Clarification Concepts for Treating Peak Wet-Weather Wastewater Flows

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Since the passage of the Clean Water Act in 1972, nearly all municipal facilities in the United States have implemented a minimum of secondary treatment. With most dry-weather pollution from sanitary sewer systems under control, the attention of the regulatory establishments has shifted to the capture and treatment of wet-weather induced overflows and bypass flows that can significantly affect receiving water quality.

Wet-weather overflows adversely impact receiving water by impairing aquatic habitat, degrading receiving water aesthetic quality, and potentially affecting human health by contaminating beaches and shellfish (1). The water quality impacts of wet-weather wastewater flows vary, depending on their frequency, magnitude, and water quality of the wet-weather discharge relative to the flow and quality of the receiving water.

Current practice depends on the type of collection system (separate or combined), location, and state requirements. Before the advent of national combined sewer overflow (CSO) regulations, most communities with combined systems continued the routine use of CSO facilities, or bypassed peak flow around parts of their wastewater treatment facilities.

Perhaps the most common practices at treatment plants have been providing preliminary and primary treatment for all flows with bypass of peak flows around secondary treatment, blending the biological effluent with the bypassed flow, disinfection, and discharge.

A variety of other wet-weather treatment strategies are in use. Principal alternatives to clarifiers for wet-weather flow management include constructing additional treatment plant capacity; using in-line and off-line wet-weather storage; and decreasing peak flow volumes through reduction of rainfall-derived infiltration and inflow, sewer separation, or rerouting flows to a different treatment plant.

Wet-weather issues came to the forefront in the later 1980s and the early 1990s (2). The U.S. Environmental Protection Agency (EPA) issued a national CSO control strategy in 1989 (40 CFR 37370, August 10, 1989) and a CSO control policy in 1994 (59 Federal Register 18688, April 19, 1994). More recently, the EPA issued a proposed policy on blending (68 Federal Register 63042, November 7, 2003).

January 1, 1997, was the deadline set by the 1994 policy for implementing minimum technology-based controls, known collectively as the "nine minimum controls." One of these controls requires that communities maximize flow to the local publicly owned treatment works (POTW).

The 1994 policy requires holders of National Pollutant Discharge Elimination System (NPDES) permits to develop long-term control plans for controlling CSOs. Long-term control plans must either demonstrate that the plan is adequate to meet water-quality requirements or implement a minimum level of treatment (2). Water-quality standards are presumed to be met if the technology-based approach is used. Some states have implemented laws or regulations that go beyond the EPA's CSO policies.

As a result of current regulations, most municipal wastewater treatment plants are expected to provide some degree of treatment for all the flow received at their facilities, regardless of the magnitude and duration. Wet-weather treatment strategies may include measures to minimize the investment in treatment facilities for peak wet-weather flows that occur infrequently, while still providing adequate protection for the receiving water.

Clarification is often a key component of wet-weather treatment strategies. Examples of wet-weather treatment strategies that incorporate clarification range from increasing the rated capacity of existing conventional primaries to constructing dedicated wet-weather clarifiers. Alternately, process modifications can be implemented to protect secondary settling tanks from the impact of periodic high flows.

Wet-weather clarifiers can be conventional clarifiers operated at traditional loading rates or clarifiers enhanced by one or more modifications designed to increase the allowable hydraulic loading or improve pollutant removals. Many names are used to describe advanced clarification processes, including high-rate clarification (HRC), enhanced high-rate clarification (EHRC), high-rate flocculated settling, dense sludge, high-rate sedimentation, microcarrier weighted coagulation, chemically enhanced high-rate separation, and microcarrier coagulation-sedimentation. High-rate clarification will be used in this article to describe advanced clarification processes that use a combination of chemical coagulation, increased floc settling velocities, and plates or tubes to improve clarifier performance.

Wet-weather clarifiers do not have to be located at the main treatment facility. Peak flows can be diverted to upstream, stormwater clarifiers with overflow to receiving water during events exceeding the design storm. Clarifier contents are returned to the sewer system after the storm flows end.

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Rather than attempting to increase primary treatment capacity, an alternate wet-weather strategy is to implement modifications to the biological process that increase the capacity of the secondary settling tanks during wet-weather flows. Common techniques are to switch the aeration tank feed pattern to a step-feed or contact stabilization activated sludge configuration, or to provide additional 'wet-weather' secondary settling tanks. Wet-weather secondary clarifiers can be constructed to serve the dual purposes of wet-weather flow storage and secondary settling; however, storage at this location in the process provides few benefits.

Another wet-weather treatment method that relies on the same basic mechanism as step-feed is aeration tank settling (ATS). Turning the air off in all or just the latter parts of an aeration tank during peak flow periods allows the mixed liquor suspended solids (MLSS) to begin to settle in the aeration tank and reduces the MLSS concentration entering the final clarifiers.

While vortex separators, also known as swirl concentrators, are commonly used to treat CSOs, they can also be used to treat peak wet-weather flows at wastewater treatment facilities. Vortex separators can be used with and without chemical flocculation in a manner analogous to conventional primary clarifiers.

Basics

Clarifiers used for wet-weather treatment conform to the same theories as primary and secondary clarifiers in traditional applications. Settling in primary clarifiers is flocculant, or Type 2 settling, whether it is used for dry- or wet-weather wastewater. Settling in secondary sedimentation tanks is hindered, or Type 3 settling. Performance of all clarification devices is determined in large part by the settling characteristics of the suspended particles, especially the settling velocity.

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Wastewater characteristics

Water quality and resulting mass loads imposed on the treatment process by storm flows differ from the base flow. Storm flows can have significantly lower concentrations of some pollutants and higher concentrations of others, depending on antecedent conditions, the magnitude of the flows, and the time since the start of a storm event.

The "first flush" of wet-weather flow often results in a transient increase in the mass load of pollutants received at a treatment plant. Prolonged and exceptionally high storm flows can re-suspend sediments deposited in the collection system or scour biomass from pipe walls and transport both to the treatment plant.

Depending on the season and location, storm flows can be colder or saltier than normal flows. Also, it is reasonable to expect that storm flows will have different amounts of organic matter and different frequency distributions of particle sizes. For instance, the fraction of particles in wet-weather flows that can be removed by gravity settling may be different from dry-weather sewage, so it is prudent that evaluations of wet-weather wastewater treatment be based as much as possible on the characterization of real wet-weather flows generated in the collection system.

Significant work has been done to characterize stormwater and, to some extent, peak wet-weather wastewater quality. Research during the past decade has attempted to quantify the settling characteristics of wet-weather sewage, including measurement of settling velocity distributions (3) (4) and settleability (5).

Research and practical experience show that both dry-weather and wet-weather wastewaters contain a complex mixture of solids. Solids present in wet-weather wastewater originate from three main sources: surface runoff that enters the collection system, biofilms or slimes that erode from the conduit walls, and the native particulate matter from sanitary waste(6). Likewise, the composition, size, and settling characteristics of these solids are a complex function of many parameters, including the range of water velocities experienced; the type of collection system (separate or combined); the size and characteristics of the service area; the duration and intensity of rainfall; and, to some extent, the historical changes in these parameters.

Settling Velocities

A number of researchers have investigated the settling characteristics of suspended matter in both dry- and wet-weather flows(4, 7-9). Typically the size, density, and settling velocity of suspended solids cover a wide range; however, certain generalizations can be made about the relative settling velocity of the suspended solids in combined wastewater. The particles in wet-weather flows tend to be heavier and denser and to settle faster than the solids in either dry-weather wastewater or street runoff (8) (3).

Two mechanisms are responsible for the increase in settling velocities observed in wet-weather flows. First, higher flows increase the shear stress at the pipe walls and the sediment transport capacity of the collection system. Second, the higher velocities erode biofilms from the pipe walls.

Coagulation/Flocculation

The total suspended solids (TSS) and BOD_5 removal efficiency that is obtained by any sedimentation process can be no better than the percentage of settleable TSS in the wastewater and the fraction of the BOD_5 or COD that is associated with the settleable solids. Coagulation is used to destabilize the small particles in wastewater so that they will more readily coalesce into larger particles that can be separated from the wastewater. Flocculation fosters the particle transport needed for the growth of the floc created by coagulation into larger particles of settleable size.

Coagulation and flocculation are typically associated with the use of chemicals; however, the energy input associated with rapid-mix and flocculation facilities will result in larger particle sizes and enhance the performance of sedimentation tanks, even without the use of chemicals (10). Conventional primary clarifiers with typical TSS and BOD_5 removal efficiencies of about 50 percent and 30 percent respectively are reasonably efficient at removing settleable particles (11) (12); however, the efficiency of primary sedimentation can be increased significantly – to 40 to 80 percent for organic carbon and to 60 to 90 percent for suspended solids – by increasing the fraction of particles of settleable size.

Changes in Suspended Solids Concentration

Mixed-liquor settling velocities in wastewater are a function of the TSS concentration. As a result, secondary clarifier capacity is a function of mixed-liquor suspended solids concentration, as well as clarifier surface area. Reducing aeration tank mixed-liquor concentration can significantally increase the flow capacity of secondary settling tanks.

Types

Conventional Primary Treatment

In conventional primary sedimentation, performance is based on the natural tendency of the particles in wastewater to agglomerate into larger particles (Type 2 settling) and settle from the water under quiescent conditions (13). Primary sedimentation has long been a staple of municipal wastewater treatment because of its simplicity and proven ability to remove a large percentage of the TSS and BOD_5 in raw wastewater at a low unit cost.

These same advantages will ensure that classic primary sedimentation will play a role in many wet-weather treatment strategies; however, there are inherent limitations in classical primary sedimentation that make it economically unattractive for occasional use. Disadvantages include the relatively low settling velocity of many wastewater particles and the relatively high fraction of suspended solids that will not settle at all. BOD_5 and TSS removal efficiency is limited by the fraction of particles that will not settle. Low settling velocities translate into relatively large sedimentation tank surface areas and high capital cost if they are used only for occasional extreme flow events.

Re-rated Conventional Primary Clarification

Studies show that primary clarifiers typically remove a significant fraction of the settleable solids in raw wastewater and that performance is only weakly related to the tank hydraulic overflow rate (12). During storm events, particle settling velocities in sewage may increase, and depending on the magnitude and duration of a storm, the suspended solids concentration may decrease due to dilution by infiltration and inflow. This implies that higher flow rates can be tolerated through primary clarifiers during storm events without a significant increase in the effluent suspended solids, unless there is a concurrent increase in the non-settleable solids concentration.

Standards for peak overflow rates for primary clarifiers in most traditional design guidelines range from about 2.0 to 5.0 meters per hour (m/h) (14). Demonstrating that a clarifier operates satisfactorily at a velocity of 5 m/h or higher during intermittent peak flows, as opposed to 2.0 m/h, means a substantial difference in wet-weather treatment capacity. This highlights the importance of quantifying the expected performance of primary clarifiers based on settling velocity distributions or by full-scale testing during actual storm events.

Chemically enhanced primary treatment

Chemically enhanced primary treatment (CEPT), whereby wastewater is chemically coagulated before clarification, is the simplest enhancement that can be made to conventional primary clarification to increase treatment capacity. Chemical coagulants, such as ferric chloride and alum, provide cations that destabilize the colloidal particles in wastewater while flocculent aids, such as polymer and microsand, function to accelerate the growth of floc, enlarge the floc, improve floc shape, strengthen floc structure, and increase particle specific gravity.

The use of chemicals allows a higher peak overflow rate during peak flow events while maintaining or increasing primary clarifier performance, thus minimizing the clarifier surface area that must be provided for peak flows. CEPT can be a full-time treatment method, but its use for controlling storm flows, its use is limited to peak wet-weather periods.

Chemically enhanced primary treatment has evolved over time. Early applications typically consisted of simply adding ferric, alum, or lime to a conventionally designed primary settling tank. Current practice uses smaller metal salt doses (20-40 mg/L) in combination with polymer addition (<1 mg/L), and includes the use of rapid mix and flocculation prior to the settling tank.

While CEPT can be practiced by simply adding chemicals to grit tanks and primary clarifier influent channels, optimum performance depends on adequate coagulation prior to sedimentation. Jar testing is essential for determining design chemicals, doses, and rapid mix and flocculation times.

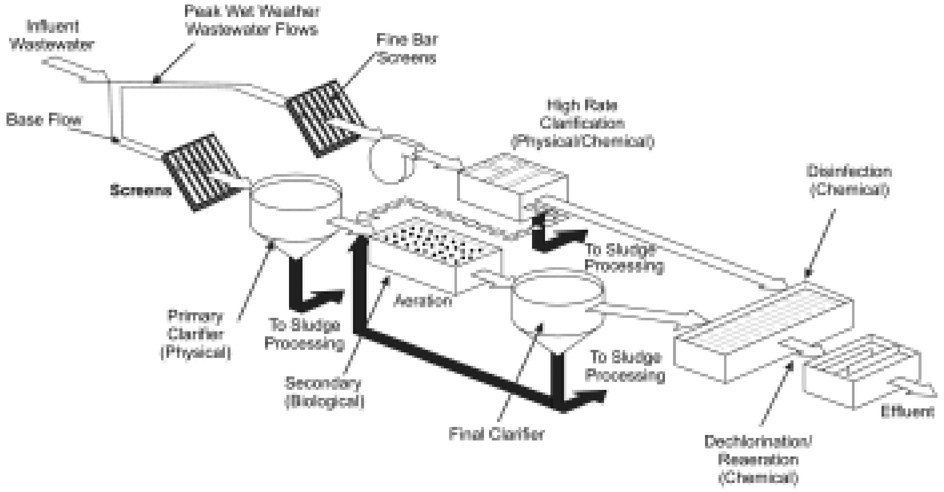

Figure 1: Use of High-Rate Clarification to Treat Peak Wet Weather Flows

Plate Clarifiers

Plates and tubes may be used to improve clarification with or without chemicals. TSS and BOD_5 removal efficiency in plate clarifiers is reported to be similar to that obtainable with conventional primary clarifiers operating at the same overflow rate, based on projected area (15). Limited data is available on TSS and BOD_5 removal efficiency for plates preceded by chemical coagulation; however, it is reasonable to expect that this, too, will be similar to conventional CEPT at comparable overflow rates.

Lamella systems typically consist of inclined parallel metal or, plastic plates, or bundles of tubes installed at the surface of the settling tank to a vertical depth of about 2 meters. Inclined plates or tubes significantly increase the allowable upflow velocity in a clarifier (based on horizontal area) by increasing the settling area by a factor of about 8 to 10, allowing a higher peak flow to be treated in a given tank surface area.

While the classic location for plates is in primary clarifiers, researchers in Germany have investigated their use at the end of the aeration tanks or at the entrance to the secondary settling tanks. Plates in either of these locations reduce the MLSS concentration entering the secondary settling tanks, thereby increasing the peak flow capacity of the secondary settling tanks.

Plates have the ability to increase the

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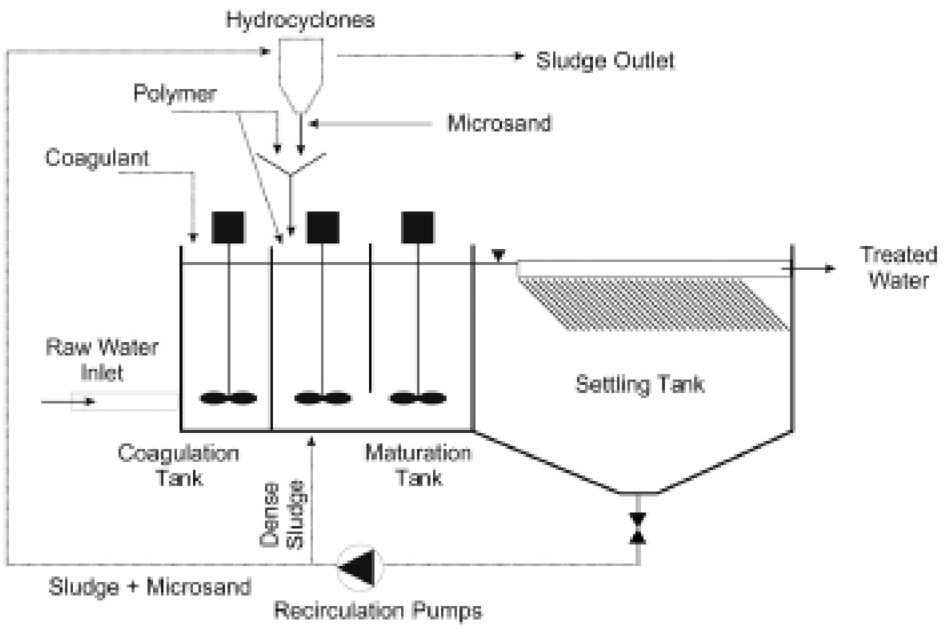

Figure 2: High-Rate Clarification Process Schematic

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capacity of an existing clarifier or reduce the land area required for new ones. In wet-weather applications, the use of plate settlers reduces the cost and space requirements to construct clarifiers for peak wet-weather flows.

The use of plates requires fine screening and satisfactory grit and grease removal prior to the plate tanks. Besides the potential for clogging, other concerns include the increased need for reasonably uniform water distribution to and within each channel, low (laminar) flow velocities, and collection of the sludge while preventing re-suspension (16). Maintenance requirements are expected to be higher for plate clarifiers due to the need for regular cleaning of the plates.

Plate clarifiers commonly have not been used in wastewater applications in the United States. This is not the case for Europe, and especially France, where they are used more frequently. About 130 full-scale wastewater facilities with plate settlers were identified from the reference lists of three manufacturers of plate equipment. Most of these are used to enhance primary treatment and are located in Western Europe, with more than half of them in France.

Design flows ranging from 3,100 m^3/d to 1,700,000 m^3/d have been reported. About 90 percent of the reported installations have a design flow less than 200,000 m^3/d.

High-Rate Clarification Processes

Figure 1 illustrates the use of the high-rate clarification processes (e.g. dense sludge and ballasted flocculation) to treat peak wet-weather flows. High-rate clarification processes are well suited for wet-weather clarification applications because of reduced space requirements; rapid start-up and response times; relative insensitivity to fluctuations in raw-water quality; and improved removal of TSS, BOD, TKN, TP, and metals. Since high-rate clarification facilities for wet-weather flows may be used only several a few times per year, several plants have located high-rate clarification after the biological treatment process, where it can also be used for tertiary suspended solids or phosphorus removal during dry weather.

Two different types of high-rate clarification processes, sometimes referred to as the dense sludge process and the ballasted flocculation process (17), are in common use. Dense sludge is a high-rate clarification process that combines chemical coagulation, sludge recirculation, and plate settling. Ballasted flocculation refers to high-rate clarification processes that increase particle size, density, and settling velocity, by binding solids to a weighting agent, or “ballast,” with metal hydroxide floc and polymer. Very small sand particles (microsand) are the most common ballast.

A typical dense sludge installation consists of influent screening, rapid mix, and flocculation, followed by clarification. **Figure 2** contains elements of both the dense sludge and ballasted flocculation processes. Coagulant is added in the rapid mix zone and a polymer in the flocculation zone. Fine screens are needed to remove large solids that might clog the tubes in the settling zone. A portion of the settled sludge is recycled to the flocculation zone. Sludge is also re-circulated internally within the flocculation zone using a draft-tube turbine mixer.

Chemical coagulation combined with sludge recycle results in the formation of relatively dense floc that settles rapidly. Tubes are used to improve clarification by removing straggler floc and by imposing an additional hydraulic headloss that reduces the formation of turbidity currents and short-circuiting. While the dense sludge process is a versatile clarification process that has been successfully used for water, wastewater, and CSO applications, it has seen limited use in wastewater clarification applications.

The ballasted flocculation process commonly consists of influent screening, rapid mixing, flocculation, clarification with plates, and sand stripping and recirculation. As with the dense sludge process, the process should be preceded by fine screens.

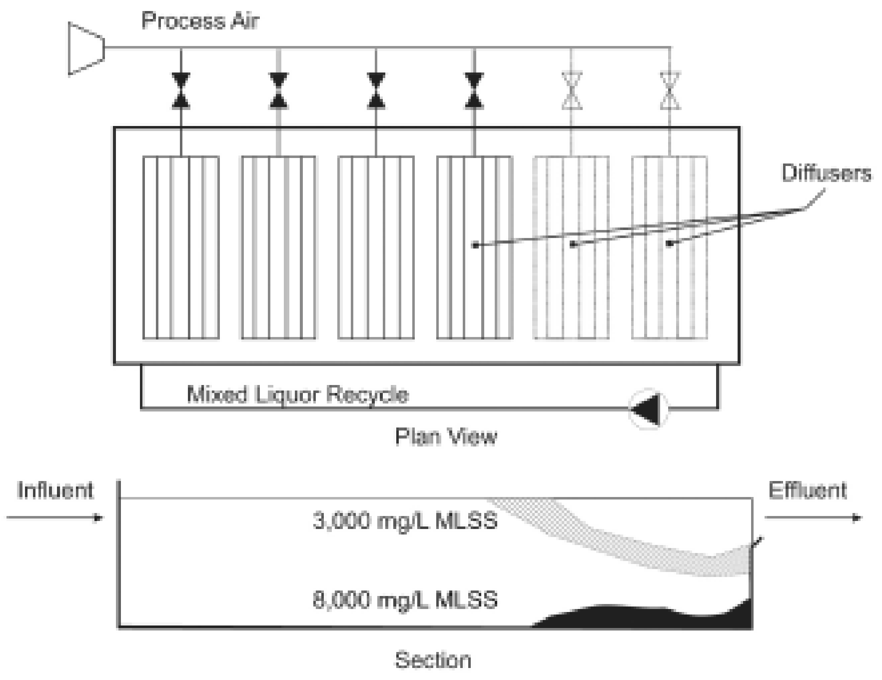

Figure 3: Aeration tank settling (from Nielsen, Beckman and Henze, 2000)

After screening, a coagulant (typically ferric chloride) is added to destabilize the wastewater. This is followed by the addition of fine sand and polymer to enlarge and weight the floc, flocculation, and a settling zone with plates. The sludge is passed through a hydrocyclone to recover the sand, which is returned to the process while the sludge is directed to further treatment.

The major disadvantage of high-rate clarification is the increased doses of metal salt and polymer required to operate the process. This, in turn, increases the annual operating costs; however, if it is only used to treat peak wet-weather flows, the total operating time during a year is relatively small and the additional chemical costs are acceptable. Another disadvantage associated with high-rate clarification processes is the use of hydrocyclones and plates, which requires fine screens before the process.

Aeration Tank Settling

Aeration tank settling is a term used for the practice of turning off the air to all or just the latter parts of aeration tanks during peak flows, as illustrated in **Figure 3**. Mixed-liquor suspended solids then begin to settle in the aeration tank, reducing solids concentration sent to the secondary settling tanks.

The reduction in the suspended solids concentration increases the sludge settling velocity and increases the clarifier capacity during peak flows, when it is most needed. For an SVI of 150 and a mixed-liquor concentration of 3,000 mg/L, a 50-percent drop in the mixed-liquor concentration increases the clarifier capacity by over 80 percent.

One patented version of aeration tank settling combines aeration tank settling with an internal mixed-liquor recycle stream and a high-level process control system. The recycle stream transfers mixed liquor from the last zone of the aeration tank (without air or mixing) to a pre-aeration anoxic zone, and extends the period of time for which aeration tank settling can be effective. Some published data (18) shows that aeration tank settling results in increased denitrification and lower effluent orthophosphate, accompanied by a slight increase in effluent turbidity.

Step-feed

Switching to a step-feed or contact stabilization mode of operation during peak flows allows a greater mass of mixed MLSS to be stored in the initial portions of the aeration tanks, and minimizes the MLSS concentration fed to the secondary settling tanks. Using a step-feed operation allows the plant to maintain a relatively high degree of treatment while treating a significantly higher flow rate.

By varying the location of aeration tank feed points during wet-weather flow events, the suspended solids concentration in the aeration tank effluent (secondary settling tank feed) can be reduced and the capacity of the secondary settling tanks increased significantly (19). In conventional activated-sludge processes, both the aeration tank influent and return activated sludge are added to the beginning of the aeration tank, resulting in a relatively uniform concentration of suspended solids throughout the tank or tanks. A suspended solids gradient can be created in the aeration tank by feeding all or a portion of the influent stream at one or more locations along the length of the aeration tank, while continuing to feed all the return activated sludge to the beginning of the aeration tank.

Using a step-feed pattern creates a high solids concentration at the beginning of the tank and a lower concentration at the end of the tank. Step-feed minimizes the solids loading applied to the final clarifiers for a given SRT and provides a greater biomass, and hence a larger SRT, for a given tank volume than conventional activated sludge. The ease and cost of modifying a conventional activated sludge process to be able to switch to a step-feed configuration during peak flows depends on the design of each facility.

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Vortex Separators

Vortex separators are cylindrical devices used to separate particulate matter from water. Also known as hydrodynamic vortex separators (HVSs) or swirl concentrators, they are characterized by tangential inlets and surface overflows. Solids settle by gravity, are moved toward the center of the unit by secondary currents, and are removed from the bottom center of the device as a dilute sludge with volume of about 5 to 10 percent of the influent flow. Solids can be removed continuously or intermittently when used in CSO applications.

Because HVSs rely on secondary currents and centrifugal forces induced by a rotary flow pattern to enhance gravity separation, they are unlike conventional clarifiers that rely only on the force of gravity. Numerous installations of vortex separation devices exist throughout Europe and North America, primarily in CSO applications; however, few installations have been reported at wastewater treatment plants (20) (21).

The three main designs in common use are described in the literature (21) (20)–the EPA Swirl Concentrator, the Storm King™, and the FluidSep™–though other designs have been developed. Despite similarities in operating principles, each type of HVS is unique with different geometries and internal components designed to stabilize the inherently unstable vortices developed by the rotary flow patterns.

HVSs lack moving parts, operate at high hydraulic loading rates, are compact, and can remove significant settleable solids when properly sized and applied. While reported to be lower in cost than conventional clarifiers, their performance is also lower, especially when operating without chemical addition and at high surface loading rates. Sludge, or underflow, from HVSs is more dilute than conventional primary sludge. Units without continuous sludge removal require cleaning after each use.

Process Selection

Selecting the best technological solution to treating wet-weather flows is a subjective, sometimes controversial process. Selection can depend on water-quality objectives and environmental regulations, characteristics of individual collection and treatment facilities, local economic conditions, policy set by the system owners, and preferences of the community and operations staff. Clarification is a strong candidate to be part of any wet-weather treatment alternative because of its relatively low capital and operating costs.

Characterizing the range of expected influent wastewater flows and quality during wet-weather periods is essential to establishing the relative performance and cost of wet-weather clarification alternatives. Another recommended, and often mandatory, first step is to determine the hydraulic and treatment capacity of the existing treatment plant. To skip this, or to do this in a cursory manner based on standard criteria, can be very costly.

Dynamic process simulation is invaluable in evaluating the response of biological treatment processes, including the level of the sludge blanket in secondary clarifiers to wet-weather flows and loads. Such evaluations of existing facilities will often spotlight bottlenecks that can be removed at a sometimes modest cost.

The ultimate goal of any wet-weather treatment program should be to protect receiving waters from adverse water-quality impacts that would result from inadequate treatment of wet-weather flows. From a rational standpoint, any combination of treatment plant and operational modifications that enable a plant to meet discharge water-quality standards should be acceptable. Then the goal becomes determining the most economical approach.

While reliable cost estimates must come from site-specific studies, in many cases the least-cost approaches are those that maximize the capacity of existing facilities by removing bottlenecks, re-rating unit processes, implementing alternative flow configurations, and providing for bypass of the biological process and blending. Approaches requiring construction of new facilities must be evaluated within the context of the individual situation.

Although capital costs are higher for new, conventional wet-weather primary or secondary clarifiers, operation and maintenance requirements are well established and additional annual costs are low. Converting conventional primaries to CEPT during wet weather also minimizes capital costs, but incurs additional annual costs in the form of chemicals and additional sludge production. Operating cost impacts such as those due to chemical use, increased sludge production, or reduced aeration costs will be proportional to the expected duration of wet weather flows, and in many cases will be relatively low.

High-rate clarification processes offer dramatically reduced footprints and often increased pollutant removal efficiencies, but incur varying degrees of additional annual costs; however, advantages due to reduced land area requirements can be substantial in highly developed urban areas with limited land for facility expansions, high land costs, and the need to minimize aesthetic impacts on plant neighbors.

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