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RESEARCH ARTICLE

Monitoring Blockage and Overflow Events in Small-Sized Sewer Network Using Contactless Flow Sensors in Hong Kong: Problems, Causes, and Proposed Solution

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ABSTRACT Effective monitoring and prediction systems for sewer overflow are essential for safeguarding public health and the environment. Flow sensors have emerged as valuable tools for understanding and measuring the hydraulic performance of sewer networks, enabling the detection of blockages and overflow events. However, previous research has predominantly focused on large-diameter sewer networks, leaving a gap in understanding the applicability and performance of flow sensors in small and medium-sized systems. Addressing this research gap and motivated by the need to improve the monitoring of small and medium-sized sewer networks, this study comprehensively assesses the performance of flow sensors in such networks, with a focus on detecting blockages and overflow. The study evaluates the performance of flow sensors in 12 locations within the Hong Kong sewer network and identifies challenges affecting accuracy. The findings reveal noteworthy shortcomings when solely relying on flow sensors, including inconsistent and unreliable observations. Notably, the correlation coefficient between the level and flow sensors was 0.36, and the average relative error in flow rate measurement was a substantial 72.14% compared to Manning's equation. An in-depth analysis reveals key factors hindering flow sensors' efficiency, such as inconsistent flow directions and pipe size variations. To overcome these limitations, the study introduces a new approach based on real-time measurement of vertical sewage velocities inside manholes. By incorporating level sensors and considering specific network characteristics, this alternative methodology provides a promising solution for detecting operational issues and improving the reliability of overflow monitoring systems.

INDEX TERMS Flow sensors, level sensors, blockage, overflow, sewage velocity.

I. INTRODUCTION

A. BACKGROUND

Sewer systems are an essential component of urban infrastructure, responsible for transporting sewage and/or storm runoff to wastewater treatment plants while also mitigating the risk of urban flooding. Generally, there are two types of sewer networks, separated and combined. The separated network is designed exclusively to carry sewage, while the combined network carries both sewage and stormwater. However, regardless of the type of sewer system, the wastewater typically contains dangerous chemicals and harmful pathogens, which are more concentrated in the separated network [1], [2], [3], [4]. Despite being underground and designed to prevent

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exposure to the public and the environment, sewer systems are prone to failure, and wastewater may overflow onto streets and other infrastructure, polluting waterways such as rivers, lakes, and seas. Sewage overflow can occur due to various factors, including deterioration of sewage materials, lack of power or pump failures, pipe corrosion, and blockage of pipes [5], [6], [7], [8]. In addition, unexpected high flows from another source directly into the pipe, excessive use of pipes to accommodate new developments or infiltration through the soil into the pipe during a severe storm are also potential causes of sewer overflow [9].

Blockages are the most common operational failure in sewage systems causing significant problems ranging from sewer breakdowns to plant failures. This results in flooding, which affects other infrastructure and can lead to traffic disruption, safety issues, and public health concerns [10], [11]. Previous studies have highlighted that blockage issues frequently occur in small-diameter local sewers [12], [13], [14], [15]. In fact, most flooding incidents occur in smaller sewers, and intermittent blockages are more common than structural failures. Researchers have recommended that continuous monitoring may provide a better approach to managing sewer blockages than predictive tools due to the unpredictable nature of the processes involved in forming pipe blockages [12], [13], [14], [15].

Authorities and utilities have implemented various preventive measures to manage blockages and overflows in small-sized sewer networks. These measures include limiting flow into the sewer system through manhole covers and vents, repairing defective or damaged pipes, increasing sewer capacity to handle peak flow, and cleaning lines to keep them free of roots and grease. However, these methods have limitations in identifying existing blockages or persistent sewage overflow and determining their locations, particularly in hard-to-reach areas [9]. To address this challenge, there has been a growing interest in forecasting discharges into sewer and wastewater systems, which can help authorities prepare for the negative impact of floods and optimize hydraulic system operations [16]. Long-term discharge forecasts have been found to play a vital role in environmental protection, effective drought management, and overall system efficiency [16]. By knowing the discharges into the networks with a certain degree of certainty, wastewater treatment plants (WWTPs) can operate more effectively, and the risks of overflows and blockages can be minimized [17].

Sewer flow measurements play an important role in understanding the hydraulic performance of a sewage system and detecting blockages and overflow situations. When a sewer becomes clogged, the flow velocity on the upstream side approaches zero, while the velocity on the downstream side increases significantly. This information can be used to pinpoint the exact location of the blockage in the pipes. However, monitoring sewage flow is complex due to the harsh environment in which it operates. The high humidity and presence of corrosive gases make it challenging to measure flow accurately. Most modern systems for volumetric flow measurement, such as positive displacement flowmeter, require installation into the sewage [18]. Despite the installation of such equipment, few devices provide in-contact measurements with wastewater, which risks being destroyed. This destruction can occur because of the rapid increases in water height and flow rate due to storm surges or blockages [16]. As a result, these systems are usually short-lived in a real sewer environment and require regular maintenance.

Fortunately, several methods for measuring sewage flow velocity include contactless devices like ultrasonic flow sensors. Several studies have used these sensors to measure wastewater flow velocity [17], [20]. An ultrasonic flow sensor measures the flow velocity by sending an acoustic pulse from the sensor to the surface of the flow and estimating the echo return time. This technology has several advantages, including non-intrusiveness, high accuracy, and low maintenance requirements [21], [22], [23]. Additionally, many studies have used image-based tracking methods to measure flow velocity [18], [19], [20], [21], [22], [23], [24], [25]. By using video cameras, these methods measure the flow rate by combining image-based methods of water level measurement and surface velocity estimation. These techniques offer an effective contactless approach for measuring sewer flow velocities while minimizing the risks of equipment damage.

Previous studies have demonstrated that various methods have been employed to measure flow velocity in open channels or relatively large-size sewers due to their accessibility for installing sensors inside pipes or channels. However, in small and medium-sized sewers, several challenges are encountered in installing these devices, including the effect of sewage level on sensors, which can negatively impact the accuracy and efficiency of flow and velocity measurements and damage the sensors. In such cases, sensors installed in manholes are recommended for measuring flow and sewage [26], [27]. In addition, recent advances in sensor technology have led to the development of wireless and remote sensing devices that offer several advantages, such as reduced installation costs, improved accessibility, and reduced maintenance requirements [28], [29], [30], [31]. Using such devices makes it possible to continuously and accurately measure flow rates and sewage levels continuously and accurately in small and medium-sized sewers, allowing for better management and control of the sewer system.

B. POINT OF DEPARTURE AND OBJECTIVES OF THE STUDY

The efficient monitoring of sewage flow in small and medium-sized sewer systems is crucial to ensuring proper functioning and avoiding blockages or other operational issues. However, a limited body of research focuses on flow sensors in these networks, with few studies focusing on wastewater flow measurement in general [22], [32], [33]. Consequently, there is a lack of established techniques and procedures for detecting potential obstructions and operational problems in these systems. Although volumetric flow measurement in rivers and open channels has been extensively studied [34], [35], [36], [37], the complex nature of sewage flow and the gaps in our understanding pose unique challenges in developing a sewage monitoring system capable of effectively identifying blockages, particularly in small- and medium-sized systems. Notably, to our knowledge, no previous studies have explored the utilization of contactless flow sensors in small- and medium-sized sewers for predicting overflow or blockage occurrences.

As part of a broader research project aimed at developing an integrated and intelligent monitoring system for Hong Kong's sewage network, 12 flow and level sensors were installed within 12 manholes to collect flow and level observations from various locations. However, the collected flow data showed low accuracy, indicating the need for a deeper investigation into the potential and efficiency of flow sensors installed in manholes for representing the sewage flow in medium- and small-sized sewer systems. Therefore, the objectives of this study are as follows:

- Assess the potential and efficiency of flow sensors in medium and small-sized sewer systems when installed in manholes: This assessment aims to evaluate the performance of flow sensors in accurately measuring the flow velocity, including horizontal flow velocity. The assumption is that the flow sensors would detect zero velocity upstream in the case of blockages and overflow. Additionally, it is important to note that the absence of in-situ measurements to directly evaluate the flow sensors necessitates a comparative analysis between different sensors. Therefore, a sensor-to-sensor comparison will be conducted to address this concern and provide a comprehensive evaluation of the flow sensors' performance.
- Investigate the potential causes of inaccurate flow sensor results in medium and small sewage systems in Hong Kong: Despite the assumption that flow sensors can measure flow velocity, preliminary results have indicated a lack of reliability. Therefore, it is imperative to delve deeper into understanding the factors contributing to inaccurate measurements. By identifying the root causes of these inaccuracies, we can address the limitations and challenges associated with flow sensors in medium- and small-sized sewer networks.
- Propose an alternative method for measuring wastewater flow that can be used to detect blockages and overflow situations in sewage networks: Based on the findings regarding the limitations of flow sensors, the study aims to explore and propose an alternative approach for accurately measuring wastewater flow. The proposed method will leverage the use of level sensors to predict and detect blockages and overflow situations in sewage networks. A more reliable solution can be developed by relying on the data collected from level sensors to mitigate the shortcomings associated with flow sensors.

To achieve the aforementioned objectives, flow and level observations were collected from 12 manholes distributed spatially to represent the sewer network of Hong Kong. This comprehensive dataset forms the foundation of our study, enabling significant advancements in sewage flow monitoring. By rigorously analyzing this dataset, our research makes substantial contributions to the state-of-the-art in sewage flow monitoring. We provide valuable insights into the potential and limitations of flow sensors, shedding light on the factors contributing to measurement inaccuracies in small and medium-sized sewer systems. Moreover, we propose an alternative method for accurate flow measurement that leverages level sensors and overcomes the shortcomings of traditional flow sensors. The significance of our work lies in the groundwork we lay for developing more efficient and reliable monitoring systems. By identifying the causes of measurement inaccuracies and offering an alternative method, we contribute to the advancement of sewage flow monitoring technology. Ultimately, these advancements improve the operation and management of small- and medium-sized sewer systems, reducing the risks associated with blockages and overflows, and promoting the protection of public health and the environment.

The remainder of this paper is organized as follows: In Section II, we provide details on the experimental materials and methods, including sensor type, data collection, data mining, and an analysis of the difficulties encountered. In addition, we describe the suggested alternative method for measuring wastewater flow. Section III presents and discusses the results of data analysis and sensor performance. Section IV identifies and discusses potential causes of flow sensor failure in Hong Kong sewers. In Section V, we present and discuss the results of the proposed alternative flow measurement method and compare them with those obtained using the flow sensor. Finally, in Sections 6 and 7, we outline the limitations of this study, suggest future research directions, and draw conclusions based on our findings.

II. MATERIALS AND METHODS

The research strategy employed in this study aimed to evaluate the potential of utilizing flow and level sensors in manholes rather than pipelines for predicting blockages in small and medium-sized pipelines in real-time. To achieve this, the following steps were taken (see Fig.1): a) Collection of real-time observations from 12 level and 12 flow sensors that were installed in manholes across four districts for one year (as depicted in Fig.2); b) Application of data cleansing and transformation techniques to ensure the accuracy and reliability of the data collected; c) Data mining, selection, and pattern evaluation to identify patterns and trends in the collected data; and d) Evaluation, analysis of difficulties, and recommendations for solutions to overcome any identified issues.

A. SENSOR INSTALLATION AND STUDY LOCATIONS

To fulfill the objectives of this study, the Drainage Services Department (DSD) provided us with real-time data sourced from both level and flow sensors installed in 12 strategically selected manholes. These specific manholes were identified based on their frequent exposure to situations requiring monitoring and analysis. Fig.2 showcases the precise locations of these 12 manholes, which are distributed across four different districts. To ensure comprehensive data collection, the equipped manholes were outfitted with smart ultrasonic-level sensors, flow sensors, and data loggers. This combination of advanced technology allowed for capturing accurate and precise measurements. Furthermore, the DSD provided essential information regarding the design features of the manholes, as well as details about the interconnected pipes, which will be discussed further in the data collection section.

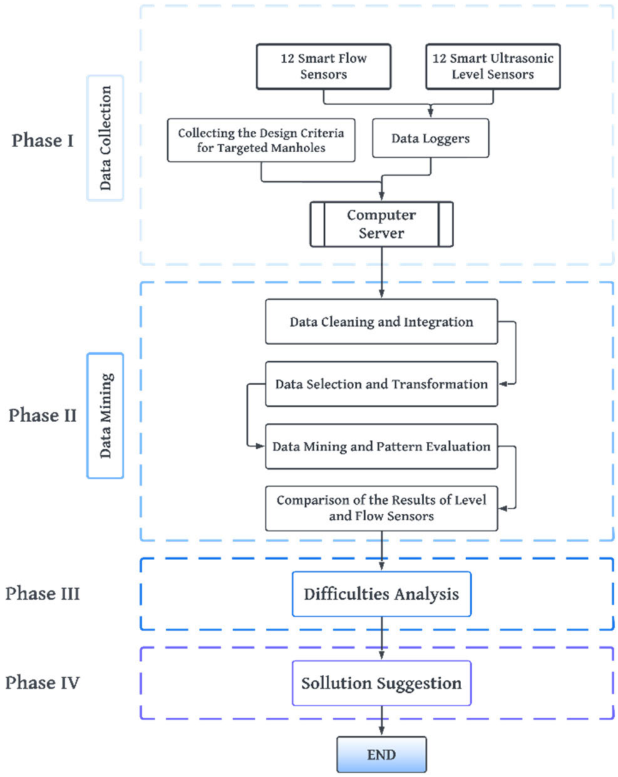

FIGURE 1. **Methodological approach for evaluating the flow sensors in small- and medium-sized sewers.**

To capture the necessary data, a systematic approach was adopted. Level and flow sensors were mounted within each manhole alongside a dedicated data logger, as illustrated in Fig.3. This setup enabled continuous monitoring and recording of crucial parameters, ensuring a reliable and comprehensive dataset for subsequent analysis. The level sensors measured the sewage depth in the manhole, while the flow sensors measured the velocity and volumetric flow rate of the wastewater passing through the pipes. The flow and level sensors were connected to a data logger, which recorded the data at regular intervals. The sensors used in this study were carefully selected based on their features and capabilities to ensure accuracy and reliability. The details of the sensors are as follows:

- **Flow sensors:** The MicroFlow-i sensors from the Pulsar Process Measurement company were chosen for their ability to provide accurate and repeatable velocity measurements of liquid flow. These sensors can be used as a single sensor or can provide a highway addressable remote transducer (HART) communication protocol or a signal supported by a 4-20mA loop in a supervisory control and data acquisition (SCADA) system. Their compact and lightweight design makes installation easy, even in confined spaces, and they do not require any interruption in the normal operating flow. The sensors work by firing a pulse at the liquid's surface, producing reflections from the entire width of the sewage flow surface. Refracted spread spectrum analysis (RSSA) algorithms are then used to analyze and combine the received signals for real-time speed calculation.
- **Level sensors:** Contactless ultrasonic level sensors were used in this study, and they are available with a choice of HART or Profibus PA communication protocols. These sensors are low-power devices and feature Pulsar's world-leading digital adaptive tracking echo measurement (DATEM) processing capability for robust and reliable measurement from 125mm to 15m.
- **Data logger:** In addition to the sensors, an efficient data logger and communication mechanisms were required to link these sensors to the central server and develop an integrated real-time sewage monitoring system. For this purpose, the HMW intelligence data logger was used, which is specifically designed for wastewater application rigors. This data logger can save data and send it to the server or other locations for analysis and storage.

B. DATA COLLECTION

The data collection process consisted of two main stages aimed at enhancing the comprehensiveness and effectiveness of our analysis. The first stage involved managing and collecting all the design criteria of the target sewage manholes. This crucial step allowed for a comprehensive understanding of the sewage conditions, enabling a robust comparison of the flow sensor level and results. Therefore, a thorough investigation of the targeted locations in the Hong Kong sewage network was conducted to identify all the relevant parameters that may affect the network's performance. The collected design criteria parameters included the manhole cover level, manhole invert level, the diameter of the inlet pipes, the invert level for inlet pipes, the diameter of the outlet pipes, the invert level for outlet pipes, and the number of inlet and outlet sewer pipes. Some of these parameters, along with the location of each manhole, are listed in Table 1. The collected data was utilized in conjunction with sensor data to gain a comprehensive understanding of the sewage network's behavior.

After obtaining the design criteria of the target manholes in the sewer network, the subsequent phase was to acquire flow velocity and level observations through the sensing system. The data collection program was performed over a span of one year, from June 2019 to June 2020, at 12 designated sites.

The extensive duration of the data collection program enabled us to acquire real-time data over the course of days, weeks, and months, thus providing a comprehensive understanding of the overall performance of the sewage network. The collected data from the sensors were processed, saved, and transmitted to the internet server through the data logger. Following this, the data was downloaded from the server for further analysis. In total, a voluminous amount of data, approximately half a million observations from 12 manholes, were collected and subsequently used for further analysis in the study.

C. DATA MINING

Data mining can be defined in various ways, with some researchers considering it a process that involves methods used to extract useful information from large, raw data sets, while others define it as a pattern extraction process. However, the most commonly accepted definition is that data mining is converting raw data into useful information using software to identify patterns in large data sets [39], [40]. The primary goal of data mining is to discover patterns that are already present in the data but are obscured by a vast number of variables and samples, the noise of the data,

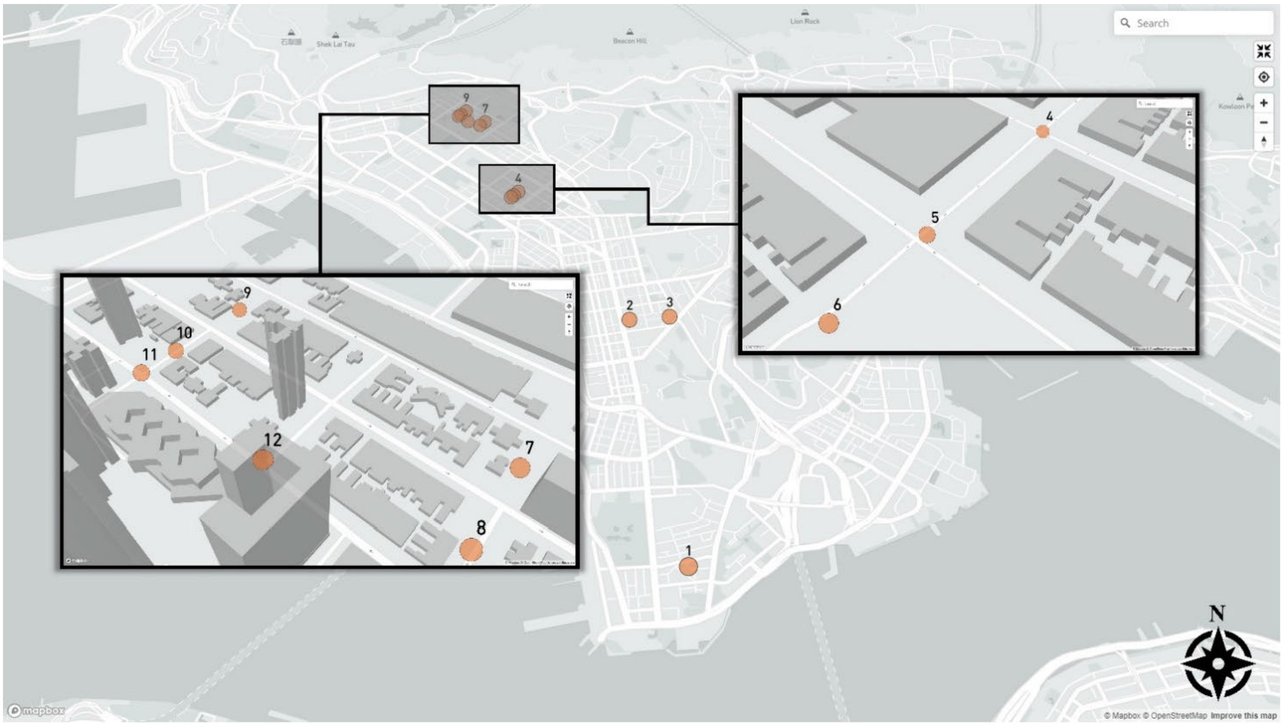

FIGURE 2. The location of our study area and the distribution of targeted manholes in Hong Kong.

TABLE 1. Information about the studied manholes (design criteria parameters and locations).

Manhole Number	Manhole Cover Level/Invert Level (m)*	No. of Inlet Pipes	Inlet Pipe Diameter (m)*	No. of Outlet pipes	Outlet Pipe Diameter (m)	Location
1	4.62/3.45	1	0.15	1	0.15	Tsim Sha Tsui (TST)
2	5.31/3.81	1	0.225	1	0.225	Mong Kok
3	5.89/4.34	3	0.225/0.225/0.15	1	0.225	Mong Kok
4	4.36/2.21	2	0.525/0.225	1	0.525	Sham Shui Po
5	4.34/2.16	2	0.525/0.15	1	0.525	Sham Shui Po
6	3.97/2.13	3	0.6/0.15/0.15	1	0.6	Sham Shui Po
7	6.12/3.41	3	0.6/0.15/0.15	1	0.6	Cheung Sha Wan
8	5.78/3.19	2	0.6/0.15	1	0.6	Cheung Sha Wan
9	6.27/3.93	3	0.3/0.15/0.15	1	0.45	Cheung Sha Wan
10	5.92/3.9	3	0.45/0.375/0.15	1	0.45	Cheung Sha Wan
11	5.74/3.66	3	0.6/0.225/0.45	1	0.6	Cheung Sha Wan
12	5.89/3.43	2	0.6/0.3	1	0.6	Cheung Sha Wan

***The listed diameters correspond to the individual inlet pipes.**

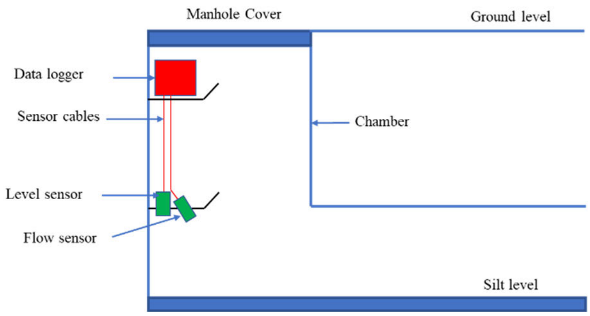

FIGURE 3. **Cross-section schematic drawing of the sensors installed in the manhole.**

or the complexity of associating more than two variables simultaneously [38].

In our study, we collected over half a million observations from various locations (i.e., 12 manholes) and times of the year, making it challenging to extract meaningful information from the data without a proper mechanism to identify patterns. To address this challenge, we adopted a descriptive data mining approach, which involves exploring and analyzing data to uncover meaningful patterns, summarize data characteristics, and reveal noteworthy correlations. The techniques employed in our study encompassed crucial stages of the descriptive data mining process, including data cleaning, integration, selection, transformation, correlation analysis, comparative analysis, and error calculation. By utilizing these techniques, we aimed to preprocess and analyze the collected data from flow sensors in order to extract meaningful patterns, evaluate the performance of the sensors, and recommend solutions for improving the sewage network's performance. The knowledge discovery process and methods used in our study are illustrated in Fig.4, with a concise description of the main components of the flowchart provided below.

1) DATA CLEANING AND INTEGRATION

The data cleaning and integration phase holds the utmost importance in any data mining project as it identifies accuracies or irrelevant segments within the dataset [41]. This study conducted an extensive collection of approximately half a million observations across 12 different sites, with each data record containing sewage level data within the manhole and sewage flow velocity measured by the level and flow sensor, respectively. However, during the initial analysis, it became evident that a significant portion of these observations suffered from inaccuracies or irrelevance, including zero values and repeated values spanning consecutive days. To address these issues comprehensively, the first step undertaken was data cleaning. This involved a dual approach utilizing the Python programming language and structured Query Language (SQL) to eliminate irrelevant columns and filter out rows containing missing or inaccurate data. The outcome of this rigorous cleaning process resulted in a refined dataset, effectively reducing the initially encompassed nine columns to a streamlined set of five columns directly pertinent to the study.

Once the data cleaning process was completed, the subsequent step entailed amalgamating all the flow and level sensor observations from the various locations into a unified file. This integration process helped to make the data more manageable and significantly reduced the file size. Furthermore, this step facilitated the understanding and analysis of the data, making it easier to extract valuable insights. By performing these data cleaning and integration processes, the dataset was prepared for the next analysis step, involving data selection and transformation.

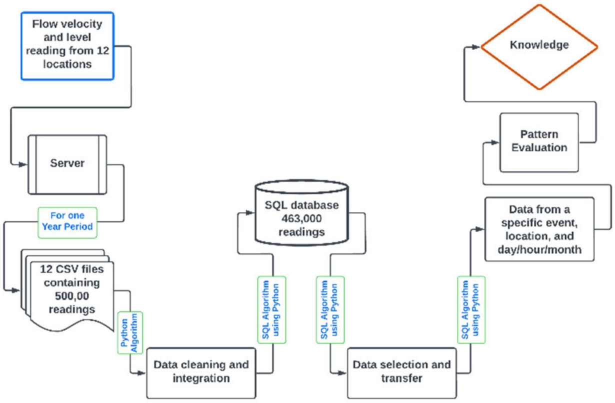

FIGURE 4. **A flow chart depicts the data mining process used in this research.**

2) DATA SELECTION AND TRANSFORMATION

After cleaning and integrating the data, we applied data selection and transformation techniques to prepare the data for analysis. Data selection is the process of retrieving data related to the analysis task from the database for use as separate data. We selected relevant features from the dataset, including the observations from the level and flow sensors, for further analysis. We also extracted data related to a specific event for investigation purposes. Additionally, we retrieved data on the flow velocity and sewage level for different locations in terms of hours, days, and months for comparison purposes. This allowed us to better understand the sewage system's behavior over time and detect any unique patterns or anomalies.

To streamline the analysis and ensure accuracy, we also transformed the times of each observation from a string format to the Unix time system using a Python algorithm. This method allowed us to find the exact time of the observations and enabled faster and more reliable analysis. Moreover, to gain a more comprehensive understanding of the network and detect any unique situations across sites, we integrated each manhole's design criteria with its corresponding sensor data. By doing so, we were able to measure the sewage depth within the manholes and identify any anomalies or deviations from the system's expected performance.

One of the transformations applied was the conversion of velocity measurements from the flow sensors to flow rates by multiplying the velocity of sewage by the corresponding cross-sectional area that was identified by the level sensor data. Additionally, the flow rate was calculated using the data generated by the level sensors and sewers design features using the Manning equation, which relates flow rate to several hydraulic parameters, including the Manning roughness coefficient, cross-sectional area, hydraulic radius, and pipe slope. The Manning equation is given by:

$$Q = \frac{1}{\mathrm{n}}{}^{*} A^{*} R^{2/3} * S^{1/2} \tag{1}$$

where Q is the flow rate, n is the Manning coefficient that considers channel roughness (m3/s) (i.e., 0.015 for concrete pipes in HK with a fair condition, although this may vary in partially full pipe scenarios), A is the cross-sectional area of flow normal to the flow direction (m2), R is the hydraulic radius calculated as the cross-sectional area divided by the wetted perimeter (m), and S is the slope of the outlet sewer.

3) PATTERN EVALUATION

After selecting relevant data based on time, location, or situation and transforming it into other tables and formats, the next step in our methodological approach was to evaluate the pattern of the collected data and draw conclusions from each studied case. To achieve this, we implemented SQL algorithms to convert the data into useful information and generate graphs that visualized the change in sewage levels within target manholes, along with flow velocity data during 2019/2020. These data patterns were then analyzed to verify the performance of the sensors in capturing various situations at different times.

Specifically, we calculated the correlation coefficient between the level and flow sensor data to quantify their relationship. A high correlation coefficient would indicate a strong agreement between the two values, aligning with Manning's equation, whereas a low correlation coefficient would suggest a poor agreement. Furthermore, we conducted a comparative analysis by estimating the flow rates using Manning's equation based on the data from the level sensors and compared them to the flow rates measured by the flow sensors. Additionally, to gain further insights, box plots were utilized to examine the distribution of Manning's flow values and flow sensor values for each manhole.

Furthermore, we quantitatively evaluated the accuracy of the flow sensors by calculating the relative error between the estimated flow rates from the flow sensors and flow rates from the level sensors using the formula:

$$Error = \left| \frac{(Q_{level} - Q_{flow})}{Q_{flow}} \right| *100\% \tag{2}$$

where Q_flow is the estimated flow rate from the flow sensors, and Q_level is flow rate from the level sensors, calculated using Manning's equation.

The relative error represented the percentage difference between the two values and indicated the accuracy of the flow sensors. A lower relative error indicated higher accuracy, while a higher relative error suggested lower accuracy. This comprehensive analysis verified the relationship between the collected flow velocities and sewage levels and tested the efficiency of using flow sensors in small and medium-sized sewer systems.

D. DIFFICULTIES ANALYSIS

Upon completion of the data cleaning, analysis, and study, it was ascertained that a considerable amount of the flow data collected was corrupted or showed inconsistent observations between the flow velocity and level sensors. Consequently, an in-depth analysis was conducted to identify the underlying difficulties that hindered the sensors from performing optimally. To facilitate this analysis, a framework was utilized, depicted in Fig.5. The analysis was initiated by examining the data gathered from each of the 12 manholes and all relevant information concerning the design characteristics of the sewage network at these sites. Pertinent details relating to the manholes included the manhole cover and invert level, the quantity and diameter of inlet and outlet pipes, and the upstream and downstream invert levels for all pipes linked to the manholes.

The subsequent stage encompassed a comprehensive analysis, where a comparison was made between the flow velocities and level observations. This comparison aimed to establish a clear relationship between the measurements obtained from both sensors, taking into account the earlier calculations of relative error and correlation coefficient, along with spatiotemporal analysis results across various scenarios. A low relative error and a high correlation coefficient indicated a consistent relationship between the observations, thereby confirming the precise operation of the flow sensors. Conversely, high relative errors and a low correlation coefficient pointed towards an inconsistent relationship between the observations, suggesting a potential lack of precision in the flow sensors' operation. In instances where inconsistencies were identified, further investigations were undertaken by comparing these instances with compatible states from the same manhole, where the flow velocities corresponded to the level observations. Subsequently, all discrepancies or deviations between the two cases were examined to determine possible causes for the inaccuracies, including design features or operational issues. The final stage of the analysis involved assessing the extent to which the identified causes were replicated across different sites with similar characteristics. It is worth noting that while the proposed causes of inaccurate flow sensor observations are based on findings from the studied manholes, other factors could potentially affect the performance of the flow sensors.

E. PROPOSED SOLUTION SUGGESTION

Accurate wastewater flow measurement is crucial in detecting blockage and overflow situations and estimating the

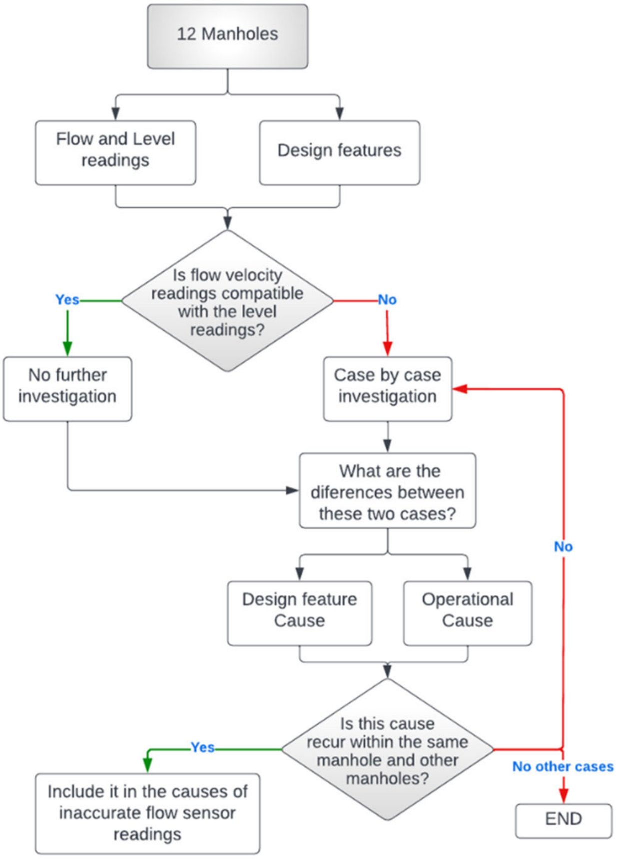

FIGURE 5. The framework used in the analysis of difficulties.

remaining time before overflow. In light of the previous phases of this study, flow sensors were found to be unreliable for measuring wastewater flow velocity in medium and small-sized sewage systems. Therefore, the final phase of this study aimed to propose a novel method for measuring sewage flow velocity. Building upon our previous findings, we have observed a distinct pattern whereby sewage levels rise inside manholes during partial and complete blockages before ultimately overflowing into the streets [42]. To leverage this phenomenon, our proposed approach incorporates the use of level sensors capable of providing precise sewage level data at 5-minute intervals. By monitoring these level measurements, we can derive the vertical velocity of the sewage as it undergoes fluctuation within the manhole. This measurement principle is rooted in the fundamental principles of fluid mechanics, wherein changes in sewage level over specific time intervals correspond to the ascending or descending rate of the sewage flow, i.e., the vertical velocity. In contrast to flow sensors, which use refracted spread spectrum analysis (RSSA) to measure flow velocity in the horizontal direction, the proposed method relies on changes in depth over time to calculate the flow velocity. Fig.6 illustrates the principles of measuring sewage flow's vertical and horizontal velocity using the proposed method.

Horizontal and vertical flow velocities provide different information about the state of the sewage system. In the case of a blockage, horizontal flow velocity will decrease in proportion to the degree of blockage, approaching zero in the case of a complete blockage. In contrast, vertical flow velocity will increase proportionally with the degree of blockage, with successive observations showing positive velocity signals indicating a blockage.

By analyzing changes in vertical flow velocity over time, including velocity value and signal (i.e., negative values indicate outflow greater than inflow, and vice versa), various situations can be detected, such as partial and complete blockages, inefficient design leading to an overflow, remaining time to overflow, and overall system performance.

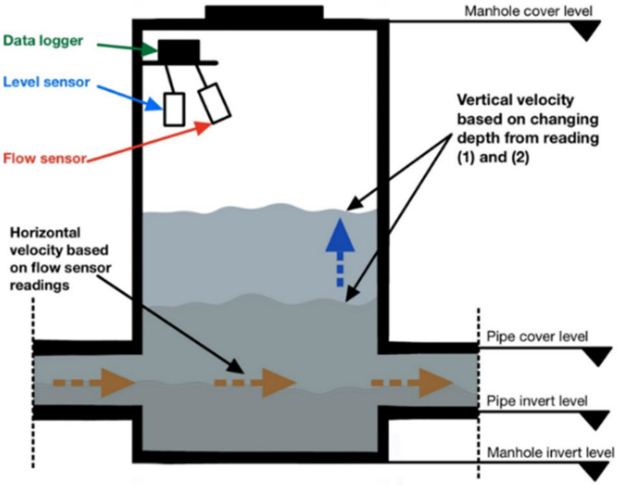

FIGURE 6. Schematic diagram of measuring the vertical and horizontal velocity of sewage flow.

Fig.6 illustrates the calculation of vertical flow velocity based on changes in sewage level over time. However, the need to calculate vertical velocity and determine the state of danger depends on the sewage level inside the manhole. For instance, if the sewage level is below the cover level of the outlet pipe, there is no risk of flooding, and there is no need to calculate vertical velocity. Therefore, to estimate vertical flow velocity and approximate overflow time in hazardous situations, simple equations and constraints can be applied, as described below.

$$MD = MCL - MIL \tag{3}$$

$$SD = SL_X - MIL \tag{4}$$

$$MFP_{manhole} = \frac{SD}{MD} * 100\% \tag{5}$$

$$PFP_{Outlet} = \min(\frac{SD}{PIL + D} * 100\%, 100\%) \tag{6}$$

where MD is the manhole depth, MCL is the manhole cover level; MIL is the manhole invert level; SD is the sewage depth, observation of sewage level; SL_X is the observation of sewage level; $MFP_{manhole}$ is the manhole filling percentage; PFP_{Outlet} is the outlet pipeline filling percentage; PIL is the pipeline invert level, and D is the pipe diameter.

Although the calculation of vertical velocity is typically required only when the outlet pipe utilization ratio reaches 100%, indicating a potential risk of overflow, in this study, it was calculated for all cases to facilitate a comparison with horizontal velocities. The constraints and framework proposed herein may serve as a basis for future research to develop an efficient sewer monitoring system. Thus, regardless of the outlet pipe utilization ratio, the following equations will be employed to calculate the vertical velocities inside the manholes:

$$\begin{aligned} \Delta L &= SL_X - SL_{X-1} \\ \Delta t &= time_X - time_{X-1} \\ \Delta V &= \frac{\Delta L}{\Delta t} \qquad (7) \\ \Delta L_{\text{new}} &= MCL - SL_X \\ \therefore Assume \Delta V_{\text{new}} &\cong \Delta V \qquad (8) \\ time_{ovelflow} &= \frac{\Delta L_{\text{new}}}{\Delta V_{\text{new}} * 60} \qquad (9) \\ Actualtime_{ovelflow} &= time_{ovelflow} + time_X \qquad (10) \end{aligned}$$

where ΔL is the difference in level between two successive observations; x represents the number of the level observation; Δt is the difference in time between two consecutive observations (5 minutes in our case); ΔV is the vertical velocity of the sewage inside the manhole; ΔL_{new} is the difference in depth between the current observation and the manhole cover level; $time_{ovelflow}$ is the remaining time in minutes to over low;$Actualtime_{ovelflow}$ is the actual time that the overflow occurs and $time_X$ represents the current time.

III. RESULTS AND DISCUSSION

A. FLOW DATA ANALYSIS AND RESULTS

1) CORRELATION BETWEEN THE FLOW AND LEVEL OBSERVATIONS

The data analysis process conducted in this study aimed to assess the effectiveness of utilizing flow sensors in conjunction with level sensors within small and medium-sized sewers in Hong Kong. The initial step involved examining the relationship between the data generated by the level and flow sensors. This was achieved by calculating the correlation coefficient for each studied location, thereby determining the extent of association between these two sets of measurements. The overall correlation coefficient between the level and flow sensors was 0.36, suggesting a moderate positive correlation. Notably, the correlation coefficients varied across different manholes, as depicted in Fig.7. Specific manholes, such as Manhole No. 2, Manhole No. 5, and Manhole No. 10, demonstrated strong positive correlations with coefficients of 0.92, 0.76, and 0.59, respectively. These findings indicate a high level of agreement between the level and flow sensors in these particular manholes. Conversely, Manhole No. 3 exhibited a negative correlation coefficient of -0.13, implying an inverse relationship between the two measurements. This suggests that flow sensor observations tend to decrease as the observations of the level sensor increase. For the remaining manholes, the correlation coefficients ranged from 0 to 0.4, indicating a weaker degree of association between the level sensors and flow sensors.

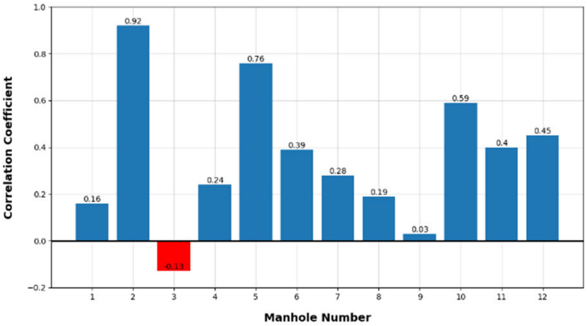

FIGURE 7. Correlation coefficients between level sensors and flow sensors for each manhole.

2) SPATIOTEMPORAL ANALYSIS OF FLOW AND LEVEL OBSERVATION BEHAVIOR

To delve deeper into the consistency between the velocities measured by the flow sensors and the sewage levels recorded by the level sensors, a comprehensive examination of the cases was conducted. The findings revealed distinct patterns within our study. A direct correlation between flow velocity and sewage depth was clearly observed in certain instances, as depicted in Fig.8 (a-c). Conversely, other manholes displayed incongruity between flow velocity and sewage depth. For instance, an anomalous scenario was identified in observations from Manhole No. 8, where the flow velocity exhibited drastic fluctuations, reaching unreasonable values exceeding 30 m/s. Remarkably, the sewage level remained relatively constant at approximately 4.75 m, surpassing the cover level of the outlet pipe and constituting approximately 60% of the manhole depth (Fig.8 (d)). These abnormal velocity observations indicate the presence of inaccuracies in the flow sensor data, as it is implausible for the sewage flow to attain such high velocities within a small and medium-sized gravity-based sewage system. Similar inconsistencies were observed in two other instances from Manhole No. 10 on different days and from Manhole No. 3 (Fig.8 (e-g)). Fig.8(e) illustrates a scenario where the sewage level remained relatively stable and below the cover level of the outlet pipe. However, the flow velocity exhibited continuous fluctuations throughout the day, ranging between 5.5 and 7.0 m/s, without any significant changes in the sewage level within the manhole. Similarly, Fig.8(f) demonstrates varying flow velocities despite a relatively constant sewage level throughout the day. It should be noted that the sewage level, in this case, was higher than the cover level of the outlet pipe. Another example from Manhole No. 3 is depicted in Fig.8(g), where the flow velocities remained constant when the sewage level was below the pipe cover level, but as the level increased above the cover level, the flow velocity

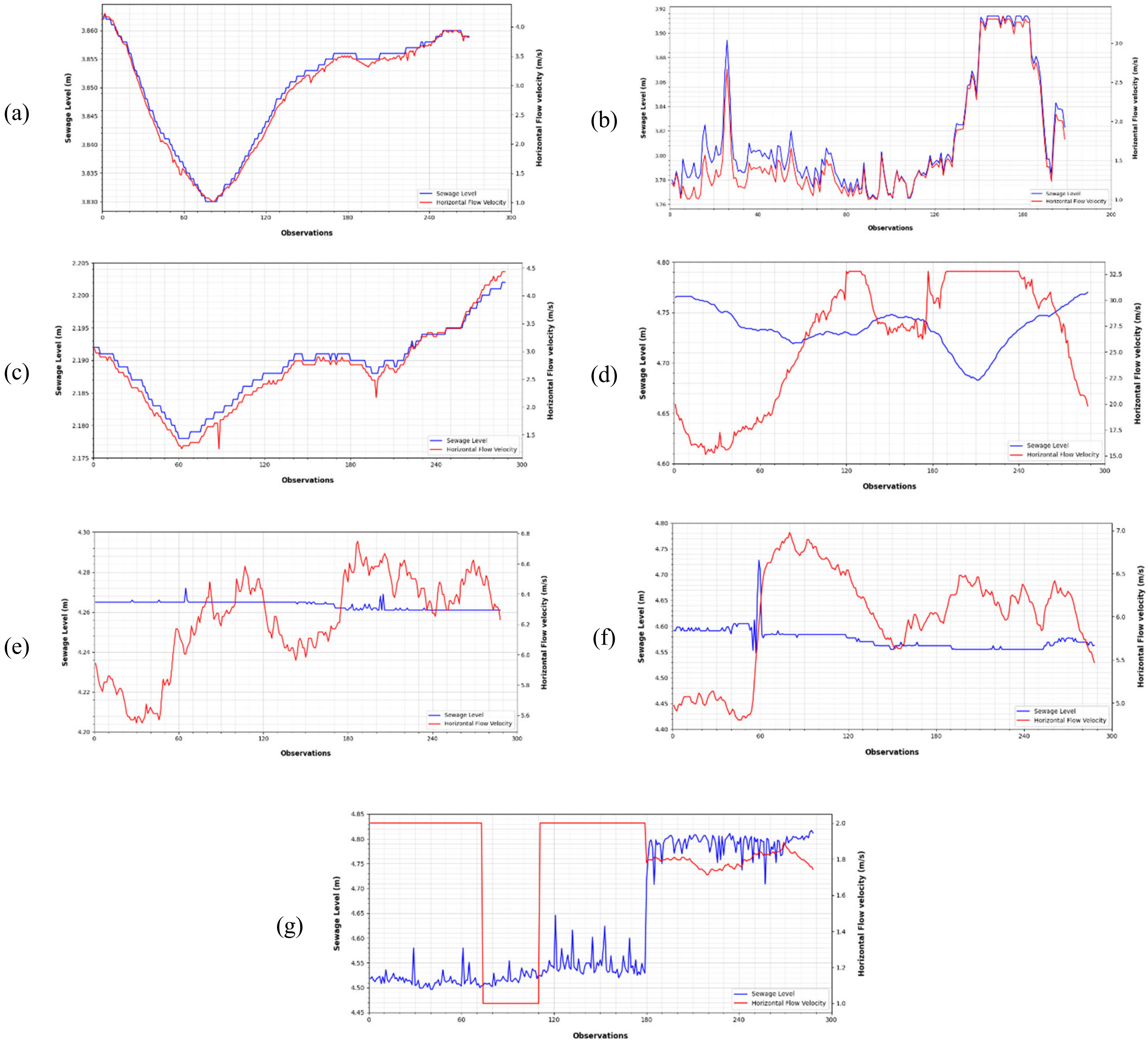

FIGURE 8. **The Flow velocity compared with the sewage level, manhole cover level, manhole invert level and outlet pipe cover level in (a) Manhole No.2 in [01/12/2019] (b) Manhole No.11 in [21/11/2019] (c) Manhole No.5 in [5/11/2019] (d) Manhole No.8 in [21/12/2019] (e) Manhole No.10 in [24/07/2019] (f) Manhole No.10 in [13/10/2019] (g) Manhole No.3 in [22/12/2019].**

started changing and decreased. These observations highlight instances where the measured flow velocities and sewage levels do not align cohesively. Such discrepancies underscore the limitations and inaccuracies within the flow sensor data, potentially stemming from factors such as sensor malfunction or inconsistent flow conditions.

3) FLOW RATES COMPARISON AND CORRELATION

The evaluation of flow sensors' effectiveness in accurately measuring flow rates in small and medium-sized sewers requires more than just assessing the consistency of data generated by individual sensors. Flow sensors primarily provide velocity data, while level sensors measure sewage depth inside manholes. Therefore, to comprehensively evaluate the efficiency of flow sensors, a comparison was conducted between the flow rate derived from flow sensors and the flow rate calculated using Manning's equation, which incorporates data from level sensors. This comparison allows for assessing how closely the flow rates determined by the two methods align. Fig.9 compares flow rates derived from both methods across the entire dataset and studied locations. The results clearly reveal a significant difference between the flow rates generated by flow sensors and those calculated using Manning's equation. In many locations, there was a noticeable discrepancy in the median values between the two approaches, suggesting limitations in either the accuracy of the flow sensors or the applicability of Manning's equation. Moreover, there is a significant disparity in the distribution of Manning's flow values and flow sensor values, indicating inconsistencies in the measurement techniques. However, it is worth noting that for Manhole No. 11, some similarities can be observed between the results obtained from the two methods (Fig.9). This suggests a certain degree of agreement between the flow rate derived from the flow sensors and the flow rate calculated using Manning's equation for this specific location.

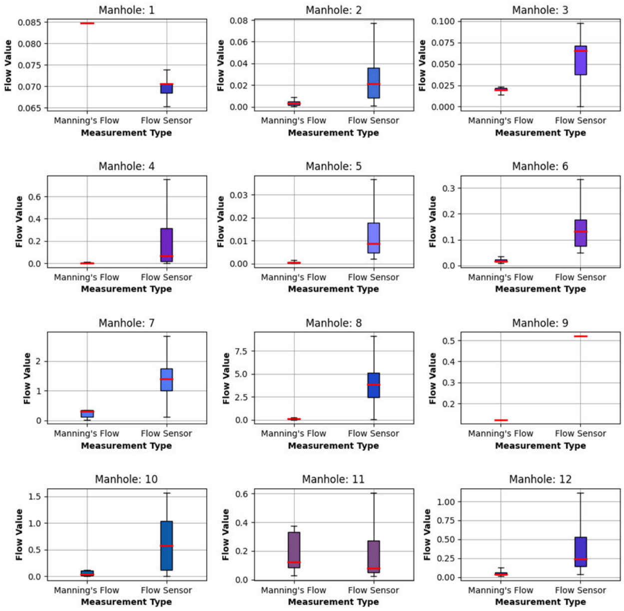

FIGURE 9. **Comparison of flow rates generated by flow sensors and Manning's equation across studied locations.**

Moreover, in order to quantitatively assess the accuracy of the flow sensors and gain a deeper understanding of the flow rates obtained through both methods, a thorough comparison was conducted by calculating the relative error between the estimated flow rates derived from the flow sensors and those estimated using Manning's equation. This analysis encompassed the entire dataset and individual locations, allowing for a comprehensive evaluation of the flow sensors' efficacy in these specific sites. Across all manholes, the calculated average relative error amounted to 72.14%. This substantial value indicates a significant discrepancy between the two measurement methods, highlighting the presence of notable errors in the flow sensor estimates of flow rates. Furthermore, Fig.10 illustrates the average relative error for each manhole, revealing varying degrees of disagreement and inconsistency between the two measurement approaches across different locations. Certain manholes displayed relatively lower levels of discrepancy, while others exhibited substantial differences. Notably, Manhole No. 8 exhibited an exceptionally high average relative error of 97.63%, signifying a considerable deviation between the flow sensor measurements and Manning's flow rates. Similarly, Manhole No. 4 and Manhole No. 5 demonstrated notable average relative errors of 96.63% and 93.9%, respectively. Conversely, Manhole No. 1 and Manhole No. 11 showcased relatively lower average relative errors of 19% and 51.32%, respectively, indicating a comparatively better agreement between Manning's flow rates and flow sensor measurements in these instances. These findings underscore the importance of conducting individual assessments for each manhole to identify variations in measurement accuracy within the hydraulic system. Thus, the average relative errors across each location were meticulously examined and graphically represented in Fig.11.

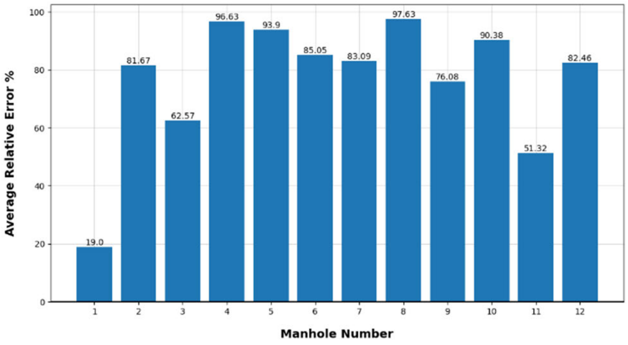

FIGURE 10. **Average relative error of flow sensor measurements compared to manning's flow rates for each manhole.**

An examination of Fig.11 reveals notable variations in the spread of errors among different manholes. The interquartile range (IQR), representing the middle 50% of the data, provides valuable insights into the variability of relative errors. Among the manholes scrutinized, Manholes No. 3 and 11 exhibit a wider spread of relative errors with large IQR values. This suggests that the relative errors for these manholes show significant variability, ranging from small to high errors. Consequently, there is a notable variation in the accuracy of flow measurements between Manning's flow and the flow sensors in these particular manholes. This variation in accuracy is further exemplified when conducting a qualitative analysis of the flow rates derived from the two methods.

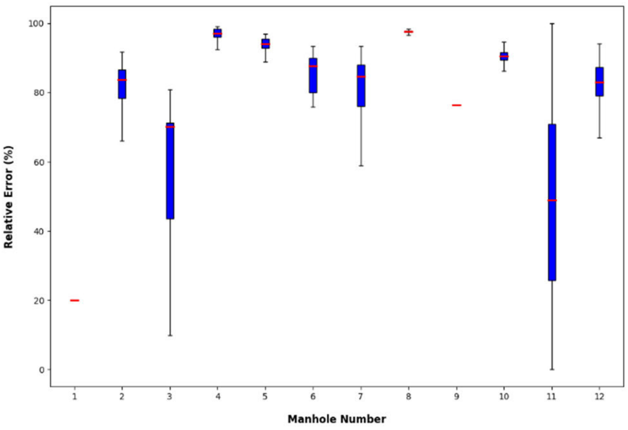

FIGURE 11. **Box plot of average relative errors across studied locations.**

Fig.12 provides a demonstration, where certain instances show a close alignment between the two methods (Fig.12 (a)), while others exhibit discrepancies (Fig.12 (b)). The presence of such contrasting observations across different manholes suggests the influence of various factors on the accuracy of flow measurements in these locations. In contrast, Manholes No. 1, 8, and 9 exhibit steady relative errors centered around the same value, indicating the consistent performance of the flow sensors throughout the data collection period. Other manholes exhibit a small spread of relative errors ranging between 60% and 90%, signifying relatively different performance, but even in the best cases, the accuracy was insufficient.

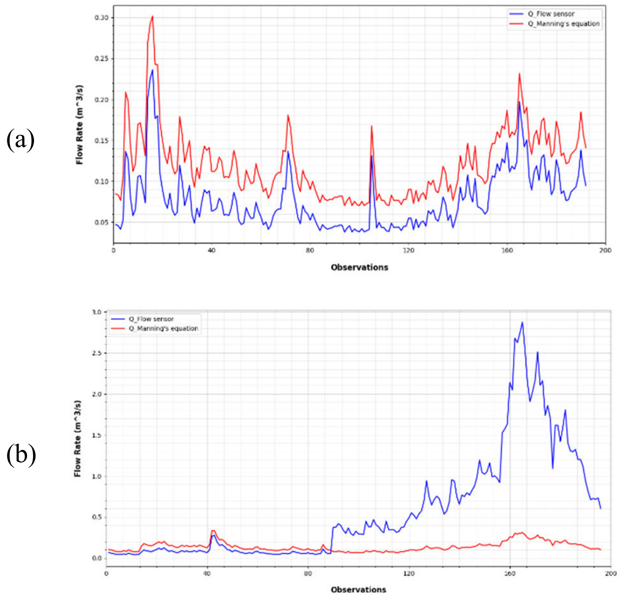

FIGURE 12. Comparison of flow rates between Manning's equation and flow sensor measurements for Manhole No. 11 in (a) [2/8/2019] and (b) [15/7/2019].

Overall, a comprehensive assessment of the efficiency of flow sensors necessitates the consideration of both the correlation between the level and flow sensors, the average relative errors, and spatiotemporal analysis. Relying solely on relative errors or correlation analysis cannot provide a holistic understanding of the accuracy of flow sensor measurements. This is particularly relevant because Manning's equation, originally developed for open channels, can be directly influenced by the sewage level inside pipes, thereby impacting its applicability to sewer systems. This was evident in the case of Manhole No. 2 (Fig.13 (a)), where a strong correlation between the level and flow measurements (0.92) coexisted with a high relative error (81.67%). This disparity could be attributed to the low sewage level within the pipe, often representing less than 20% of the pipe diameter. Another example emerged in Manhole No. 1, where the analysis revealed a low correlation between the level and flow sensor data (0.16) alongside a low relative error (19%). This can be attributed to the flow sensor consistently providing the same flow velocity values over extended periods due to specific influencing factors, despite the continuous variations in the sewage level (Fig.13 (b)). In contrast, certain cases demonstrate alignment between the correlation coefficient, relative errors, and spatiotemporal analysis. For example, in the case of Manhole No. 11, a moderate correlation (0.4) exists between the level and flow sensor data, accompanied by a moderate relative error (51%). This finding is supported by the spatiotemporal analysis of data from this manhole, which indicates consistency between the measurements from both sensors in some instances, while significant inconsistencies are observed in others (Fig.13 (c)).

Collectively, the findings derived from quantitative analyses and visual interpretation of flow behavior suggest that flow sensors often generate inaccurate and inconsistent observations, compromising overflow monitoring systems' reliability.

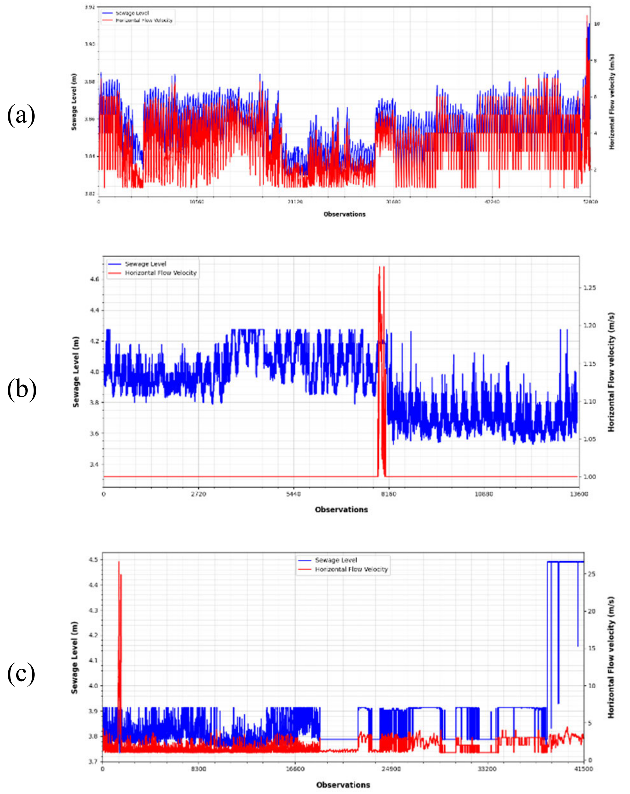

FIGURE 13. Variations in flow velocity and sewage level in (a) Manhole No. 2, (b) Manhole No. 1, (c) Manhole No. 11.

B. FACTORS AFFECTING ACCURACY OF FLOW SENSOR OBSERVATIONS

The data analysis conducted in this study revealed two primary issues related to the use of flow sensors in detecting overflow and blockage status in small and medium-sized sewage networks. Firstly, a significant concern was identified in the form of high observation errors, with a relative error of 72.141%. This finding indicates a substantial deviation between the measured values and the actual flow rates. Secondly, a lack of consistency was observed between the flow velocities and sewage levels, as evidenced by an overall correlation coefficient of 0.36. As a result, further analysis was carried out to identify the underlying difficulties that compromised the effectiveness of flow sensors in small and medium-sized sewage networks, utilizing the framework depicted in Fig.5. The twelve locations were studied, with a focus on the manholes that showed partially effective cases, where the flow sensors functioned efficiently in some cases and inadequately in others. Comparing these cases facilitated an understanding of why the flow sensor is insufficient for monitoring and detecting blockages and flooding in small and medium-sized sewage networks. The results of the difficulties analysis identified several factors that may have contributed to large amounts of errors and inconsistencies in the flow sensor observations. The three main reasons identified through our framework and constraints (Fig.5) include the size of the sewers and the installation location, the sewage level inside the manhole, and the presence of multiple inlet and outlet pipes connected to the manhole. The following subsections concisely describe the suggested causes of flow sensor failure.

1) THE SIZE OF SEWER PIPES AND INSTALLATION LOCATION

The diameter of sewer pipes is a critical factor that can impact the efficiency of flow sensors in sewage networks. In our study, flow sensors were installed inside manholes at a 45-degree angle since the small size of the sewer pipes (ranging from 0.15-0.6 m in diameter) did not allow for sensor installation inside the pipes, as recommended by the sensor manufacturer. Thus, manhole installation is the only viable option for measuring flow velocity in these systems. Although the location of the flow sensors inside the manholes can influence their accuracy, some cases showed accurate results for flow velocity and consistency with the sewage level, while others did not. Therefore, we compared accurate and insufficient cases to understand when sewer size affects velocity measurements.

The comparison was carried out between data collected from Manholes No. 1 and 2, where most of the observations collected from Manhole No. 1 were insufficient, while most observations from Manhole No. 2 showed consistency between velocity and sewage level. These two manholes have similar design features (i.e., one input and output pipes) except for the size of the inlet and outlet pipes, with the diameter of both pipes measuring 0.15 m for sewers connected to Manhole No. 1 and 0.225 m for sewers connected to Manhole No. 2. The comparison revealed that when the sewage level is relatively low inside the pipe, and subsequently, the flow velocity is relatively low according to Manning's formula, the flow sensor will operate efficiently. In contrast, when the sewage level is high inside a small-sized pipe, the flow sensor is less reliable.

The limitations of contactless flow sensors in measuring flow velocity accurately within small sewer systems can be attributed to the methodology employed by these sensors. Such sensors function by firing a pulse at the sewer surface, which is refracted at angles across the flow axis. As a result, the accuracy of the velocity measurement is dependent on the flow direction. When the outlet pipe size is small, the flow direction tends to be inconsistent while ejecting the manhole, as shown in Fig.14(a). This inconsistency, combined with the method used to calculate the flow velocity (i.e., RSSA), may cause inaccurate velocity values. However, accurate velocity values may be obtained when the sewage level is shallow, resulting in low flow speeds and no inconsistency at the entrance to the outlet pipe, as illustrated in Fig.14(b).

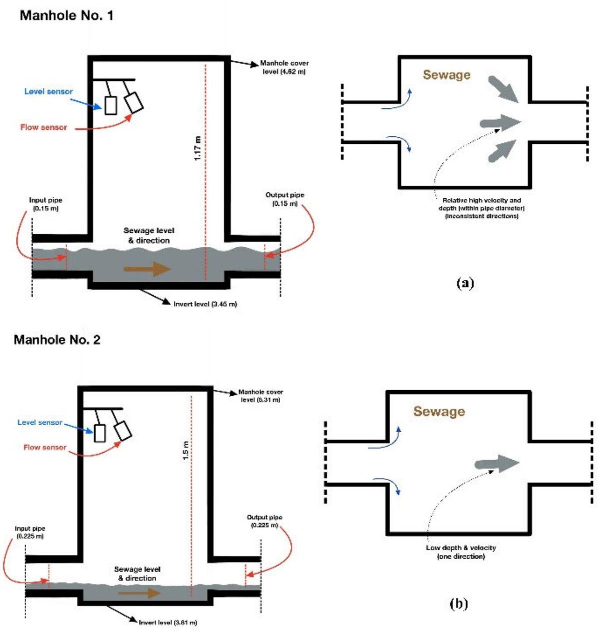

FIGURE 14. The effect of output pipe size in Two cases of flow sensor measurement (a) results in inaccurate values and (b) results in accurate values.

This case is frequently observed in Manhole No. 2. Furthermore, it is important to note that this limitation affects small sewer systems more than larger systems. In larger systems, the size of the outlet pipes is typically sufficient to allow for consistent flow direction and accurate velocity measurement. However, in small systems, the limited size of the outlet pipes can result in a more erratic flow direction and, consequently, inaccurate velocity values.

2) THE SEWAGE LEVEL INSIDE THE MANHOLE

Despite the findings from the previous section indicating that the accuracy of flow sensors decreases as the sewage level rises, it was observed that under specific circumstances where the sewage flow follows a unidirectional pattern, the sensor can still provide accurate velocity observations. However, the majority of manholes examined in this study revealed that once the sewage level exceeded the height of the outlet pipes, the flow sensor failed to provide any accurate measurements of sewage flow. This was particularly evident in the case of Manhole No. 4, where a strong correlation between flow velocities and level observations was observed when the sewage levels were below the cover level of the outlet pipe (i.e., 2.735m) (Fig.15(a)). Conversely, a lack of consistency was observed when the sewage level increased beyond the cover level (Fig.15(b)). This observation emphasizes the sewage level's critical influence on flow sensors' effectiveness. When the sewage level surpasses the height of the outlet pipes, it creates conditions that are challenging for accurate velocity measurement. The flow patterns become more complex, with potential backflows and turbulent flows, making it difficult for the flow sensor to provide reliable observations.

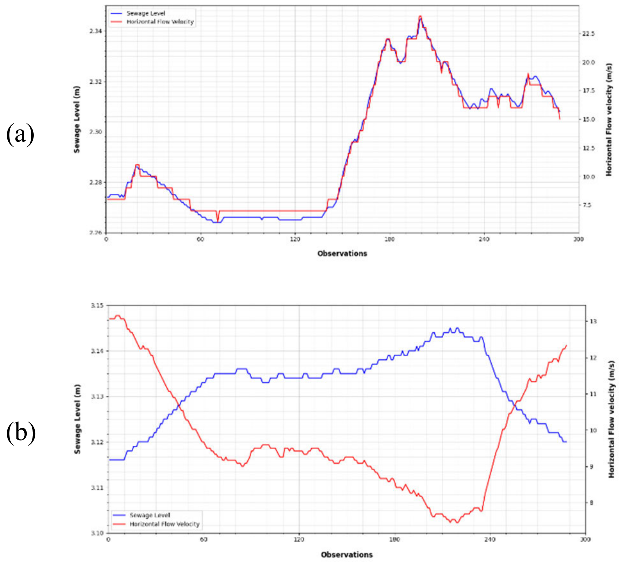

FIGURE 15. **The Flow velocity compared with the sewage level in Manhole No.4 when the sewage level is (a) lower than the outlet pipe cover level and (b) higher than the outlet pipe cover level.**

In scenarios where blockages occur, the sewage level rises above the cover level of the outlet pipe and continues to escalate until it overflows from the manhole. However, the operational mechanism of flow sensors relies on capturing the pulse reflected from a moving surface of the flow. Consequently, when the sewage level exceeds the outlet pipe's diameter, the sewage surface's movement becomes predominantly vertical rather than horizontal. As a result, the flow sensor observations approach zero. Even if there is some residual movement, it tends to have inconsistent directions, leading to inaccurate velocity values. Notably, during the study, the sensors recorded implausible observations at very high velocities (ranging from 15 to 34 m/s) when the sewage level exceeded the cover level of the outlet pipe (Fig.8(c)). It has been observed that in the case of small and medium-diameter sewers, a substantial number of level observations exceeded the diameter of the outlet pipe, even in the absence of actual blockages. Consequently, false alerts pertaining to blockages and overflow scenarios may be erroneously triggered. This highlights the potential implications of such discrepancies on the overall effectiveness of flow sensors. Fig.16 provides a simplified illustration of how the sewage level affects the performance of flow sensors.

Overall, flow sensors showed a deficiency in all instances where the sewage level increased over the outlet pipe's cover level. As a result, the flow sensors were unable to accurately predict blockages or overflow conditions and differentiate between scenarios where the sewage level rises due to an increase in usage or a partial and complete blockage within the outlet pipe. In such instances, the flow sensor observations were either zero or produced inconsistent results with the sewage level, as shown by Fig.8(c-e).

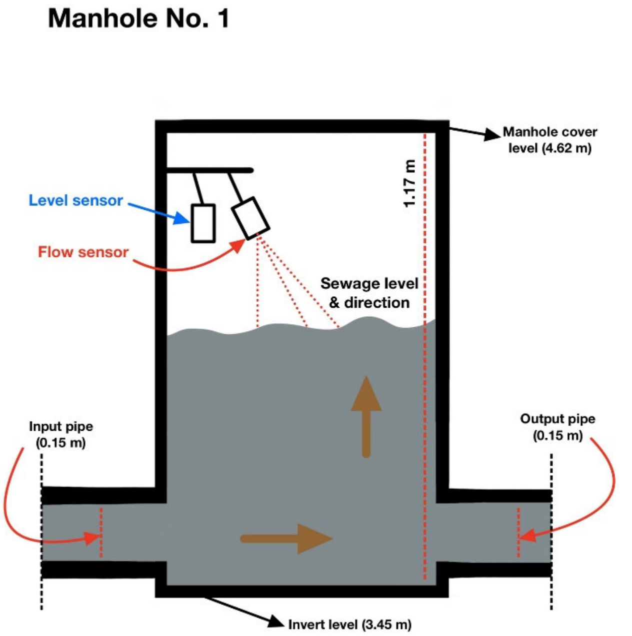

FIGURE 16. **The effect of sewage level in the Manhole on the flow sensor observations.**

3) MULTIPLE INPUT & OUTPUT SEWER PIPES

Although flow sensors tend to provide more accurate flow observations when the sewage level remains within the diameter of the outlet pipe, this statement only holds true for manholes with one inlet and outlet pipe and reasonable flow velocities. However, challenges arise when dealing with manholes that incorporate multiple inlet or outlet pipes, leading to increased inconsistency in flow directions. Based on the data collected from 12 target locations, it was observed that ten manholes had 2 or 3 inlet pipes, as shown in Table 1. The presence of multiple input and output pipes was identified as one of the primary causes of inaccurate flow observations and negative values. This issue arises because the flow sensor measures the flow velocity upstream of the outlet pipe by reflecting pulses from the flow surface, which can be influenced by the inflow from different inlet pipes. Fig.17 exemplifies three scenarios wherein the presence of multiple inflow and outflow pipes adversely impacted flow velocity measurements within the targeted manholes.

Nonetheless, it is worth acknowledging that other circumstances may yield similar outcomes.

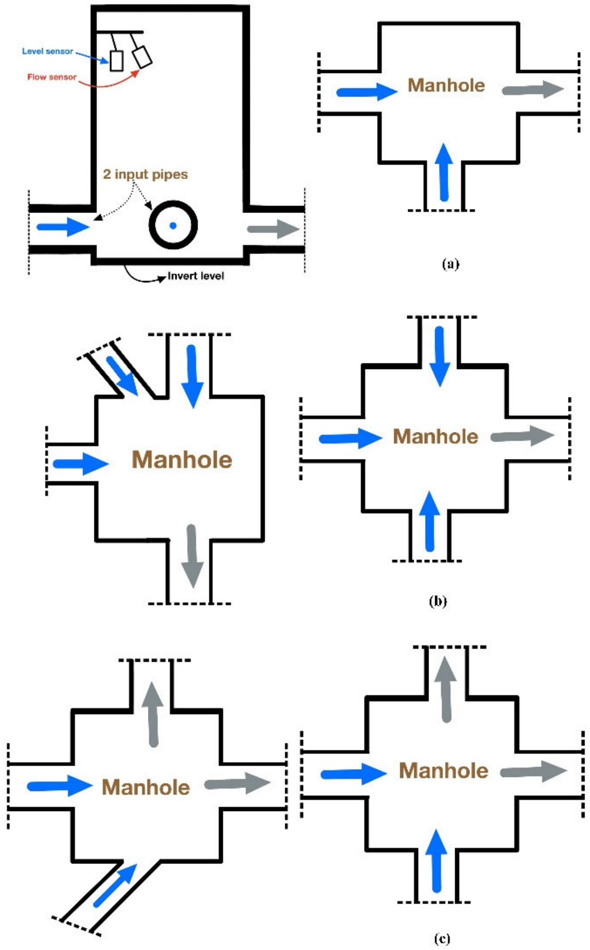

FIGURE 17. **The cases where multiple input & output pipes will affect the flow sensor observations(a) when two input and one output pipes (b) when three input and one output pipes (c) when two input and two output pipes.**

In addition to the challenges posed by multiple inlet and outlet pipes, another factor contributing to the flow sensor's lack of accuracy is the variation in downstream invert levels of the inlet pipes. This variation was observed in half of the examined manholes, namely Manholes No. 3, 6, 11, 12, 9, and 10. For instance, Manhole No. 3 was equipped with three inlet pipes, featuring diameters of 0.3 m, 0.15 m, and 0.15 m, respectively, and an outlet pipe with a diameter of 0.45 m. Although two pipes originated from the same direction, they possessed different downstream invert levels. Specifically, the first pipe, with a diameter of 0.3 m, had a downstream invert level of 3.93 m, the second pipe, with a diameter of 0.15 m, had a downstream invert level of 4.15 m, and the third pipe, situated in the opposite direction, had a downstream invert level of 5.17 m, also with a diameter of 0.15 m. Additionally, the upstream invert level of the outlet pipe stood at 3.9 meters. These variations in invert levels frequently resulted in inconsistent flow sensor observations due to the diverse flow directions and elevations. To visually illustrate this particular case and emphasize the design features of Manhole No. 3, refer to Fig.18.

While most of the results align with this observation, there were instances where accurate results were obtained despite two or three inlet pipes. Manhole No. 5, for example, exhibited accurate observations despite having two inlet pipes, with the main pipe featuring a diameter of 0.525 m and the second inlet pipe measuring 0.15 m in diameter. In this case, the flow contribution from the second inlet pipe was considerably smaller than that of the main pipe, thus exerting minimal influence on the direction of sewage flow. Consequently, the presence of this additional pipe did not significantly impact the efficacy of flow sensor observations. Conversely, in manholes where multiple pipes significantly contributed to the inflow, such as Manhole No. 3, the flow sensor demonstrated deficiencies in accurately measuring flow velocity across different directions.

C. FLOW MEASUREMENT DEPENDING ON THE LEVEL SENSOR'S OBSERVATIONS (PROPOSED METHOD)

The analysis of the difficulties has identified three main reasons that directly affect the efficiency of the flow sensors. Some of these reasons are related to design features, such as the pipes' size and the presence of many inlet and outlet pipes connected to the manhole, resulting in inconsistent sewage flow directions. Other reasons may be operational causes, such as overuse of the sewage system, causing the sewage level to increase more than the outlet pipe cover level without severe risks of overflow or blockage, which can affect the consistency of the sewage flow direction inside the manhole. Therefore, it has become evident that relying solely on flow sensors for predicting blockages and floods can lead to numerous false alerts and inconsistent observations in sewer networks characterized by these features. Consequently, implementing such sensors may result in inaccurate and unreliable overflow monitoring systems in small and medium-sized sewers.

While level sensors are useful for measuring the sewage level inside manholes and detecting overflow situations when integrated into a monitoring system, they have limitations in identifying underlying issues within the sewer network, such as partial or complete blockages, excessive usage, and imminent overflow events. To overcome these limitations, this study proposes a novel approach that utilizes level sensors to capture the hydraulic performance of small and medium-sized sewer networks. This approach serves as an alternative to conventional flow sensors, aiming to improve the development of integrated sewer monitoring systems capable of detecting blockages and predicting overflow timings. By focusing on hydraulic performance, particularly sewage flow velocity, a more comprehensive understanding of the sewer network's behavior can be achieved, enabling effective management and timely intervention. The proposed method was applied to the data collected from 12 manholes to establish a correlation between the sewage level

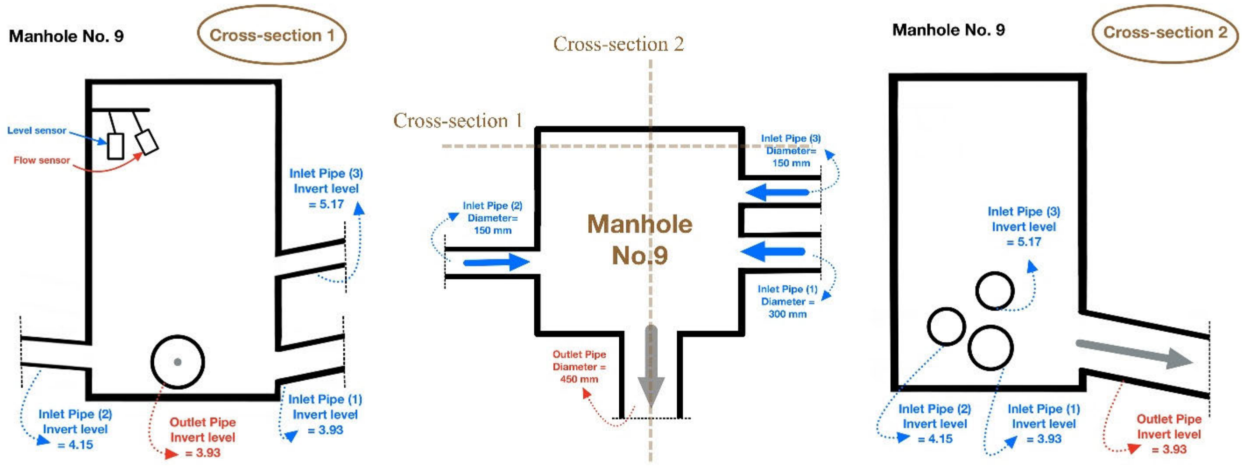

FIGURE 18. Schematic Diagram of Manhole No. 3 Showing Inlet and Outlet Pipes with Varying Downstream Invert Levels.

and calculated velocities and to evaluate its effectiveness in capturing the hydraulic performance of the sewer network.

The results of applying this method revealed a high degree of consistency between the measured velocities and the sewage level. Fig.19 compares the calculated vertical velocities and the horizontal velocities measured by flow sensors for two specific cases. Fig.19(a) and Fig.19(b) depict the results obtained from the flow sensors and the proposed method, respectively, along with the corresponding level sensor observations for the first case. Notably, the flow sensor observations exhibited inconsistency with the level observations. The magnitude of changes in horizontal flow velocities was disproportionately high compared to the sewage level, indicating a discrepancy with Manning's equation. Conversely, the vertical velocities demonstrated exceptional capability in accurately detecting variations in the inflow, as evidenced by an extremely high correlation (nearly 100%) observed between the cumulative vertical velocities over time and the actual sewage level. This strong correlation highlights the effectiveness of vertical velocity as a reliable indicator for identifying operational risks within the system. For instance, as depicted in Fig.19(b), the site under consideration showed no signs of operational issues, blockages, or overflow risks at that particular time. Similar results were obtained in the case presented in Fig.19(c) and Fig.19(d), where the flow sensors recorded the same horizontal flow velocity value (Fig.19(c)), while the vertical velocities exhibited consistent variations corresponding to changes in the sewage level (Fig.19(d)). These findings highlight the proposed method's superiority in capturing the wastewater's hydraulic performance within the sewer network, enabling the detection of operational anomalies and facilitating the prediction of overflow events.

The application of the proposed method yielded noteworthy findings regarding the significance of two key features in vertical velocities for blockage and flood forecasting. These features include the sign of the velocity, whereby a positive value indicates an increase in sewage flow, while a negative sign suggests a decrease in the sewage level. The importance of these signs lies in their ability to detect blockage situations. For instance, in cases of complete blockage, the sign of the velocity will consistently be positive.

The presence of consecutive positive velocities accompanied by a rise in the sewage level indicates blockage occurrences. In contrast, relying solely on the sewage level may lead to situations where the level exceeds the outlet pipe cover level but exhibits variations in the signs of vertical velocities. Such cases may indicate either excessive usage or partial blockage without a high risk of overflow. However, monitoring these locations is recommended to mitigate potential flood risks. Alongside the velocity signs, the magnitude of vertical velocities also plays a crucial role in predicting the remaining time until an over-flow occurs and differentiating between complete and partial blockages. In the case of complete blockages, the vertical velocity tends to be faster. Incorporating this information effectively into the monitoring system allows the sewage network management group to respond in real-time and anticipate the onset of overflow, providing an estimate of the remaining time.

Overall, the findings suggest that measuring the vertical velocity of sewage inside manholes is a promising approach for predicting blockages and overflow situations, surpassing the effectiveness of flow sensors that measure horizontal velocity. In contrast, to flow sensors, which can be costlier, this approach takes advantage of more affordable level sensors. By leveraging data from these level sensors and considering the specific characteristics of manholes and connected pipes, the proposed method offers a cost-effective alternative for monitoring small and medium-sized sewer systems. The use of level sensors not only reduces the upfront costs associated with installing dedicated flow sensors but also eliminates the need for additional sensors exclusively for velocity measurements. Furthermore, the proposed method captures the hydraulic performance of wastewater, enabling a holistic approach to sewer network monitoring. Integrating this method into logical models as a future research direction holds significant potential. It not only allows for the detection

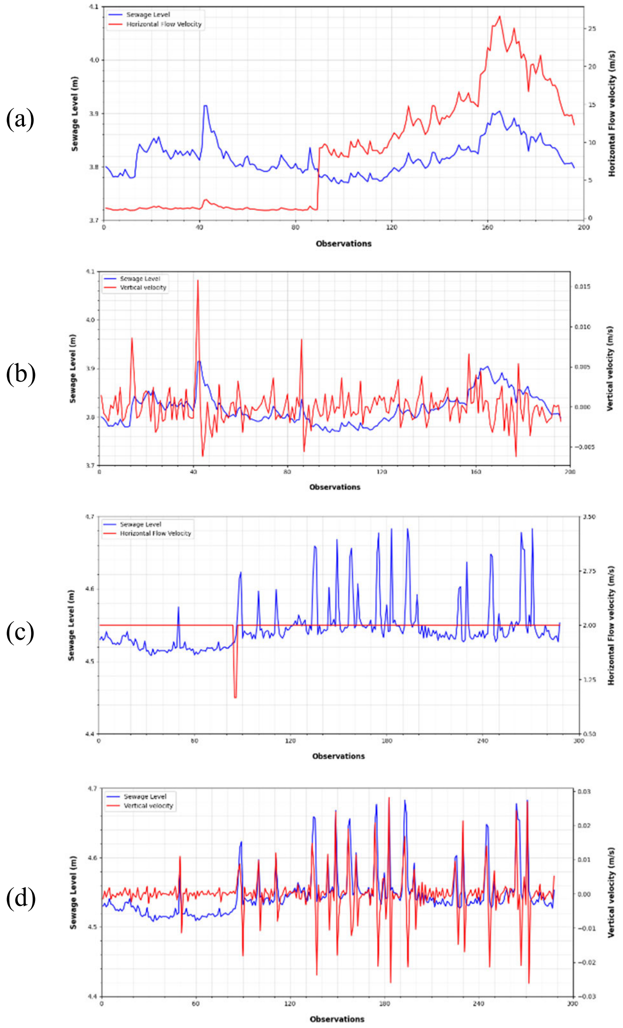

FIGURE 19. **A comparison of horizontal and vertical velocities along with level sensor observations (a) Horizontal flow velocity from Manhole No. 11 in [15/07/2019] (b) Vertical flow velocity from Manhole no. 11 in [15/07/2019] (c) Horizontal flow velocity from Manhole No. 3 in [13/07/2019] (d) Vertical flow velocity from Manhole no. 3 in [13/07/2019].**

of overflow situations but also facilitates the identification of potential blockages, excessive usage patterns, and other hydraulic anomalies that may cause system failure.

IV. LIMITATIONS AND FUTURE WORKS

While this study provides valuable insights into the use of flow sensors in the Hong Kong drainage network, certain limitations need to be acknowledged, along with potential areas for future research and improvement:

- Expanded Data Collection: One limitation of this study is the limited data coverage, as the analyses and findings were based on data collected from only 12 locations in Hong Kong. To address this limitation, future research should prioritize expanding the data collection efforts to include more manholes and a more diverse range of sewer network characteristics. This broader dataset will provide a more comprehensive understanding of the challenges associated with flow sensor usability and allow for more robust conclusions regarding their efficiency in different scenarios.
- Enhanced Flow Velocity Measurement Devices: The results of this study clearly demonstrated the limitations of flow sensors in detecting blockages in small and medium-sized sewage networks. To overcome this limitation, it is crucial to focus on developing improved flow velocity measurement devices specifically designed for such networks. Future work should explore alternative sensor technologies and innovative measurement techniques that can accurately capture the velocity of wastewater flow, while considering these networks' unique characteristics and complexities.
- Validation of the Proposed Method: The proposed method was evaluated using data collected from 12 manholes that did not exhibit any overflow or blockage situations. While this allowed for initial testing and validation, it is necessary to assess the method's efficiency under different scenarios, including cases of complete and partial blockages and instances of excessive usage.
- Development of Integrated Monitoring Systems: A promising future direction for research involves the development of integrated monitoring systems that incorporate the insights gained from this study. By integrating vertical sewage velocities, level sensor observations, sewage network design features, and logical models based on hydraulic performance, a comprehensive monitoring system can be established. This system would have the capability to detect and predict various situations, including blockages, overflow risks, and excessive usage. Future research should focus on developing and implementing such integrated monitoring systems to enhance the performance and resilience of sewer networks.

By addressing these limitations and pursuing the suggested future works, researchers can contribute to advancing flow measurement techniques, improving the effectiveness of sewer network monitoring, and enhancing the overall management and maintenance of wastewater systems. These efforts will ultimately lead to more efficient, reliable, and sustainable wastewater management practices.

V. CONCLUSION

Sewer overflow poses significant threats to public health and the environment, making its prevention a critical area of research. While previous studies have primarily explored the use of sewer level and flow velocity sensors in large-diameter sewer networks, limited research exists on their applicability in small and medium-sized systems. Therefore, this study aimed to comprehensively assess the performance of flow sensors in small and medium-sized sewer networks. The results of this study clearly demonstrate the limitations and challenges associated with relying solely on flow sensors for monitoring and predicting blockages and overflow situations.

The correlation coefficient between the level sensors and flow sensors indicated a weak agreement of 0.36, highlighting the discrepancies between the two measurements. Furthermore, the average relative error of 72.14% in flow rate measurement, compared to Manning's equation, underscored the substantial inaccuracies inherent in flow sensor observations.

Accordingly, a thorough analysis was conducted to investigate the underlying reasons for the limitations of flow sensors. Key factors such as inconsistent flow directions, variations in pipe sizes, and the presence of multiple inlet and outlet pipes were identified as significant contributors to the reduced effectiveness of flow sensors in small and medium-sized sewer networks. To address these challenges, a new approach was introduced based on the real-time measurement of vertical sewage velocities inside manholes. By integrating level sensors and considering the specific characteristics of manholes and connected pipes, this alternative methodology overcomes the limitations of flow sensors. The findings demonstrated a high degree of consistency between sewage levels and the measured velocities, indicating the effectiveness of this method in capturing the hydraulic performance of small and medium-sized sewer networks. Additionally, the study outlines future research directions, including the development of a logical model that incorporates the proposed method to predict remaining overflow time and differentiate between various blockage scenarios. This necessitates a comprehensive investigation into the hydraulic performance of sewage networks under complete and partial blockage conditions, as well as cases of excessive usage. Implementing such a model would enable accurate identification of high-risk situations, facilitate proactive decision-making, and contribute to the development of an integrated overflow monitoring system.

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