SOLIDS INVENTORY CONTROL FOR WASTEWATER TREATMENT PLANT OPTIMIZATION

A BEST PRACTICE BY THE NATIONAL GUIDE TO SUSTAINABLE MUNICIPAL INFRASTRUCTURE

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INTRODUCTION

INFRAGUIDE – INNOVATIONS AND BEST PRACTICES

Why Canada Needs InfraGuide

Canadian municipalities spend $12 to $15 billion annually on infrastructure but it never seems to be enough. Existing infrastructure is aging while demand grows for more and better roads, and improved water and sewer systems responding both to higher standards of safety, health and environmental protection as well as population growth. The solution is to change the way we plan, design and manage infrastructure. Only by doing so can municipalities meet new demands within a fiscally responsible and environmentally sustainable framework, while preserving our quality of life.

This is what the National Guide to Sustainable Municipal Infrastructure: Innovations and Best Practices (InfraGuide) seeks to accomplish.

In 2001, the federal government, through its Infrastructure Canada Program (IC) and the National Research Council (NRC), joined forces with the Federation of Canadian Municipalities (FCM) to create the National Guide to Sustainable Municipal Infrastructure (InfraGuide). InfraGuide is both a new, national network of people and a growing collection of published best practice documents for use by decision makers and technical personnel in the public and private sectors. Based on Canadian experience and research, the reports set out the best practices to support sustainable municipal infrastructure decisions and actions in six key areas: 1) municipal roads and sidewalks 2) potable water 3) storm and wastewater 4) decision making and investment planning 5) environmental protocols and 6) transit. The best practices are available on-line and in hard copy.

A Knowledge Network of Excellence

InfraGuide's creation is made possible through $12.5 million from Infrastructure Canada, in-kind contributions from various facets of the industry, technical resources, the collaborative effort of municipal practitioners, researchers and other experts, and a host of volunteers throughout the country. By gathering and synthesizing the best Canadian experience and knowledge, InfraGuide helps municipalities get the maximum return on every dollar they spend on infrastructure – while being mindful of the social and environmental implications of their decisions.

Volunteer technical committees and working groups – with the assistance of consultants and other stakeholders – are responsible for the research and publication of the best practices. This is a system of shared knowledge, shared responsibility and shared benefits. We urge you to become a part of the InfraGuide Network of Excellence. Whether you are a municipal plant operator, a planner or a municipal councillor, your input is critical to the quality of our work.

Please join us.

Contact InfraGuide toll-free at **1-866-330-3350** or visit our Web site at <***www.infraguide.ca***> for more information. We look forward to working with you.

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The dedication of individuals who volunteered their time and expertise in the interest of the *National Guide to Sustainable Municipal Infrastructure* is acknowledged and much appreciated.

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EXECUTIVE SUMMARY

Proper and effective control of solids inventory within each unit process of a wastewater treatment plant (WWTP) is the most important technique that can be used by plant operating staff to control the process. Control of solids inventory has a direct effect on plant performance, process capacity, and system operating cost. It is the essential first step in optimizing the WWTP.

Despite the importance of effective solids inventory control and the emphasis placed on it in textbooks, manuals of practice, and operating manuals, good control of the solids in a WWTP or within a unit process comprising the WWTP is not always achieved. This best practice provides WWTP operating staff with the fundamental information needed to complete a solids mass balance around a unit process within their WWTP and to conduct a sludge accountability analysis. An overall best practice entitled *Wastewater Treatment Plant Optimization* has been published by the *National Guide to Sustainable Municipal Infrastructure: Innovation and Best Practices.*

Effective solids inventory control in a WWTP can:

- allow additional capacity to be realized in individual unit processes;
- potentially allow nitrification to be achieved without the construction of additional biological treatment capacity;
- reduce the energy use and costs associated with aeration in biological processes;
- reduce biosolids management costs by reducing the quantity of solids requiring processing;
- improve the settling characteristics of the biomass;
- improve the ease and stability of plant operations; and
- result in an overall improvement in effluent quality.

A sludge accountability analysis compares the amount of solids leaving a WWTP as biosolids, in the plant effluent, and through other routes (incineration, landfill, etc.) with the theoretical amount of solids that should have been produced by the WWTP. Through the completion of a sludge accountability analysis, the performance and operating data for the WWTP can be validated, the precision of the plant flow meters and sampling procedures can be assessed, and a quality assurance check can be completed on the laboratory analytical procedures. This best practice provides an illustration of the method used to complete a sludge accountability analysis for a hypothetical WWTP. A significant discrepancy in the sludge accountability analysis necessitates a review of the plant performance data, and a check on the accuracy of the plant flow meters or other measures prior to initiating steps to optimize the WWTP.

Step-by-step procedures to complete solids mass balances around simple, conservative unit processes like primary clarifiers, and around more complex, non-conservative unit processes like biological treatment systems are described in this best practice. In addition, approaches to control the solids inventory effectively in a number of unit processes, including primary clarifiers, biological treatment processes, secondary clarifiers, sludge digesters, and thickeners, are described.

Application of the solids inventory control approach that best suits the specific configuration, size, and type of WWTP being operated will provide an opportunity to realize the benefits associated with WWTP optimization.

1. GENERAL

1.1 INTRODUCTION

This best practice summarizes the key elements of solids inventory control at a wastewater treatment plant (WWTP). Methods to achieve adequate control are presented for a variety of unit processes, as are approaches to determine whether adequate solids inventory control has been accomplished. Effective solids inventory control is an essential first step in optimization of WWTP capacity and performance. This best practice describes one step in WWTP optimization, an overview of which has been published by *The National Guide to Sustainable Municipal Infrastructure: Innovation and Best Practices*, entitled *Wastewater Treatment Plant Optimization*

1.2 PURPOSE AND SCOPE

This best practice provides information for mechanical WWTPs of all types and sizes on approaches to achieve effective solids inventory control. It applies to the control of solids inventory in various unit processes of WWTPs (e.g., biological reactors or bioreactors, clarifiers, and digesters).

Solids inventory control is one of the most important process control parameters with broad implications on plant performance and efficiency, plant capacity, and operating costs. Precise control of solids inventory allows accurate control of such key operational parameters as the food-to-micro-organisms (F/M) ratio, the solids retention time (SRT) or sludge age, blanket levels in clarifiers, solids loadings, and others. Typically, when the solids in the process are controlled properly, the WWTP will be operating in a stable and reliable fashion.

1.3 HOW TO USE THIS DOCUMENT

This best practice provides WWTP operating staff with the fundamental information needed to complete a solids mass balance around any unit process within a treatment plant and conduct a sludge accountability analysis. The benefits that can accrue from proper solids inventory control are described in Section 2.

The concept of a sludge accountability analysis is introduced in Section 3.1. The methods used to complete a solids mass balance are presented in Section 3.2, starting with simple unit processes where solids are neither created nor destroyed (conservative processes) and increasing in complexity to unit processes where solids are created or destroyed (non-conservative processes).

Section 3.3 describes methods that can be used in various common unit processes to achieve effective solids inventory control and realize some of the benefits noted in Section 2.

1.4 GLOSSARY

Biochemical oxygen demand (BOD) — The quantity of oxygen consumed, expressed in mg/L, during the biochemical oxidation of organic matter over a specified time period (i.e., five day BOD or BOD_5) at a temperature of 20ºC.

Bioreactor — The component of the WWTP where biological reactions including BOD_5 oxidation, nitrification, denitrification, and biological phosphorus removal occur. The terms “bioreactor,” “biological reactor,” “aeration basin,” and “aeration tank” are used interchangeably in the text.

Chemical oxygen demand (COD) — The quantity of oxygen required in the chemical oxidation of organic matter under standard laboratory procedures, expressed in mg/L.

Food-to-micro-organism ratio (F/M) — The ratio of the influent mass loading (usually expressed in kg/d) of BOD or COD to the mass of volatile suspended solids in a wastewater treatment aeration tank. The units of F/M are typically d^{-1}.

Mixed liquor suspended solids (MLSS) — The concentration of dry solids in mg/L of mixed liquor biomass in the aeration tank of a suspended growth (activated sludge or extended aeration) wastewater treatment plant.

Mixed liquor volatile suspended solids (MLVSS)— The portion of the mixed liquor suspended solids (MLSS) burned off at 550 ± 50°C expressed normally as mg/L. It indicates the biomass content of the mixed liquor.

Return activated sludge (RAS) — That portion of the activated sludge separated from the mixed liquor in the secondary settlement tanks, which is returned to the aeration tanks.

Solids retention time (SRT) — A measure of the theoretical length of time the average particle of suspended solids has been retained in the biological reactor. It is usually presented in days and is also referred to as mean cell residence time (MCRT) or sludge age.

Total Kjehdahl nitrogen — The sum of the organic and ammonia nitrogen in a water sample expressed in mg/L.

Total suspended solids (TSS) — Solids present in a water sample that are retained on the filter paper after filtering the sample, expressed in mg/L.

Volatile Suspended Solids (VSS) — The amount of total suspended solids burned off at 550 ± 50°C expressed normally as mg/L. It indicates the biomass content of the mixed liquor.

Waste activated sludge (WAS) — The excess portion of the activated sludge separated from the biological treatment process.

2. RATIONALE

2.1 Background

The Water Pollution Control Federation (WPCF, now called the Water Environment Federation, WEF), in its Manual of Practice (MOP) No. 11, *Operation of Wastewater Treatment Plants* (WPCF, 1990), states that “the important technique used to control the activated sludge process is controlling the solids inventory in the system. The wasting of sludge affects the process more than any other process control adjustment.” This statement could have been expanded to cover virtually all wastewater treatment processes in use today. The importance of solids inventory control in wastewater treatment plant operation has been emphasized in textbooks, operating manuals, and operator training courses practically since wastewater treatment was first used to protect the receiving water environment from the impacts of human activities. Control of solids inventory has a direct effect on plant performance, process capacity, and operating costs and is, therefore, an essential element of WWTP optimization.

Despite the importance of solids inventory control in a wastewater treatment plant, effective control is often not achieved in actual operation. In 1991–92, an investigation was undertaken to determine the major factors that contribute to poor performance in municipal WWTPs (XCG Consultants Ltd., 1992). The study included 19 WWTPs in Ontario and assessed the impacts of operational, administrative, and design factors on plant performance. The most frequently encountered and most important factor limiting the performance of these WWTPs was inadequate sludge wastage and disposal. Similar findings have been reported in the United States (Gray et al., 1979; Hegg et al., 1979, 1980). The causes of inadequate control of solids inventory in WWTPs are many and varied. The direct effect of poor solids inventory control is deterioration in effluent quality. The indirect effects include loss of capacity in the WWTP and higher operating costs related to power and biosolids management.

2.2 EXPECTED BENEFITS OF IMPROVED SOLIDS INVENTORY CONTROL

Effective solids inventory control in a WWTP may:

- allow additional capacity to be realized in individual unit processes;
- potentially allow nitrification to be achieved without the construction of additional biological treatment capacity;
- reduce the energy use and costs associated with aeration in biological processes;
- reduce biosolids management costs by reducing the quantity of solids requiring disposal;
- improve the settling characteristics of the biomass;

- improve the ease and stability of plant operations; and
- result in an overall improvement in effluent quality.

2.3 RISKS

Without proper and effective solids inventory control, optimization of the performance and capacity of the individual unit processes that comprise the WWTP cannot be achieved. Excess energy will be consumed in the biological treatment processes and higher costs will be incurred for biosolids management. The quality of the treated effluent discharged from the WWTP will also be compromised.

Despite the importance of effective solids inventory control to realizing optimum WWTP performance and capacity, other factors such as temperature, wet weather, pH, dissolved oxygen concentrations, and chemical dosages, will also affect the WWTP. Achieving effective solids inventory control alone is not a guarantee of optimum performance. All the factors that influence the operation of each unit process must be considered in a comprehensive optimization program. A best practice for WWTP Optimization has been developed by the *National Guide to Sustainable Municipal Infrastructure: Innovation and Best Practices.* Reference should be made to the *Wastewater Treatment Plant Optimization* best practice to ensure that the overall WWTP performance and capacity is optimized.

3. WORK DESCRIPTION

Achieving effective control of the solids inventory in a WWTP or within any specific unit process within the WWTP requires:

> a knowledge of how to determine the amount of solids that enter and leave the unit process or the overall WWTP; and,
>
> an understanding of the methods that can be used to control the solids inventory or the amount of solids in an specific process.

A Sludge Accountability Analysis is a method that can be applied to determine whether the data that are used to conduct a mass balance on the WWTP, such as analytical results or flow data, are valid and accurate. It can also be used to determine whether there are streams adding or removing solids from a unit process or the overall WWTP that are undefined in terms of flow or concentration. Completing a Sludge Accountability Analysis is an essential first step in the optimization of a WWTP, as described in the *National Guide*'s best practice entitled Wastewater Treatment Plant Optimization. The fundamentals of a Sludge Accountability Analysis are described in Section 3.1 below. A Sludge Accountability Analysis is basically a solids mass balance.

Specific procedures for completing solids mass balances around relatively simple WWTP unit processes in which solids are neither created or destroyed (conservative processes) as well as unit processes in which solids are created or destroyed (non-conservative processes) are described in Section 3.2. Completing and monitoring a solids mass balance around an individual unit process and trending the findings will indicate to the plant operator whether the amount of solids or the solids inventory in the process is increasing or decreasing, or if the solids inventory is being controlled at a constant, stable level.

Approaches that can be used to control the solids inventory in common WWTP unit processes are described in Section 3.3. For many unit processes, several different methods to control the solids inventory may be available. The best approach to use for a specific unit process will depend on the design of the process, the monitoring equipment available (i.e. flow meters, sampling points, on-line monitoring equipment), the level of sophistication of the operating staff, the performance requirements, the variability of the wastewater, and other factors. Operating staff should experiment with different approaches and select the approach that is best suited to their needs.

3.1 SLUDGE ACCOUNTABILITY ANALYSIS

A sludge accountability analysis compares the amount of solids leaving a WWTP as biosolids, in the plant effluent and through other avenues (incinerated, landfilled, etc.) with the theoretical amount of solids that should have left the WWTP.

A sludge accountability analysis should cover an extended period (several months to a year). This ensures that short-term effects, such as solids accumulated in storage or within the process, do not bias the results. Plant records for the period of interest are reviewed to determine the mass of solids (kilograms or dry tonnes of total solids) removed from the WWTP compared to the amount that should have been produced based on the quantities and strengths of wastewater treated and the unit processes in use.

The amount of solids that should theoretically be produced at a WWTP depends on the wastewater strength, the type of treatment plant, and the biosolids stabilization processes used. WWTP design and operating manuals provide guidance on typical sludge production rates. Process models such as GPS-X^{TM} or BioWin^{TM} can be used to provide more accurate estimates of sludge production rates since WWTP-specific wastewater quality data and design parameters can be used in the prediction. Table 3–1 presents typical sludge production rates for typical domestic wastewater for some common wastewater treatment processes.

Table 3–1: Typical Sludge Production Rates

Treatment Process	**Dry Solids (g/m^3)**	
	BNR[1] or No Chemical Phosphorus Removal	**With Chemical Phosphorus Removal**
Primary sedimentation and conventional activated sludge	180	220
Primary sedimentation and conventional activated sludge with anaerobic digestion	115	150
Extended aeration	90	120
Extended aeration with aerated sludge holding tank	80	110
[1] BNR — Biological nutrient Removal		

Source: Ontario, MOE (1984).

Process models such as GPS-X^{TM} and BioWin^{TM} predict biosolids production based on COD rather than BOD_5, as the use of COD allows a mass balance on the biological process to be completed. These models also consider the inert and degradable particulate matter and the particulate and soluble fractions of the COD present in the raw sewage, as well as the effects of such variables as temperature and SRT on sludge production. Process models, calibrated using the actual characteristics of the raw sewage being treated, can provide more accurate estimates of sludge production rates than those based on typical literature values

For a cursory analysis of sludge accountability, typical sludge production rates, such as those presented in Table 3–1 are sufficiently accurate. However, it is cautioned that estimates of sludge production rates in Table 1 assume that the raw wastewater strength concentration is typical of domestic sewage. If higher or lower concentrations of BOD_5 or suspended solids are experienced, more sophisticated process models or sludge production rates based on waste strength, such as shown in Table 3-3, should be used. The most appropriate way to estimate the theoretical sludge production at a specific WWTP will depend on the

---

[1]

characteristics of the wastewater, the design of the WWTP and the resources available to plant staff (i.e. availability of process models). The best method should be selected and used consistently in conducting the Sludge Accountability Analysis and results from different methods should not be compared.

Table 3–2 provides an illustration of a sludge accountability analysis for a hypothetical WWTP using the sludge production rates in Table 3–1. In this illustration, the measured sludge production is 104 percent of the theoretical production based on typical sludge production rates. Exact agreement between actual and theoretical sludge production is rarely found. A discrepancy of less than 15 percent is considered acceptable; however, a discrepancy of more than 15 percent indicates the need for further assessment to resolve the cause of the inconsistency (WEAO, 1996). The common sources of discrepancies in sludge accountability include:

- non-representative samples (analytical accuracy, sampling techniques);
- in accurate flow measurement;
- discharges of high strength wastewater into the WWTP from industrial sources; and
- assumptions made concerning accumulations.

If sludge accountability within about 15 percent is not realized, the causes of the discrepancy must be identified by a thorough review of the possible sources of the discrepancy itemized above.

The benefits of conducting a sludge accountability analysis include:

- validating performance data collected;
- confirming accuracy of flow meters;
- confirming representativeness of sampling procedures; and
- providing quality assurance for analytical procedures.

The sludge accountability calculations can be readily set up in a spreadsheet to allow operators to complete the analysis quickly and easily by inserting the required flow and concentration data. During calculation of sludge accountability and in preparing a solids mass balance using any of the examples in Section 3.2, it is important to ensure that consistent units of flow and concentration are used for all inputs and outputs. For example, all flows should be in m^3/d and all concentrations in mg/L (10 000 mg/L = 1.0% TS).

Trend graphs which show the mass of solids retained in key unit processes such as clarifiers or bioreactors can be produced from the spreadsheet calculations. These trend graphs illustrate the changes in the mass of solids with time (daily or weekly) to ensure that the unit process is being well controlled. The objective of solids inventory control is to minimize the variation in the solids mass in the unit process.

Table 3–2: Example Sludge Accountability Analysis

Plant type	Conventional activated sludge with chemical phosphorus removal and anaerobic digestion
Average day flow	25 000 m^3/d
Raw wastewater strength	BOD_5 = 200 mg/L; TSS = 225 mg/L
Final effluent quality	BOD_5 = 10 mg/L; TSS = 15 mg/L
Biosolids hauled to land application	43 000 m^3/yr at 3.0 % (30 kg/m^3) TS
Calculated sludge: Biosolids land applied = 43 000 $\frac{m^3}{yr}$ x $\frac{30\ kg}{m^3}$ x $\frac{1}{10^3}\frac{tonne}{kg}$ =1290 tonnes/yr plus Effluent solids = 25 000 $\frac{m^3}{d}$ x 365 $\frac{d}{yr}$ x15 $\frac{mg}{L}$ x $\frac{1000L}{m^3}$ x $\frac{1}{10^9}$ $\frac{tonne}{mg}$ = 137 tonnes/yr Equals Total production = 1427 tonnes/yr	
Theoretical sludge at production of 150 g/m^3 *	= 25 000 $\frac{m^3}{d}$ x365 $\frac{d}{yr}$ x150 $\frac{g}{m^3}$ x $\frac{1}{10^6}$ $\frac{tonne}{g}$ = 1369 tonnes/yr
Sludge accounted for (percent)	= $\frac{1427}{1369}$ x 100 = 104%
Conclusion	Sludge accounted for is within 85% to 115% of theoretical. Good accountability is confirmed.
* Refer to Table 3–1	

3.2 SOLIDS MASS BALANCES

Conducting solids mass balances around individual unit processes is a key to achieving effective solids inventory control.
The solids mass balance is simply expressed as follows:

Solids entering a process in all incoming streams
plus
Solids produced within the process
minus
Solids destroyed in the process
equals
Solids exiting from the process in all exiting streams
plus
Solids accumulated within the process

The accumulation term is assumed to be negligible for a plant at steady state, but for a short time frame (i.e., days or hours) must be considered. For example, accumulation of solids in a clarifier would be reflected by an increase in the sludge blanket level.

Solids mass balances are simplest to complete around unit processes in which solids are not created or destroyed (i.e., a clarifier). These are termed “conservative processes.” Mass balances around unit processes where solids are created (e.g., biological reactors) or are destroyed (e.g., digesters) are more difficult since the amount of solids created or destroyed must be estimated. These processes are termed “non-conservative.”

Examples illustrating how solids mass balances are done for some simple and more complex WWTP unit processes are provided below. Example calculations for mass balances for some unit processes are provided in Appendix A.

Mass balances around individual unit processes in a WWTP can be combined to produce a detailed mass balance for the entire WWTP. The output of one individual unit process becomes the input for the next downstream unit process. Multiple unit process mass balances can be used to estimate an input or output of a conservative process if no actual measurement is available. For example, the solids returned to a unit process from a recycle stream can be estimated in the absence of actual data, and this estimate may highlight the need to undertake additional sampling or flow measurement of the recycle steam.

3.2.1 PRIMARY CLARIFIER SOLIDS MASS BALANCES

Figure 3–1 presents a diagram illustrating the parameters needed to carry out a solids mass balance around a primary clarifier.

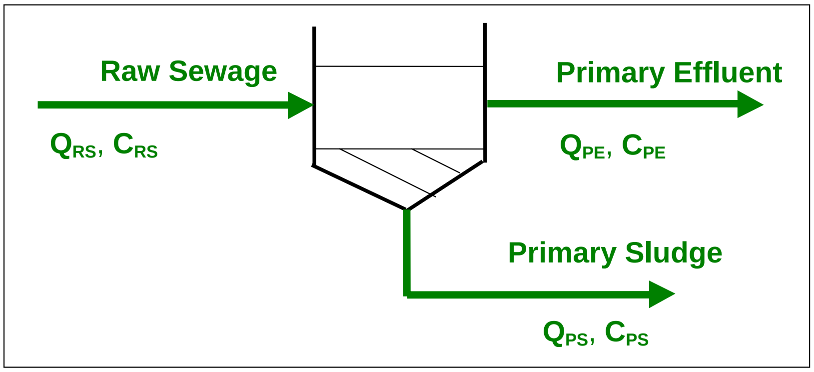


Figure 3–1: Solids Mass Balance Around a Primary Clarifier

Based on Figure 3–1, the solids mass balance around the primary clarifier is mathematically described as:

Solids In = Solids Out + Solids Accumulation

$Q_{RS} * C_{RS} = (Q_{PE} * C_{PE} + Q_{PS} * C_{PS})$ + Accumulation where

Q_{RS} = raw sewage flow
C_{RS} = raw sewage solids concentration
Q_{PE} = primary effluent flow
C_{PE} = primary effluent solids concentration
Q_{PS} = primary sludge flow
C_{PS} = primary sludge total solids concentration.

As noted previously, consistent units of flow and concentration must be used for all inputs and outputs. For example, all flows should be in m^3/d and all concentrations in mg/L (10 000 mg/L = 1.0% TS).

If the sludge blanket in the clarifier is maintained at a reasonably constant level, the accumulation term can be neglected. If the calculated solids in and solids out are not within ±15 percent of each other, accumulation in the clarifier may be significant or the other sources of discrepancy discussed in Section 3.1 may be the cause.

When primary clarifiers receive recycle streams from processes, such as sludge dewatering or are used to co-thicken WAS, the solids mass balance becomes more complex and additional sources of discrepancy are introduced. Figure 3–2 illustrates this more complex case.

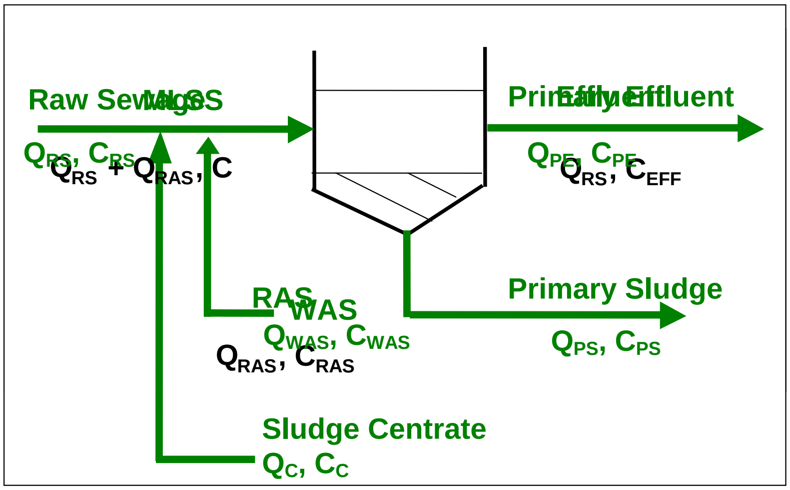


Figure 3–2: Solids Mass Balance Around a Primary Clarifier with Recycle Streams

The introduction of recycle streams or WAS to the primary clarifier increases the complexity of the mass balance somewhat. In this case, to complete the mass balance and confirm that solids are accounted for, measurements of flow and strengths of all streams are necessary. The mass balance, ignoring accumulation within the clarifier, is expressed as follows:

Solids In = Solids Out

$$Q_{RS}*C_{RS}+Q_C*C_C+Q_{WAS}*C_{WAS} = Q_{PE}*C_{PE}+Q_{PS}*C_{PS}$$

where the additional terms not previously defined are:

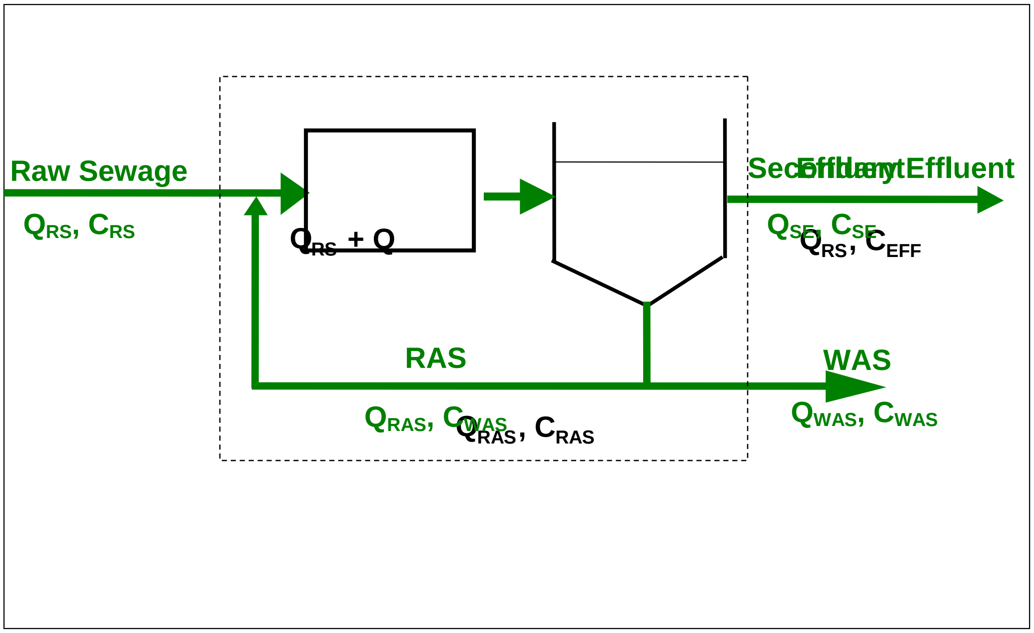
Q_C = centrate flow
C_C = centrate solids concentration
Q_{WAS} = WAS flow
C_{WAS} = WAS solids concentration.

A discrepancy of more than ±15 percent in the mass balance often reflects inaccuracies or lack of data related to the recycle steams and can point to a need to review the impact of the recycle stream on the process. If recycle streams are not responsible for the poor mass balance, other sources of discrepancy noted in Section 3.1 should be evaluated.

3.2.2 SECONDARY TREATMENT SOLIDS MASS BALANCES

In conducting a solids mass balance or sludge accountability analysis on the biological treatment component of a WWTP, the aeration basin (or bioreactor) and the secondary clarifier are considered as one process unit. With a sequencing batch reactor (SBR), both functions occur within the same tank, which simplifies the process. Figure 3–3 illustrates the key parameters needed to complete a solids mass balance on an extended aeration plant (aeration tank plus secondary clarifier).

Figure 3–3: Solids Mass Balance Around an Extended Aeration Plant



Biological treatment is a non-conservative process since biomass is produced in the bioreactor; therefore, the sludge production must be estimated. Typical sludge production values for a range of different types of treatment processes are summarized in Table 3–3.

Table 3–4: Unit Sludge Production Values for Projecting Sludge Production from Suspended Growth Biological Treatment Processes

Process Type	kg TSS (Sludge)/kg BOD_5 Removed
Activated sludge w/ primary clarification	0.7
Activated sludge w/o primary clarification	0.85
Conventional [1]	0.65
Extended aeration [2]	1.0
Contact stabilization	

Notes:

[1] Includes tapered aeration, step feed, plug flow, and complete mix with wastewater detention times <10 hours.

[2] Includes oxidation ditch.

Source: U.S. EPA (1989)

The RAS stream does not need to be considered in the mass balance since it does not leave the unit process. If an external recycle stream (i.e., digester supernatant) is added to the raw sewage, the solids mass contributed by this stream must be taken into account. In this case, the mass balance for the process illustrated in Figure 3–3 is expressed as follows:

$$(Q_{RS} * C_{RS} * \text{Biomass Growth}) = Q_{SE} * C_{SE} + Q_{WAS} * C_{WAS} + \text{Accumulation}$$

Biomass growth can be estimated with sufficient accuracy from typical values (Table 3–3) or can be predicted by process models such as GPS-X™ or BioWin™. The biomass yield term based on BOD_5 incorporates both the solids accumulated from the raw sewage TSS and the biomass growth.

If chemicals are added to the secondary plant for phosphorus removal (alum or iron salts), additional sludge production will occur due to the precipitation of phosphorus and metal hydroxide. The additional sludge production resulting from chemical addition can be estimated based on the following (U.S. EPA, 1976):

- Al: 4.52 to 2.89 mg suspended solids per mg AL added
- Fe: 2.70 to 1.92 mg suspended solids per mg Fe added

3.2.3 DATA REQUIREMENTS

As illustrated in the previous example, completion of a sludge accountability analysis and accurate solids mass balances requires knowledge of the flows and concentrations of all streams entering and leaving the process, including recycles. In processes where solids can accumulate (e.g., sludge storage tanks), it will also be necessary to measure the accumulation in the process and take the accumulation into account in the mass balance.

A significant value of the sludge accountability analysis and solids mass balance is the ability to identify deficiencies, such as inaccuracies in the flow measurement or analytical data used. Incomplete mass balances or poor sludge accountability often point to the presence of streams that enter or leave the process that are not monitored.

Measuring solids concentrations in liquid or sludge streams requires sophisticated laboratory equipment, such as analytical balances, drying ovens, and filtration equipment, and is time consuming. A centrifuge test has been used as a quick method to estimate the amount of solids in a sludge stream that does not require as much analytical equipment. By centrifuging a sample at a fixed time and speed, the volume of the concentrated solids in a graduated centrifuge tube is an indication of the mass of solids in the sample and can be used as a measure of the solids inventory. Sludge units (SLUs) are used by some operators for control of solids inventory and solids mass balances where the sludge unit is the volume of sludge as a percent in the centrifuge tube times the volume of the reactor. A more detailed explanation of the use of the sludge unit concept is included in West (1975) and Clifton and Schuyler (1998). It is always beneficial to conduct occasional laboratory analyses of TS or TSS to confirm the results of the centrifuge test.

3.3 SOLIDS INVENTORY CONTROL APPROACHES

Solids inventory control involves establishing the optimum amount of solids in a process (i.e., mixed liquor in a bioreactor, sludge blanket in a clarifier) that results in the most stable and reliable performance, and then implementing a control strategy to maintain the optimum solids inventory.

The optimum solids inventory for a process will depend on a number of factors, including:

- the design of the process;
- the characteristics of the wastewater;
- the variability of the flow to the process; and
- the performance requirements.

Operating manuals and design guidelines can provide guidance on the optimum solids inventory; however, establishing the optimum operating point for a specific process requires experimentation by plant operating staff to determine the point where process operation is most stable.

In the following subsections, approaches to achieve good solids inventory control in a variety of unit processes are described. All these approaches have been used successfully and the best approach for any particular WWTP or specific unit process must be selected based on:

- the design of the process;
- the amount of instrumentation and control equipment available;
- the operating and laboratory resources (equipment and personnel); and
- the knowledge and experience of the operating staff.

3.3.1 PRIMARY CLARIFIERS

Primary clarifiers separate the readily settleable and floatable solids from the raw wastewater. Primary tanks can also provide equalization of sidestream flows (e.g., digester supernatant, dewatering filtrate) and removal of the BOD associated with settleable solids. This process typically removes 50 to 70 percent of the influent suspended solids and the BOD removal is generally 30 to 40 percent. Many treatment plants also use primary sedimentation tanks to co-settle and thicken waste activated sludge (WEF, 1996).

Chemicals may be added to enhance settling of the solids, or to remove nutrients, such as phosphorus. If a metal salt is added (e.g., alum, ferric chloride, etc.), this will increase sludge production as noted in Section 3.2.2. The addition of polymer will improve solids removal due to flocculation, but will not result in any additional solids production.

Improper solids inventory control in primary clarifiers will inhibit successful operation of the downstream processes, resulting in:

- carry-over of solids from the primary clarifier into the downstream biological reactors;
- solubilization of organic matter from the sludge and an increase in BOD loading to the secondary processes;
- pumping of dilute sludge and hydraulic overloading of the sludge management processes; and
- an increase in sludge pumping rates leading to an increase in sludge heating costs prior to anaerobic digestion.
-

For primary clarifiers, the two main solids handling activities are collection and removal of solids. The collection process entails moving settled solids to a point in the settling tank where it is drawn off. Continuous collector operation allows easy operation of an automatic withdrawal system; however, intermittent operations may be necessary if the primary tanks are used to thicken the WAS from the secondary process or if primary sludge is pumped directly to digestion or dewatering units (WEF, 1996).

The rate of removal of sludge from the clarifier impacts on the sludge concentration transferred to downstream processes. Primary sludge is typically 3.5 to 8 percent solids when WAS is not added for co-thickening and 2 to 7 percent solids when WAS is co-thickened (MOE, 1984). With control of solids inventory, the operator can optimize the concentration in the settled sludge. Two approaches are commonly practised to control solids inventory in the primary clarifiers:

- total solids (TS) control; or
- sludge blanket level control.

These two approaches can be used individually or in combination. The most appropriate inventory control approach depends on factors, such as the impact of sludge concentration on downstream sludge management processes, and the effect of high sludge blanket levels on downstream liquid treatment processes. Whichever method of solids inventory control is used in the primary clarification process, Albertson and Walz (1997) recommend that the sludge retention time in the clarifier be no more than 6 to 12 hours. Sludge retention time in the clarifier is determined by dividing the total mass of sludge in the clarifier by the mass removed by sludge pumping. To calculate the sludge retention time, the total mass of sludge in the clarifier must be monitored as well as the mass into and out of the clarifier.

TS Control

This solids inventory control strategy involves establishing the optimum total solids concentration range for the primary sludge removed from the primary clarifier and setting sludge withdrawal rates (sludge pumping frequencies and durations) to maintain the sludge within the optimum concentration range.
TS control can be done manually by sampling the sludge at the appropriate times during the sludge pumping cycle and measuring the TS concentration. Sampling at various times in the pumping cycle can be done to determine the most appropriate time to sample to ensure representative results. If the sludge is too dilute at the start of the pumping cycle, the pumping frequency should be reduced to allow the sludge to compact and thicken before the next pumping cycle is initiated. If the sludge is too dilute at the end of the pumping cycle, the pumping duration should be reduced so the thinner sludge is allowed to stay in the clarifier and thicken before it is removed in the next pumping cycle.

Automation of the TS control strategy is also possible using on-line sludge density analyzers that continuously measure the TS concentration in the pumped sludge. Interfacing the sludge density analyzer with the sludge pump will turn the sludge pump on or off when the pumped sludge is at pre-set concentrations.

Sludge Blanket Level Control

This solids inventory control strategy involves establishing the optimum sludge blanket level in the primary clarifier and setting sludge withdrawal rates (sludge pumping frequencies and durations) to maintain the sludge blanket level within the optimum range. The operator needs to find a blanket level that provides a thick sludge without adversely affecting removal efficiency, overloading collector equipment, or allowing decomposition and resolubilization of organics in the bottom of the clarifier.

Blanket level control can be done manually by routinely determining the sludge blanket level in the clarifier with a “Sludge Judge “ or a hand-held blanket level detector. The sludge pumping cycle can then be adjusted to increase or decrease the level as needed.

Automation of the sludge blanket control strategy is also possible using an on-line sludge blanket level detector that continuously measures the depth of the blanket. Interfacing the blanket level detector with the sludge pump will turn the sludge pump on or off to maintain the blanket at the pre-set level.

Combined TS and Sludge Blanket Level Control

TS and blanket level control can be practised simultaneously if set points are established for optimum sludge concentration and blanket depth. Automated systems incorporating both sludge density meters and sludge blanket detectors make the implementation of this combined primary clarifier sludge inventory control strategy easier.

3.3.2 BIOLOGICAL TREATMENT

Operation of a biological treatment process depends on living micro-organisms. Control of the number and types of micro-organisms present in the aeration tank and their activity is critical to optimize performance. Although the biological activity can be affected by influent conditions and other operational variables such as dissolved oxygen (DO), pH, and alkalinity, the wasting rate is generally considered to be the most influential control variable. The wasting of sludge affects the effluent quality, the growth rate and type of micro-organisms, oxygen consumption, mixed liquor settleability, nutrient requirement, and nitrification. Through wasting, the operator has direct control over the inventory of sludge in the biological system.

Control of the solids inventory in the biological process is achieved by adjusting the rate of wasting based on one of the following control strategies:

- solids retention time (SRT) control;
- food-to-micro-organisms (F/M) ratio control;
- mixed liquor suspended solids (MLSS) concentration control; and
- total biomass control.

It should be noted that the solids inventory control approaches identified above and described in the following subsections do not apply to fixed film processes, such as rotating biological contactors (RBCs) or trickling filters. In these biological treatment systems, the operator cannot actively control the amount of solids removed from the system by wasting; hence, there is no direct control of the SRT or the amount of biomass present in the system. For hybrid systems (e.g., IFAS[1], BAF[2], SAF[3]) the principles described in this section are still valid as the operator can actively control the biomass present in the system.

The plant operations staff should keep in mind that it can take two to three SRTs of operating time for the biological system to stabilize after a process change. Thus, an operator should allow enough time for the process to respond after a change in the wasting rate. Also, changes in the wasting rate should be implemented gradually (e.g., 10 percent in any one day with no more than 20 percent per week). For parameters used in the process control calculations, such as secondary influent BOD or COD, MLVSS, RAS VSS, F/M ratio, and WAS, seven-day moving averages are recommended to smooth out large fluctuation often seen in daily measurements (WEF, 1996). An example calculation of a moving average as applied to SRT is provided in Appendix B.

A seven-day moving average is determined by calculating the SRT on a daily basis and averaging the daily values for the most current seven days. Each day that a new SRT is calculated, the SRT from the first day in the sequence is dropped and a new average is determined.

SRT Control

Solids retention time, which is also referred to as sludge age and mean cell residence time (MCRT), is basically the average number of days micro-organisms are kept in the biological treatment process. SRT controls the growth rate of micro-organisms, thereby influencing the composition of biomass in the process. SRT is calculated as follows:

$$\text{SRT (days)} = \frac{\text{Total mass of solids within the aeration tank (or bioreactors)}}{\text{Total mass of solids leaving the process each day}}$$

$$= \frac{C_{MLSSX}V_{AERATION}}{(Q_{WAS} \text{ X } C_{WAS}) + (Q_{EFF} \text{ X } C_{EFF})},$$

where C_{MLSS} = solids concentration in MLSS
$V_{AERATION}$ = volume of aeration tank
Q_{WAS} = WAS flow
C_{RAS} = solids concentration in WAS stream
Q_{EFF} = clarifier effluent flow
C_{EFF} = solids concentration in clarifier effluent.

As noted, consistent units of flow and concentration must be used for all inputs and outputs. For example, all flows should be in m^3/d and all concentrations in mg/L (10,000 mg/L = 1.0% TS).

SRT control is accomplished by maintaining the SRT at a predetermined optimum set point by adjusting the wasting rate. The target SRT is site-specific, and can change due to process variations over time and seasonal effects.

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[1] IFAS: Integrated Fixed Film and Activated Sludge.

[2] BAF: Biologcal Aerated Filters.

[3] SAF: Submerged Aerated Filters.

Therefore, it is often necessary for an operator to select a target SRT every month or seasonally. The actual SRT should be within 10 to 20 percent of the target SRT (WEF, 1996). Typically, a lower SRT is required in summer as the reactions in the system occur faster at higher temperatures. Table 3–4 presents the typical SRT values for various biological treatment processes.

Table 3–4: Typical SRT Values

Treatment Process	SRT (days)	
	Without Nitrification	With Nitrification
Conventional activated sludge	4 – 8	(> 4 at 20° C > 10 at 5 ° C)
Extended aeration	> 15	> 15
High rate	4 – 6	Not suitable
Contact stabilization[1]	4 – 10	Not suitable
Note: [1]Considering contact and re-aeration volumes.		

Source: Ontario, MOE (1984).

F/M Ratio Control

The food-to-micro-organisms (F/M) ratio is the ratio of food fed to the micro-organisms (usually measured as BOD_5) to the mass of micro-organisms retained in the aeration tank (usually measured as MLVSS), and calculated as follows:

$$\text{F/M, d}^{-1} = (\text{influent BOD}_5\text{, kg/d})/(\text{MLVSS, kg}).$$

The F/M ratio control method is used to ensure that the biological process is being loaded at a rate that allows micro-organisms in the biological reactor to consume most of the food supply (BOD_5) in the wastewater being treated. Typical F/M ratios for various biological treatment processes are summarized in Table 3–5. The optimum F/M is site specific and temperature dependent, and should be determined by trial and error. Generally, plants should operate at low F/M ratios during the colder months. A high F/M ratio correlates to a shorter SRT while a low F/M correlates to a longer SRT.

Table 3–5: Typical F/M Ratios

Treatment Process	F/M (d^{-1})	
	Without Nitrification	With Nitrification
Conventional activated sludge	0.2 – 0.5	0.05 – 0.25
Extended aeration	0.05 – 0.15	0.05 – 0.15
High rate	0.3 – 0.5	Not suitable
Contact stabilization[1]	0.2 – 0.5	Not suitable
Note: [1] Considering contact and re-aeration volumes.		

Source: Ontario, MOE (1984).

F/M control of solids inventory in the biological system depends on having an available measure of the amount of food entering the system. Although on-line BOD_5 monitoring equipment is available, it is expensive and requires regular maintenance. Since measurement of BOD_5 by traditional laboratory methods requires at least five days, F/M control based on BOD_5 is not practical. Therefore, plants that practise F/M control depend on surrogate measures of BOD_5 such as COD. The relationship between BOD_5 and COD varies from plant to plant and should be established for the particular plant before using COD as a basis for F/M control.

MLSS Control

The MLSS control is a relatively simple method of solids inventory control that involves a minimum amount of laboratory work. In this method, the operator selects and maintains an MLSS concentration in the bioreactor that produces the best effluent quality and the highest removal efficiencies. Sufficient MLSS should be maintained for the desired degree of treatment. The maximum MLSS concentration is limited by the available air supply and the design of the downstream secondary clarifiers. To select the target MLSS that produces a good quality effluent, the operator should start at a recommended F/M ratio and experiment with slightly different ratios. Each ratio should be maintained for a few weeks for the system to stabilize. Once an F/M ratio that produces good quality effluent and good settling sludge is found, the average MLSS during this time becomes the target MLSS (WEF, 1996).

Once a target MLSS is selected, the target MLSS concentration is maintained by adjusting the wasting rate. If the MLSS drops below the target concentration, wasting is reduced or stopped until the MLSS increases to the desired level. If the MLSS concentration is above the target level, wasting of the excess solids should be increased. The increase or decrease in the wasting rates should be implemented gradually (no more than 20 percent per week), and it is better to waste continuously than to waste intermittently.

It is important that the MLSS measurements are accurate, and the samples collected are representative of the overall condition in the reactor. This method can be employed if the influent wastewater characteristics (e.g., flow, BOD, TKN, TSS) are fairly constant. With widely varying influent characteristics, this control method may result in poor effluent quality due to highly variable F/M ratios.

Total Biomass Control

In this solids inventory control method, the total biomass inventory in the overall biological treatment system (i.e., aeration tank and the secondary clarifier) is maintained at a constant preset level. The set point is determined based on previous experience, and trial and error. The solids inventory will be maintained at the target level by adjusting the WAS rate.

Total biomass control depends on measuring the MLSS concentration in the aeration basin as is done in any of the other control methods, but also depends on estimating the amount of sludge in the clarifier. A “Sludge Judge ” can be used to obtain a core sample of the clarifier contents. This sample is then analyzed for TSS. The mass of solids in the clarifier is then calculated by multiplying the concentration in the core sample by the clarifier volume. Care must be taken to obtain a core sample that is representative of the entire clarifier contents. Alternately, multiple core samples could be taken and averaged to obtain a representative solids concentration.

The total biomass control approach is beneficial in plants where a significant inventory of solids is kept in the clarifier (high sludge blankets) or where the amount of sludge kept in the clarifier can vary significantly from day to day or during the day, because of varying sewage flow rates or RAS rates.

Automated Control

An automatic waste control system can be installed for constant and accurate control over solids inventory in the biological treatment process. An automatic sludge wasting control approach could be based on any one of the above control methods or a combination. Automation merely replaces the manual control steps the operator would perform to maintain the solids inventory at the designed set point with actions initiated by a computer control system.

Implementation of an automated solids inventory control scheme will require some or all of the following on-line measurements: solids concentration in mixed liquor, RAS, WAS, final effluent, flow rate of influent, effluent WAS and RAS, and possibly sludge blanket level and concentration in secondary clarifiers. Proprietary control systems are available. For more details on automatic sludge wasting control, the reader is referred to:

- Automated Process Control Strategies, A Special Publication (WEF, 1997);
- Sensing and Control Systems: A Review of Municipal and Industrial Experiences (WERF, 2002); and
- Five Case Histories of Automatic Sludge Age Control (Hill et al., 2002).

3.3.3 SECONDARY CLARIFIERS

Secondary clarifiers have three basic functions:

- remove the biomass from the bioreactor effluent;
- collect the settled solids for return to the bioreactor; and
- provide scum removal.

The biomass settles in a clarifier, and the return activated sludge system pumps the settled sludge, concentrated as much as practical, from the clarifier back to the aeration tank. Controlling the RAS system ensures that the sludge blanket level and the RAS concentration are maintained at an optimum level in the secondary clarifier. Otherwise under high flow conditions, the sludge will be transferred from the bioreactor into the clarifier at a higher rate than it is removed by the RAS system causing the sludge blanket to rise and potentially overflow the clarifier weir. Under low flow conditions, the sludge will be removed from the clarifier faster than it is entering the clarifier from the bioreactor, preventing the sludge from thickening effectively, which leads to dilute return sludge and wasted energy. The RAS control should have the following objectives depending on the design of the system and desired result (WEF, 1996):

- prevent gross process failure (no solids washout during high flow);
- minimize effluent suspended solids;
- prevent denitrification;
- maximize thickening for solids processing;
- prevent thickening failure caused by bulking solids or inadequate clarifier capacity; and
- optimize performance in terms of operations and maintenance costs.

Various control options exist for returning sludge into an aeration tank to meet the aforementioned objectives and achieve solids inventory control in the secondary clarifier. The commonly practised RAS control strategies include:

- constant RAS rate control;
- flow proportioned RAS control; and
- sludge blanket level control.

The goal of the RAS control strategy is to maintain a relatively constant solids retention time in the clarifier and a stable balance of the amount of the mass of sludge in the clarifier and the mass in the bioreactor. Wheeler et al (2001) describe how the control of these parameters were effectively applied to improve the performance of a WWTP

Constant RAS Rate

The simplest approach is to set the RAS pumping at a constant rate throughout the entire day. Due to its simplicity and minimum control requirements, this method is used more often at small plants with limited flexibility, and is typically implemented manually by adjusting a valve position or pump speed to control the flow. Generally, when a constant RAS rate is used, the RAS pumps are operated at their maximum output at all times. If pump speeds or valve positions can be changed, the operator can then vary the RAS rate from day to day in response to changes in sludge settleability or other operating conditions.

Constant RAS rate control results in variable MLSS in the aeration process, variable sludge blanket levels in the secondary clarifiers, and variable RAS concentrations. When the plant flow is higher during the day, solids are entering the clarifier at a rate that is faster than the rate at which they are returned to the aeration tank. This results in an accumulation of solids in the clarifier that must be considered in the control of solids inventory in the overall secondary process. Similarly, when the plant flow is lower, the solids are returned to the aeration tank at a faster rate than the rate at which they are entering the clarifier. In essence, the clarifier acts as a storage tank for MLSS, and the clarifier has a constantly changing depth of sludge blanket as the MLSS moves from the aeration tank to the clarifier and vice versa.

Flow Proportioned RAS

In flow proportioned RAS control, the RAS pumping rate is changed as the plant flow rate changes. To be effective, automatic control of the RAS rate is needed. The automatic control system will consist of flow measurement devices for RAS flow and influent flow to the secondary process, and the capability to change the RAS rate in response to a signal from the control system. The control system would be programmed to maintain a RAS flow at a constant percentage of the aeration tank influent flow rate. However, under high influent flows, variable RAS flow control may cause clarifier failure (WEF, 1997). If implemented manually, frequent adjustments of RAS rates are required based on the influent flow rates.

Compared to constant RAS rate operation, flow proportioned RAS will result in a more consistent sludge blanket height at the sidewall in the secondary clarifier and a more constant MLSS concentration in the bioreactor. As the flow of MLSS into the clarifier increases, the rate of recycle of sludge from the clarifier to the bioreactor also increases, and thus sludge is not allowed to accumulate in the clarifier.

Sludge Blanket Level Control

This method of solids inventory control is based on maintaining a relatively constant sludge blanket height in the secondary clarifier. The operator should review daily blanket levels and return rates for the previous several days, and try to maintain a RAS rate within the target range, which is determined based on previous experience. In circular clarifiers, the blanket height at the sidewall should be maintained at between 0.3 m and 0.9 m in the clarifiers, and typically not be allowed to rise beyond 25 percent of the nominal side water depth of the tank (WEF, 1996). In rectangular clarifiers, blanket height will vary along the length of the tank but should be kept at a level that prevents blanket carry-over.

A high sludge blanket may cause effluent quality to deteriorate, and is indicative of clarifier overloading due to high flows, an inappropriate (too high or too low) return rate, or too high an MLSS concentration due to insufficient wasting. A high blanket combined with a low solids concentration may be caused by poor sludge settling, and typically indicates a process problem in the bioreactors. With bulking sludge, the operator must exercise caution since an increased return rate with bulking sludge may cause the blanket to rise further. In addition, increased flows into the clarifier can cause turbulence and short circuiting.

As the sludge blanket level varies throughout the day due to varying wastewater flow and characteristics, it is best measured during the maximum daily flow when the clarifier is under the highest loading rate. Consistent measurement of the sludge blanket level with respect to location, time of day, and measurement method should be exercised. The sludge blanket level can be measured manually, or with an on-line automatic sludge blanket detector. The RAS flow is adjusted based on the target blanket level.

Sludge blanket level control allows changes in sludge settleability, that affect the sludge blanket level, to be detected and the RAS rate be altered to reflect these changes. This is an advantage compared to flow proportioned RAS control that does not respond to changes in sludge settleability. Automated sludge blanket level control does require more sophisticated instrumentation, including on-line sludge blanket level detectors, than the other control methods.

3.3.4 SLUDGE TREATMENT PROCESSES

The objectives of the sludge treatment processes can include stabilizing the solids, reducing the mass and the volume of solids requiring further treatment or land application, and conditioning the solids so that they can be effectively dewatered. Biological stabilization, either by aerobic or anaerobic digestion, is the most common sludge stabilization process. Optimizing the operating conditions in digestion processes can often be effective in improving their performance. Controlling the solids inventory in the digestion process, which controls the hydraulic and solid retention time in the system, is often the key to optimizing process performance.

Pre-thickening of the sludge to increase the sludge concentration and decrease the volume of sludge fed to the digester proportionately increases the retention time in the digester, enhancing digester performance. In anaerobic digestion processes, heat requirements to pre-heat the sludge are also reduced (WEF, 1996) and gas production is increased if a higher level of volatile solids destruction is achieved. Pre-thickening by gravity settling or mechanical processes such as centrifuges or drum thickeners can be used.

Co-thickening of WAS with the primary solids in the primary clarifier is a common practice, but results in a more dilute sludge being pumped to the downstream sludge processes. Separate WAS thickening using processes such as centrifuges, drum thickeners, gravity belt thickeners, or dissolved air flotation thickeners, will produce a more concentrated sludge (4 to 8% TS), provide additional capacity in the primary clarifier, and reduce the risk of overloading the biological process due to solids carryover from the primary clarifier to the downstream bioreactor. Separate thickening of WAS can be particularly beneficial in extended aeration plants to increase the capacity and improve the performance of the aerobic digesters commonly used at this type of plant. Post-thickening using mechanical thickeners or by gravity settling of the digested sludge reduces the volume of biosolids that must be managed. In conventional two-stage aerobic or anaerobic digestion, the second stage of the process is intended to post-thicken the stabilized biosolids. Managing the inventory of solids in the process is critical to provide adequate settling time in the secondary digester to optimize sludge concentration.

The Water Environment Research Foundation (WERF) has recently completed a review of automation systems to optimize the operation of mechanical thickening and dewatering processes (WERF, 1998). This study identified and evaluated several proprietary automation and control systems for optimization of thickening and dewatering operations. Automation was shown to reduce chemical costs and increase thickened sludge concentrations, but the instrumentation associated with the automation systems required significant maintenance.

3.3.5 FERMENTERS

Primary sludge fermentation, normally associated with Biological Nutrient Removal (BNR) processes, is performed to produce a source of rapidly biodegradable organics for the microorganisms involved in biological phosphorus removal. These organic compounds can also serve as the energy source for biological denitrification processes in which nitrate is converted to nitrogen gas in the absence of molecular oxygen. Maintaining a sludge inventory in the fermenter involves establishing the optimum amount of solids in the fermenter to achieve a solids retention time (SRT) between 4 to 8 days. The control of the solids inventory is aimed at avoiding conditions that will allow methane production in the fermenter when the SRT is too long. Waste fermented sludge is continuously withdrawn from the fermenter and pumped to the sludge handling processes.

- In order to control the solids inventory, two methods can be used:
- Monitoring the sludge blanket level; and,
- Controlling the solids rate of the primary sludge feed.

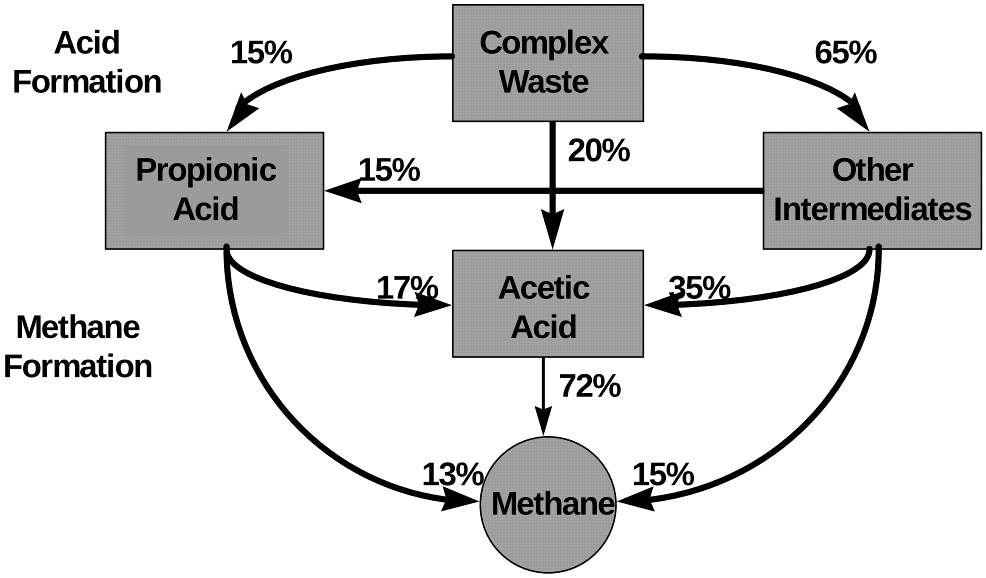
The microorganisms involved in biological phosphorus removal need a carbon source (volatile fatty acids – VFA) as feedstock, and gain a competitive advantage when the short chain VFAs, principally acetate and/or propionate, are available. About 4 to 6 g of VFA are needed to remove 1 g of phosphorus. If biological denitrification is also occurring, about 4 g of VFA are needed to denitrify 1 g of nitrate-nitrogen. In many BNR processes, the same carbon source can be used by the microorganisms for both nitrogen and phosphorus removal.

There are four types of primary sludge fermenter configurations commonly used to generate VFA in BNR processes:

- activated primaries;
- completely mixed fermenter;
- static fermenter; and,
- complete mix/thickener.

Most fermenters both thicken and ferment the primary sludge. Figure 3-4 represents the primary sludge fermentation pathway:

Figure 3-4 Primary Sludge Fermentation Pathway



Source: Dr. James Barnard
Seminar on Biological Nutrient Removal in Cold Climates, Presented by James L Barnard, Ph.D., P. Eng, March 18-19 2004, Edmonton Alberta Canada, Sponsored by Alberta Environment - Northern Region and the City of Edmonton.

4. APPLICATIONS AND LIMITATIONS

4.1 APPLICATIONS

The elements of this best practice for solids inventory control apply to any size or type of mechanical WWTP. Since effective solids inventory control is essential to achieve optimum WWTP performance, the principles described are applicable to all unit processes at a WWTP. A sludge accountability analysis should be routinely done each month and on an annual basis to confirm that a mass balance on solids in the WWTP can be completed and as a quality assurance check on the operation of the plant.

4.2 RESOURCES

Manual implementation of the solids inventory control techniques described in this best practice does not require any new tools or measurement techniques other than those routinely undertaken at most WWTPs. These include measurement of key flows such as raw sewage, return sludge (RAS), waste sludge (WAS), primary clarifier sludge, and digested sludge, and analysis of key wastewater and sludge streams for solids concentration or solids volume.

Automation of some of the solids inventory control techniques will require on-line measurement of parameters, such as sludge concentration and sludge blanket level, and a sophisticated SCADA system to implement the control logic.

4.3 LIMITATIONS

This best practice focuses on mechanical WWTPs rather than lagoon-based systems. The accumulation of solids in a lagoon is difficult to determine accurately and an accurate sludge accountability analysis and solids mass balance cannot be completed on a lagoon-based WWTP.

A sludge accountability analysis can and should be done for any type of mechanical treatment plant (i.e., primary treatment, secondary treatment using any type of suspended growth or fixed film biological process, tertiary treatment); however, the concepts described in this best practice to control the solids inventory in the biological treatment process do not apply to fixed film biological processes, such as rotating biological contactors (RBCs) or trickling filters. In these processes (unlike the suspended or hybrid systems), the operator cannot control the wasting rate from the process. As a result, the operator does not have the ability to control the SRT or the solids inventory.

5. EVALUATION

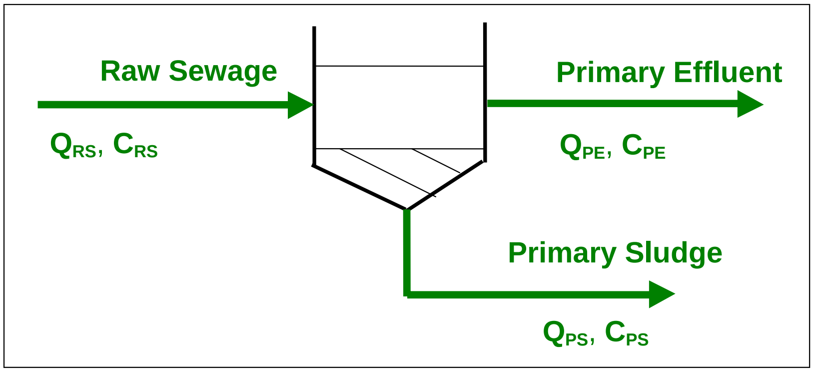
Implementation of a solids inventory control program must include monitoring and tracking of the solids in the process to determine if the control strategy being used is effective. The total solids inventory should be determined daily and displayed graphically in terms of solids retention time (SRT), sludge mass (kg or tonnes), centrifuged volume (percent), or sludge units (SLUs). To minimize the impacts of normal daily variation, seven-day moving averages of the key control parameter should be calculated and plotted.

Good solids inventory control should maintain the selected control parameter within 10 to 20 percent of the target value. Long-term tracking of the selected control parameter in each unit process (e.g., SRT, F/M, MLSS or total biomass in the biological system) will demonstrate that effective control has been achieved. When effective control has been realized at the optimum set point, more reliable WWTP performance will be observed, effluent quality will be improved or maintained, and opportunities will be available to increase the capacity of the system.

APPENDIX A: EXAMPLE MASS BALANCE CALCULATIONS

A.1 PRIMARY CLARIFIER

Figure A1: Solids Mass Balance Around a Primary Clarifier



Where:

$Q_{RS} = 1000\ m^3/d$

$C_{RS} = 200$ mg/L TSS

$C_{PE} = 80$ mg/L

$Q_{PS} = 5\ m^3/d$

$C_{PS} = 4.5\%$ TS

= 45 000 mg/L TS

SOLIDS IN = $Q_{RS} * C_{RS}$

$$= (1000\frac{m^3}{d} x \frac{200mg}{L} x \frac{1000L}{1m^3} x \frac{1kg}{10^6 mg})$$

= 200 kg/d solids

SOLIDS OUT = $Q_{PE} * C_{PE} + Q_{PS} * C_{PS}$

Where $Q_{PE} = Q_{RS} - Q_{PS}$

$= 1000\ m^3/d - 5\ m^3/d$

$= 995\ m^3/d$

$$\text{SOLIDS OUT} = (995\frac{m^3}{d} x80\frac{mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6} mg) +$$

$$(5\frac{m^3}{d} x45{,}000\frac{mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6 mg})$$

$$= (\,79.6\frac{kg}{d}\,) + (\,225\frac{kg}{d}\,)$$

$$= 304.6\ \frac{kg}{d}$$

Therefore, Solids Out (304.4 $\frac{kg}{d}$) exceeds Solids In (200 $\frac{kg}{d}$) by 52 percent.

Conclusion:

- Mass balance does not close within ±15 percent.
- Operator should:
- verify accuracy of raw sewage and sludge flow meters;
- confirm sampling protocols are representative for raw sewage, primary effluent, and sludge;
- verify analytical methods for suspended and total solids; and
- check that sludge blanket level (solids accumulation) in clarifier has not decreased over period of record.

A.2 PRIMARY CLARIFIER WITH RECYCLES

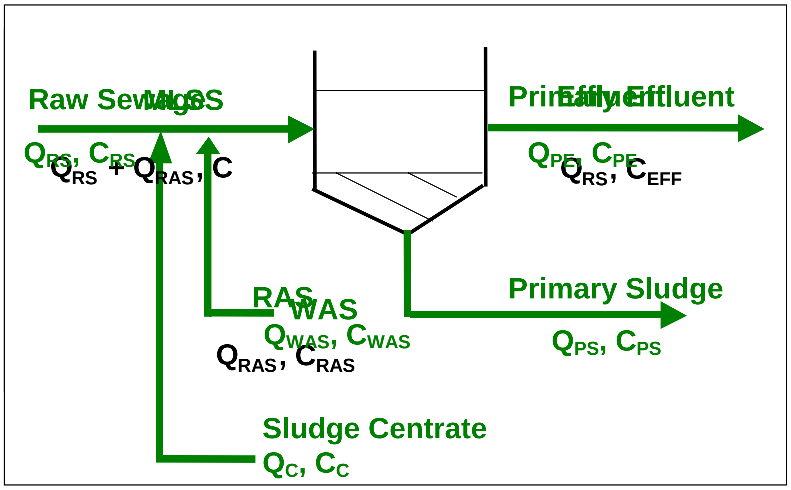


Figure A–2: Solids Mass Balance Around a Primary Clarifier with Recycle Streams

Where:

Q_{RS} = 1000 m^3/d

C_{RS} = 200 mg/L TSS

Q_{WAS} = 16 m^3/d

C_{WAS} = 8000 mg/L TSS

Q_C = 3 m^3/d

C_C = 2500 mg/L TSS

C_{PE} = 80 mg/L

Q_{PS} = 10 m^3/d

C_{PS} = 3.0% TS

= 30 000 mg/L TS

SOLIDS IN = $Q_{RS} * C_{RS} + Q_C * C_C + Q_{WAS} * C_{WAS}$

$$= (1000\frac{m^3}{d} x \frac{200mg}{L} x \frac{1000L}{1m^3} x \frac{1kg}{10^6 mg})$$

$$+ (3\frac{m^3}{d} x \frac{2500mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6 mg})$$

$$+ (16\frac{m^3}{d} x \frac{8000mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6 mg})$$

$$= (200 \frac{kg}{d}) + (75 \frac{kg}{d}) + (128 \frac{kg}{d}) = 403 \frac{kg}{d}$$

$$= 403 \frac{kg}{d}$$

$$\text{SOLIDS OUT} = Q_{PE} * C_{PE} + Q_{PS} * C_{PS}$$

$$\text{Where } Q_{PE} = (Q_{RS} + Q_C + Q_{WAS}) - Q_{PS}$$

$$= (1000\,\frac{m^3}{d} + 3\,\frac{m^3}{d} + 16\,\frac{m^3}{d}) - 10\ m^3/d$$

$$= 1009\,\frac{m^3}{d}$$

$$\text{SOLIDS OUT} = (1009\frac{m^3}{d}x80\frac{mg}{L}x\frac{1000L}{1m^3}x\frac{1kg}{10^6}mg) +$$

$$(10\frac{m^3}{d}x30{,}000\frac{mg}{L}x\frac{1000L}{1m^3}x\frac{1kg}{10^6 mg}$$

$$= (80.7\frac{kg}{d}) + (300\frac{kg}{d})$$

$$= 380.7\,\frac{kg}{d}$$

Therefore, Solids Out (380.7 $\frac{kg}{d}$) is 94.5% of Solids In (403 $\frac{kg}{d}$).

Conclusion:

- Mass balance closes within ±15 percent and information is reliable.

A.3 SECONDARY TREATMENT

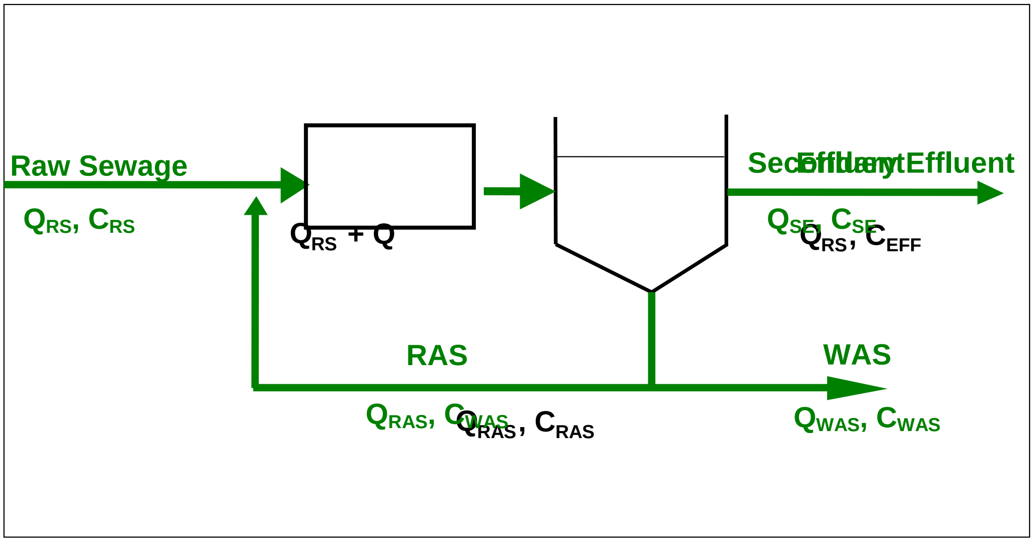


Figure A–3: Solids Mass Balance Around an Extended Aeration Plant

Where:

Q_{RS} = 1000 m^3/d

C_{RS} = 200 mg/L BOD_5

Q_{WAS} = 16 m^3/d

C_{WAS} = 4000 mg/L

Q_{SE} = 15 mg/L TSS and 15 mg/L BOD_5

SOLIDS IN = Q_{RS} * C_{RS} * Biomass Yield

Where Biomass Yield per Table 3 = 0.65 kg TSS/kg BOD removed.

SOLIDS IN =

$$[1000\frac{m^3}{d}x(\frac{200mgBOD_5}{L}-\frac{15mgBOD_5}{L})x0.65\frac{kgTSS}{kgBOD_5}x\frac{1000L}{m^3}x\frac{1kg}{10^6mg}]$$

$$= 120.25\ \frac{kgTSS}{d}$$

SOLIDS OUT = Q_{SE} * C_{SE} + Q_{WAS} * C_{WAS}

Where Q_{SE} = $Q_{RS} - Q_{WAS}$

$$= (1000\ \frac{m^3}{d}\ -\ 16\ \frac{m^3}{d})$$

$$= 984\ \frac{m^3}{d}$$

$$\text{SOLIDS OUT} = (984\frac{m^3}{d} x 15\frac{mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6 mg}) +$$

$$(16\frac{m^3}{d} x 4{,}000\frac{mg}{L} x \frac{1000L}{m^3} x \frac{1kg}{10^6 mg}$$

$$= (14.8\frac{kg}{d}) + (64\frac{kg}{d})$$

$$= 78.8\ \frac{kg}{d}$$

Therefore, the measured Solids Out (78.8 $\frac{kg}{d}$) is 65.5% of the estimated Solids In (120.25 $\frac{kg}{d}$).

Conclusions:

- All the solids that should have been produced (120.25 kg/d) are not accounted for in the amount of solids exiting the process (78.8 kg/d).
- The mixed liquor in the aeration tank should be reviewed to see if the solids inventory in the tank increased by an amount equal to the discrepancy in the mass balance (120.25 kg/d – 78.8 kg/d = 41.45 kg/d).
- The sludge blanket in the clarifier should be reviewed to determine if the mass of solids not accounted for in the mass balance has accumulated in the clarifier as an increase in sludge blanket level or concentration.
- If the solids inventory in the aeration basin or clarifier has not changed, other sources of discrepancy (flow measurement, sampling, analytical method, unknown recycle streams, etc.) should be evaluated

APPENDIX B:
EXAMPLE MOVING AVERAGE CALCULATION

A moving average provides trend information that a simple average of all data would not provide by smoothing out the fluctuations in the data set. A seven-day moving average SRT is calculated by the following formula:

$$7\text{ - day Moving Average} = \frac{\text{sum of actual SRT values for the last 7 days}}{7}.$$

Table B–1 presents the actual daily SRT values and the corresponding seven-day moving averages for a period of 28 days. Figure B1 shows the plot of actual SRTs and seven-day moving averages for the 28 days.

Table B–1: Actual SRT and Seven-Day Moving Average

Day	SRT	
	Daily (day)	Seven-Day Moving Average (day)
1	13.1	N/A
2	13.6	N/A
3	14.7	N/A
4	12.1	N/A
5	10	N/A
6	5.4	N/A
7	6.7	10.8
8	6.6	9.9
9	7.1	8.9
10	8.1	8.0
11	7.9	7.4
12	14.3	8.0
13	14.8	9.4
14	13.1	10.3
15	12.1	11.1
16	14.6	12.1
17	12.8	12.8
18	10	13.1
19	8.2	12.2
20	8.6	11.3
21	6.7	10.4
22	6.5	9.6
23	8.8	8.8
24	10.1	8.4
25	10.6	8.5
26	13.5	9.3
27	13.1	9.9
28	14.8	11.1

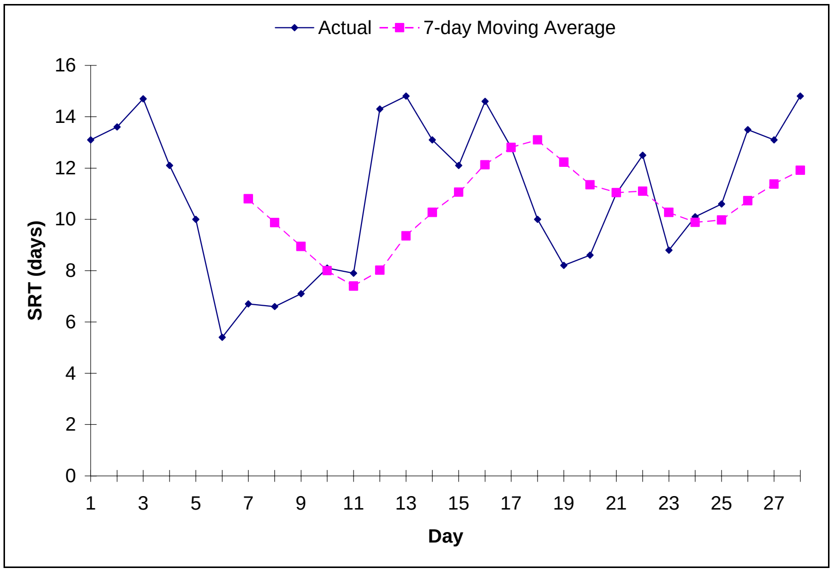


Figure B–1: Actual SRT and Seven-Day Moving Average

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