.2 Summary of methods used in practice to address key sources of uncertainty and variability (*Continued*).

Source of Uncertainty	Uncertainty or Variability	Risk	How Practice Addresses Risk
Nutrient Uptake rate	Variability of pH, DO, temperature in wastewater Abundance of readily biodegradable organic matter in wastewater	Exceeding permit requirements Oversizing of anoxic zones which can result in phosphorus release in bio-P systems	Sizing reactor for permit condition requirements Use of empirical equations for anoxic zone sizing for facilities not employing bio-P Addition of supplemental carbon source Addition of post-denitrification capabilities Process simulation
Process air system design	Design condition (max day/max week) Oxygen inputs upstream of system (cascades)	Inadequate air at high demand conditions Overdesign at low flow/start-up conditions Affects nitrifier growth rate Affects system microbiology (filamentous organisms)	Provide equipment available to meet peak demand Have flexibility to turndown oxygen delivered Dissolved oxygen control via instrumentation
Effluent design criteria related to the effluent permitting requirements	Accuracy of water quality models predicting receiving water quality. Variations in receiving water quality and flow Seasonal permit limits Accuracy in models in predicting effluent quality Future changes in regulations Facility operations	Permit compliance	Use of lower design effluent limits as compared to permit requirements

2.4 IMPLICATIONS OF CURRENT PRACTICE ON DEGREES OF FREEDOM IN ENGINEERING DECISIONS

Depending on jurisdiction, design approaches can vary from highly prescriptive to very open, resulting in varying degrees of freedom in the decision-making process.

The use of strict industry standards in design (similar to strictly following a recipe in a cookbook) automatically reduces the degrees of freedom in the decision-making process. If one assumes that decisions on loads and effluent requirements have been taken and the industry standard is to be strictly followed, then the design becomes an automatic procedure that does not require any decision making. This approach 'buries' uncertainty, which is not seen by the stakeholders, and normally increases project costs significantly.

In most cases though, even when industry standards are purported, engineering judgment is still required and parameters that differ from the default values might be used by the designer (industry standard is used as a guideline). In this case, the designer/engineer will need to select values for the design inputs such as safety factors for nitrification or a sludge volume index to mitigate his/her risk.

When no industry standard is purported, and the engineer is free to choose the design methodology, the degrees of freedom increase dramatically and by extension so do the sources of uncertainty to be considered. In this case, the engineer is able to make decisions on the selection of a guideline or a process model as well as the values for all of the design inputs.

It is evident that in the first case (strict adherence to a guideline), no competition in the design can arise and both the design engineer and the owner are legally protected in case of failure by having followed a pre-selected state-of-the-art procedure. However, in this case there is little possibility to seek out opportunities and to look for optimised or competitive solutions. Also, the choice of technologies and configurations will be restricted which may lead to non-optimal solutions. At the other extreme, in case 3, the encountered uncertainties may give rise to both a risk of failure as well as opportunities that arise from competition. It could be argued that the industry is moving from case 2 to case 3 where the consortium needs to cover for risk of failure but is also able to reap the benefits from innovative ideas. In case 3, the need for structured appraisal of sources of uncertainty and variability gains importance.

2.5 SUMMARY

Risk discussed in this chapter is associated with uncertainty in the design process. Uncertainty during the design process results in (usually) the selection of conservative assumptions for the basis of design. This uncertainty is addressed through the use of statistical methods that discard outliers in data, the use of safety and peaking factors in design, the use of effluent criteria that are lower than permit standards, and generally accepted methods for determining nutrient uptake rates and oxygen requirements. Each of these decisions impact both the operational flexibility of the facility and the construction and operational costs.

Ultimately, designers/engineers, owners, contractors, and regulators, need to understand the interactions between making conservative assumptions in design and the impacts of those assumptions on the project lifecycle cost. The cost of providing conservative water quality standards, coupled with the safety factors used during the design process, will most likely not cause a linear increase in project cost but rather an exponential increase depending on the conservatism used for major design decisions. Future work that could determine the overall 'conservatism' contained in a facility arising from all decisions taken from the creation of water quality standards all the way through to process design would be very valuable.

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