Analysis and Optimization of Hydraulic Calibration for Maximum Performance of Wastewater Treatment Plants

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Abstract. The hydraulic calibration of treatment units in wastewater treatment plants is a crucial task. It involves demonstrating the relative placement of these various units in relation to the water line that traverses the plant, and helps indicate the ground surface for establishing the optimal elevations of the plant's structures and hydraulic controls. This process is meticulous, complex, and prone to errors. Special attention must be given to the issue of varying hydraulic loads that the plant will receive, particularly at the inlet. Such variations can disrupt hydraulic operation and negatively impact the plant's performance. For these reasons, the hydraulic calibration of treatment units must always be verified and analyzed for most of the common hydraulic constraints encountered in practice. This article focuses on the different types of flow and their regimes commonly found in wastewater treatment plants, and aims to guide users on how to optimize the hydraulic profile. It highlights the impact of head losses and integrates a range of potential alternatives for achieving hydraulic efficiency in a wastewater treatment plant.

1 Introduction

The hydraulic design of wastewater treatment plants represents a significant challenge. These facilities are typically designed to promote gravity flow, thus reducing the reliance on pumps [1]. At the plant's entrance, an appropriate drop height is sometimes required to ensure water flows through the various treatment stages [2]. Optimal hydraulic design allows for efficient handling of a wide range of flows while minimizing energy consumption. Conversely, inadequate design results in higher energy and operational costs over the plant's lifespan. Therefore, it is essential for designers to anticipate future modifications and expansions, along with their hydraulic requirements[3].

To ensure the flexibility needed to manage flow variations while adhering to physical and treatment constraints, various solutions must be considered. The plant must be capable of operating under all hydraulic conditions, whether flows are low or high. Given that multiple

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units are generally provided for each treatment process, it is crucial to account for scenarios where one basin is out of service and others must handle the increased flow. Hydraulic conditions must be verified for low, medium, and high flows, as well as when a basin is out of service. Backflow must be avoided at all costs; the plant should never be flooded, and overloaded sewers are unacceptable.

The critical design flow rate varies depending on the treatment unit. In extreme conditions, guidelines may occasionally be violated. For instance, at low flow rates, velocities in channels may be insufficient to prevent solids deposition. Designing to achieve scouring velocities at all flow rates is impractical, as it would increase energy losses and could lead to abrasive scouring at higher flows.

Accuracy in estimating head losses is fundamental for ensuring the efficiency of the treatment plant. Head losses, resulting from friction and turbulence in pipes and equipment, must be carefully calculated for each component of the plant, including channels, pumps, valves, and treatment units. Accurate estimation of head losses enables optimization of the hydraulic profile calculation and ensures efficient, energy-saving operation.

Understanding the different types of flow encountered in the treatment plant is also crucial. Flows can range from laminar to turbulent, affecting head losses and overall treatment efficiency. Knowledge of each flow type's characteristics allows for the design of systems that operate optimally under all flow conditions. This study aims to comprehensively present the methods for calculating the hydraulic profile in a wastewater treatment plant, identify the various types of flow within the different treatment units and their components, and evaluate them with high precision to best reflect reality. Special attention will be given to the accuracy in estimating head losses for each component of the wastewater treatment plant to optimize overall efficiency and performance [3].

2 Type of Flow

In wastewater treatment plants (WWTPs) and sewage treatment plants (STPs), the typical flow types include free-surface flows (HSL) in channels and pressurized flows in connecting pipes. Free-surface flows are inherently more complex than pressurized flows because they interact with the atmosphere and vary in cross-sectional area depending on the flow rate. Additionally, the water depth in the channel, along with the channel's geometric features and roughness, further complicates free-surface flow dynamics [4]. Flow regimes are categorized by the variability of hydraulic characteristics, such as water depth and velocity, which can fluctuate over time (steady versus unsteady) and space (uniform versus non-uniform)[5]. The following figure illustrates the comparison between conduit flow and open channel flow

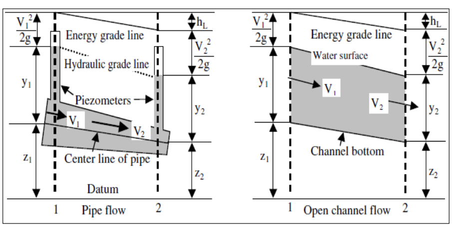

Fig. 1. Comparison of pipe flow and open channel flow [6]

Flow in pressurized pipes is described by Bernoulli's equation.

For clarity, the classification of open-channel flow is summarized as Follows [6]:

A. Steady flow
   1. Uniform flow
   2. Varied flow
      a. Gradually varied flow
      b. Rapidly varied flow

B. Unsteady flow
   1. Unsteady uniform flow (rare)
   2. Unsteady flow (i.e., unsteady varied flow)
      a. Gradually varied unsteady flow
      b. Rapidly varied unsteady flow

In this article, we examine a gradually varied flow where the discharge is constant and governed by a first-order differential equation, which defines the water surface profiles or backwater curves that develop in prismatic channels. The classification of backwater curves, long adopted, is based on the type of channel slope and two reference depths: the uniform depth Y0 and the critical depth Yc. Two example figures illustrating each case are provided.

1. Steady Slope Channel

The backwater curves that develop in a steep slope channel are all of type T, and depending on the zone they are in, they will have indices 1, 2, or 3.

2. Zero Slope Channel

The backwater curves that develop in a zero slope channel are all of type HT, and depending on the zone they are in, they will have indices 1, 2, or 3.

3. Gentle Slope Channel

If the channel has a gentle slope, the backwater curve is designated by the letter F, indicating that if the flow in the channel were uniform, it would be fluvial.

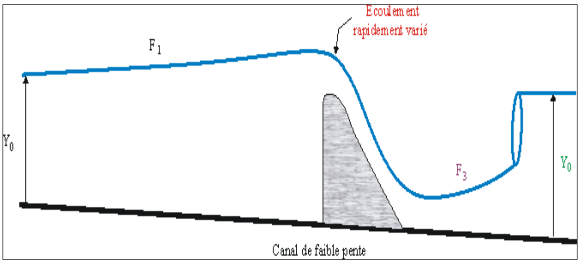

Fig. 2. Backwater Curves in Low-Slope Channels

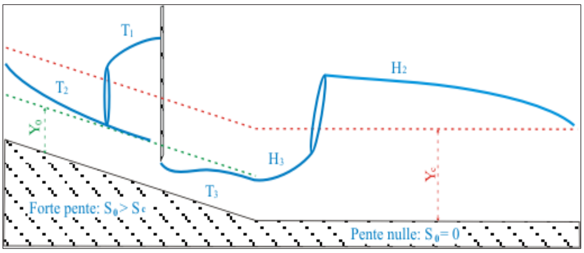

Fig. 3. Backwater Curves in High-Slope and Zero-Slope Channels

3 Impact of Hydraulic Calibration

One of the initial steps in developing the plan for a wastewater treatment plant is to establish the preliminary hydraulic profile of the proposed treatment basins [7]. Once this profile is determined, it becomes possible to define the elevations of the upper and lower parts of the main basins[8]. These elevations, along with their relationship to the site's topography, are crucial elements for the optimal placement of the basins on the site.

The more treatment processes involved, the greater the total head loss in the plant [7]. To avoid the need for intermediate pumping, the site must have a sufficient slope to allow for gravity flow. If necessary, upstream processes can be elevated to create the required hydraulic head [9], but this increases construction costs, complicates maintenance operations, and negatively impacts the station's aesthetics[7].

The optimal placement of structures relative to the ground level depends on the site's topography[10], soil conditions, and hydraulic profile. Generally, it is desirable for the treatment units to be approximately half underground and half above ground[10]. When treatment basins are primarily underground, excavation costs, buoyancy issues, and pipeline depth increase. Conversely, when basins are mainly above ground, access becomes less convenient, connecting pipes are shallower, and the basins become more aesthetically intrusive.

Many wastewater treatment plants have encountered significant operational challenges due to insufficient hydraulic gradient across various units. It is therefore essential for the design engineer to take the necessary precautions when developing the hydraulic profile [2].

Inadequate hydraulic adjustment can lead to various problems, such as insufficient detention times, the formation of dead zones within the treatment system, and the accumulation of suspended solids. These issues reduce the effectiveness of the treatment plant and compromise the quality of wastewater treatment.

4 Processes of Hydraulic Profile Calculation

Site selection and plant layout are often presented as successive steps: first selecting the site, followed by determining the optimal layout of facilities for that site. However, it is crucial to recognize that these two steps are not strictly sequential and are closely interconnected.

Before site selection can begin, a preliminary plant plan is necessary. Without this plan, it is challenging to assess potential sites considering factors such as the shape of the parcel, topography, and other aesthetic considerations [7].

The hydraulic design of the plant must be addressed from the outset of the project. This involves developing a hydraulic profile to establish the elevations of the structures and their relationships. The layout of the facilities on the site should take advantage of the available terrain to optimize the station's hydraulics while minimizing excavation work. The placement of the facilities must also consider various site-related factors, such as:

- Elevation variations in the topography.
- Safety and buffer requirements.
- Physical characteristics and internal constraints of the site.

- Floodplain boundaries and flood protection requirements.
- Provisions for drainage and stormwater retention.
- Pipelines and conduits between structures.
- Access and parking for personnel, the public, and deliveries.
- Routing of utilities (gas, electricity, sewage, telephone).
- Aesthetics of the plant and public acceptability.
- Protection of archaeological, historical, or cultural resources.

During the hydraulic design phase of WWTPs and sewage treatment plants , three main approaches are typically used:

1. Standard Approach: Hydraulic profiles are established after the process flow diagram is selected and the facility sizes are determined[2].
2. Early Approach: The hydraulic profile is calculated in the early design stages to adjust the site elevation and determine the site's suitability for the WWTP [7].
3. Iterative Approach: The hydraulic profile is developed iteratively as the sizing of the structures progresses, enabling continuous interaction between the plant designer and the hydraulic engineer[4].

The hydraulic profile is typically developed from four control points:

a. Effluent weir at the rapid mix level.
b. V-notch weir at the sedimentation basin level.
c. Filter back-pressure weir at the common filter bay level.
d. Weir at the chlorine contact channel level, just above the light wells.

Engineers typically use the elevation of the filter back-pressure weir to begin hydraulic calculations [11]. The hydraulic profile is typically calculated by beginning at the downstream control point and progressing upstream. Some designers work backward from the control point, while others start from upstream or the middle of the profile, making adjustments to water elevations in both directions as needed. [5] [2].

It is crucial to establish hydraulic calibration for all major flow paths within the plant. In a wastewater treatment facility, various flow control points manage the hydraulic profile both upstream and downstream.

5 Hydraulic Formulas

Henry Darcy and Julius Weisbach developed the Darcy-Weisbach equation around 1850 to calculate friction in circular pipes, factoring in wall roughness and flow turbulence. While versatile, this equation can be complex in practice. In the late 19th century, the Manning equation was introduced for open channels and adapted for closed pipes. The Hazen-Williams equation, developed in the early 20th century, offers a simpler and more practical approach for water and wastewater pipe calculations, making it a preferred choice in modern applications.

5.1 Major head losses

Liquid movement always involves energy loss, which occurs due to friction with solid walls and between moving liquid particles. In a pressurized water system, the primary source of head loss is the reduction in pressure along the pipe caused by friction between the water and the pipe's interior surfaces. This loss usually represents the largest portion of the pressure drop in such systems [4].

Engineers are well-versed in calculating head losses in pipelines, with numerous technical references providing detailed analyses on the subject. It is crucial not to exceed a total head loss of 4.5 to 6 meters in a hydraulic structure.

In practice, the Hazen-Williams equation is commonly used for pressure pipes, while the Manning equation is preferred for open-channel flows and canals. Although the Darcy-Weisbach equation is theoretically the most accurate for calculating head losses, its complexity and the number of steps required for its application limit its use in the design of wastewater treatment plants and in the environmental field in general [6].

5.2 Minor Head Losses

Head losses in a conduit are primarily due to friction against its internal walls. Additionally, any changes in the direction or speed of the fluid, as well as the presence of obstructions such as valves and measuring devices, exacerbate these losses. Although these obstructions are typically classified as "minor losses" in fluid mechanics, they can become significant in short conduits, such as those found in wastewater treatment plants, due to their substantial impact on flow.:

1. Friction losses within the unit.
2. Losses at the unit's inlet.
3. Losses at the unit's outlet.
4. Losses due to accessories associated with the unit.

The losses due to wall friction in treatment basins are typically deemed negligible because of the relatively low flow velocities in these basins [3] . Additionally, in a basin with few obstructions, the water surface is assumed to be uniform and horizontal.

6 Comparison and Discussion

This article explores the key elements necessary to ensure the hydraulic efficiency of wastewater treatment plants, focusing on optimizing the hydraulic profile to adjust the size of treatment units. The software used to model water behavior in basins, channels, and conduits facilitates the calculation of important parameters such as flow velocity, water height, head losses, and flow rate while allowing for the visualization of hydraulic profiles.

However, it has been observed that these models do not always account for crucial constraints such as flow type and site topography. This omission can lead to suboptimal designs, as these factors significantly impact the actual performance of the systems.

Current tools, while effective for general simulations, often lack the flexibility to incorporate these specific aspects. To enhance the accuracy of simulations and the reliability of designs, it is essential to integrate these constraints into the models. This could involve developing additional modules or validating the models using experimental data.

The following table should provide a useful summary to understand these limitations in detail and guide future improvements.

Table 1. Hydraulic Models and Constraints

Software	Flow regime	Topography	Hydraulic Design	Hydraulic profile
ARTS	Uniform Gradually Varied Rapidly Varied	Yes	Yes	Yes
GPS X	Steady	No	Yes	Yes
DATAR	Steady	No	Yes	Yes
AQUAVETAE	Not mentioned	No	Yes	Yes
STOAT/PLANT STOAT	Steady	No	Yes	Yes
AQUASSIM	Steady	No	Yes	Yes
HYDRAULIX CAROLLO	Steady	No	Yes	Yes
HYDRO	Steady	No	Yes	Yes
VISUAL HYDRAULIC	Gradually Varied	No	Yes	Yes

To improve the accuracy of simulations and the reliability of designs, it would be beneficial to incorporate these constraints into the models. This could involve developing additional modules or validating the models with experimental data. Furthermore, this study examines the hydraulic models of wastewater treatment plants, revealing significant gaps and identifying the key parameters for hydraulic calibration, while also analyzing their impact on the modeling and operational practices of the treatment plants.

The analysis of software dedicated to hydraulic wastewater treatment plants is complex, as they often overlook certain key factors affecting hydraulic calibration. Each software developer tends to propose their own methods without comparing them to others. These tools can be categorized into three groups: first, published and documented software, which provides good transparency regarding their methods; second, published but undocumented software, which lacks critical details; and finally, unpublished models that have technical documentation, which, while not publicly accessible, offer a partial understanding of their functionality.

Descriptions of hydraulic modeling software often lack detail, making their evaluation challenging. It is crucial to obtain specific information about their features and performance. While these tools offer advantages for wastewater treatment plants, they also have limitations that require technical expertise.

Generally, two types of models can be distinguished: commercial models, which provide ready-to-use features but may lack precision, and spreadsheet models, which are more flexible but often less user-friendly. Despite the development of numerous software options, limitations persist, making it essential to consider all factors influencing hydraulic design.

Among the analyzed software, ARTS stands out for its consideration of numerous parameters, followed by Visual Hydraulics. However, ARTS is not easily accessible and lacks scientific studies on its hydraulic calibration, while Visual Hydraulics relies solely on commercial brochures without research validation. This raises doubts about the credibility of both tools due to the absence of scientific validation.

Another software has relevant publications but lacks clear information on its usage, which also creates uncertainties for users. Furthermore, the methodology for calculating hydraulic profiles in these software programs is often insufficiently detailed, making it challenging to evaluate their performance in modeling for wastewater treatment plants. More transparent and comprehensive documentation of the calculation methods is essential for assessing the effectiveness of these tools in hydraulic calibration of wastewater treatment plants.

7 Conclusion

In conclusion, this article focuses on the Hazen-Williams equation, recognized for its relevance and effectiveness in calculating head losses within water pipeline systems. Its ease of use and adaptability to common pipe conditions make it the preferred tool for engineers in this field.

The article highlights the importance of thoroughly understanding head losses in both pressurized and open channel flows, which are crucial for accurate simulation and calculation of the hydraulic profile in wastewater treatment plants. It also emphasizes the need for a detailed analysis of the various flow types encountered in practice, including the backwater curves in channels with varying slopes for gradually varied flows.

By addressing these aspects, the article contributes to better hydraulic management in wastewater treatment plants. It enables engineers to refine the hydraulic calibration of treatment units by incorporating different flow typologies and their specific classifications. This approach facilitates more precise simulations of water levels in each treatment unit and enhances the overall management of the hydraulic system.

By optimizing the hydraulic profile of wastewater treatment plants, the article provides a solid foundation for improving operational efficiency and ensuring more effective wastewater treatment. The recommendations offered enable users to make informed decisions by considering crucial hydraulic variables, leading to better design and optimized management of facilities.

In a WWTP, the flow is typically unsteady, non-uniform, and turbulent. However, for the sake of simplification, it is often modeled as steady and uniform. This oversimplified approach, commonly used in modeling software, overlooks phenomena such as backwater effects, which can compromise the accuracy of the results. Additionally, the head losses associated with the plant's equipment can significantly impact the calibration of hydraulic profiles. These losses directly affect the performance of pumps, screens, and clarifiers, leading to inefficiencies in the wastewater treatment process.

Additionally, wastewater treatment plants face several constraints, including flow variations and elevation differences between upstream and downstream areas. These factors present extra challenges during hydraulic design. For example, the elevation difference influences the need for excavation and construction work. On flat terrain, efforts may be balanced, whereas on sloped terrain, the geotechnical characteristics of the soil whether rocky or loose often complicate excavation. This adds construction difficulties and impacts the overall hydraulic configuration.

Currently, no in-depth study has been conducted on the hydraulic layout of WWTPs that fully considers various topographical configurations. The impact of these factors on plant design and project costs remains insufficiently analyzed. Greater attention must be given to these parameters to ensure optimal design and reduce head losses, which is essential for improving the operational efficiency of WWTPs.

A large portion of the information regarding the hydraulic calibration of WWTPs remains unclear, particularly concerning the mathematical equations used. This lack of transparency can create uncertainties for those trying to grasp the underlying mathematical methods. Therefore, it is crucial to clearly disclose the calculation methodologies to ensure the appropriate use of these tools. Comparing hydraulic formulas such as Hazen-Williams, Darcy-Weisbach, and Colebrook-White is essential, as the adjustment of head losses must rely on well-established equations to ensure the accuracy of the results.

Additionally, topography and its various configurations, such as flat or sloping terrains, have not been adequately explored in studies on hydraulic profiles, despite their critical importance for the hydraulic behavior of systems. Moreover, steady-state flow conditions are rarely addressed in publications, even though they play a key role in design and operational performance.

References

1. Merufinia, E., Naveh, H., 2015. The Hydraulic Design of the Grit Chamber of the Urmia Wastewater Treatment Plant with Hydraulic Approach 85–93, (2015)
2. George Tchobanoglous, H. Stensel, RyujiroTsuchihashi, Franklin Burton. Metcalf & Eddy ,Wastewater Engineering_ Treatment and Resource Recovery-McGraw-Hill Education. Fifth Edition, (2014)
3. Ronald Droste and Ronald Gehr .TheoryandPracticeofWaterandWastewaterTreatment, SecondEdition, (2019)
4. Frank R. Spellman.Handbook of water & wastewater treatment plant operations,(2003)
5. Syed R. Qasim and Guang Zhu "Wastewater Treatment and Reuse Theory and Design Examples Volume 2: Post-Treatment, Reuse, and Disposal", (2018)
6. Chow, V. T. Open-Channel Hydraulics. New York: McGraw-Hill, (1959)
7. Peter J. Barthuly. Barthuly Hydraulics & Pumping Engineering, Inc., Burlington, Massachusetts. (Chap. 16), (2005)
8. Anastasios I. Stamou. Hydraulic design of sewage treatment plants using lotus 1-2-3c", http://dx.doi.org/10.1080/09593339309385285, (1993)
9. Syed R. Qasim and Guang Zhu "Wastewater Treatment and Reuse Theory and Design Examples Volume 2: Post-Treatment, Reuse, and Disposal", (2018)
10. Lane, Th. J., and Barthuly, P. D., "Water Treatment Plant Design" McGraw-Hills, New York. (2004)
11. Qasim, S. R., Motley, E.M. and Zhu, G, "Water Works Engineering", Chiang, Patel and Yerby, Inc., Dallas, Texas, (2000)