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Development of a Low-Cost Prototype System for Pipeline Operational and Vandalism Spillage Detection and Validation Framework

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Abstract

Crude oil spillage is a major challenge in Nigeria. It affects the environment, health, life, and livelihood of residents of the Niger Delta region, where oil is explored, processed, and transported via a network of pipelines. Oil spillage is primarily caused by vandalization/sabotage and operational issues such as corrosion, equipment failure, operation, and maintenance errors. Thus, prompt response is required to mitigate the impact of oil spills. In this study, we deployed low-cost Arduino systems, including sensors (vibration and flow), modules (GPS and Wifi) and an IoT platform (ThingSpeak) to detect spillage caused by vandalism and operational inefficiencies proactively. The results demonstrate that low-cost sensors can detect changes in the flow volume between the inflow and outflow attributable to spillage, and vibration shocks caused by vandalism can be detected and linked to the cause of the spillage and communicated in real time to inform response action. Moreover, we proposed a framework for field validation utilizing KoboToolBox (a crowdsourcing/citizen science platform). The prototype system designed and programmed showed promising results, as it could detect spillage for vandalism and operational scenarios in real-time, quantify the volume of spillage, and identify the location and time of spillage occurrence; indicators relevant for response planning to minimize the impact of oil spillage. A video demonstration of the prototype system developed is accessible via: https://youtu.be/wKa9MZvYf1w.

Keywords

Crude Oil, Leakage, Pipeline, Vandalism, Arduino, Crowdsourcing, Niger Delta

1. Introduction

Crude oil is one of Nigeria's primary natural resources and contributes significantly to Nigeria's foreign exchange earnings, budgetary resources, and economic development [1]. Crude oil and other multi-product are typically transported via pipelines of 666 km and 4315 km, respectively, that traverse the Niger Delta region (**Figure 1**), connecting 22 petroleum storage depots and four (4) refineries situated in Portharcourt (2), Kaduna and Warri, as well as offshore terminals in Excravos (Delta) and Bonny Island (Rivers) and jetties in Alas Cove (Lagos), Calabar (Cross River) and Warri (Delta) [2]. These pipeline networks are susceptible to spillages due to vandalism and operational issues faced by international and local oil and gas companies, such as corrosion, equipment failure and operation and maintenance errors [3]. When oil spills, it constitutes environmental and economic hardship for the country and contributes to environmental degradation and contamination of land and water that negatively affects the health and livelihoods of Niger Delta residents in impacted areas [1] [4] [5].

Over the years, various approaches have been adopted to monitor spillage caused by company operations and vandalism, including the differential pressure approach adopted by oil and gas companies to detect possible crude oil diversion. These include the use of 1) Acoustic sensors such as hydrophones and electromagnetic acoustic transducers to detect signals emitted from punctured pipes [6], 2) Accelerometers, such as Piezoelectric sensors that help detect vibration on the pipeline due to external disturbance [7], 3) Gound penetration such as the use of geophones devices to detect seismic signals from underground pipes [2], 4) Use of Unmanned Aerial Vehicles mounted with instrumentation system payloads for inspection and surveillance gas leakages [8], 5) Negative pressure approach that uses pressure sensors to detect instantaneous pressure wave alteration detecting instantaneous pressure wave alteration [9], and 6) Interior computational-based approach to detect oil and gas leakage from pipelines through the analysis of pressure points and variations in mass-volume balance [10]. Still, it does not provide information on the possible location and cause of spillage [11] [12]. Other methods include human surveillance assisted by dogs [13], computational and technological solutions such as satellite remote sensing, unmanned aerial vehicles, acoustic, accelerometer, and ground penetration [6]. Furthermore, once the spill is detected, a joint investigation (JIV) team comprising relevant stakeholders is deployed to the field to ascertain the cause of the spill and gather additional information on the volume of the spill, area and ecosystem affected [14]. All these approaches provide several advantages and disadvantages. Still, they could benefit from improvements that reduce the time between the spill incident, reporting and the joint investigation team visit [15] [14] and provide information on the potential location and cause of the spill, thereby enabling early detection and management of spillages to curb the environmental, health and economic impact of oil spillage.

When spills occur, they can have short-term to long-term consequences due to the contamination of land and groundwater [4] [16], bioaccumulation of plants and animals ingested and air inhaled by residents pose a health risk [17], loss of livelihoods caused by environmental degradation [18], economic loss due to the quantity and cost of oil spilt [19] and increased restiveness and agitations by militant groups [20]. Therefore, crude oil pipelines require constant monitoring to proactively identify and prevent damages to the pipelines, deter illegal syphoning of petroleum products [2] and reduce the additional cost of pipeline repairs and environmental rehabilitation. Moreover, JIV surveillance team mobilization costs valuable time and resources, and Rim-Rukeh, [14] noted that the JIV process lacks independence and transparency.

This study proposes a low-cost operational and vandalization spill detection system. In addition to detecting the occurrence of spillage, the project will attempt to identify the location and possible causes of the spillage using IoT (Internet of Things) technology/sensors. This study will build on previous studies by Aba *et al.*, [21], Uddin *et al.*, [22], and Lukman *et al.*, [7], where sensors and microcontrollers were applied for pipeline leakage detection, but explore additional innovative sensor components, such as vibration, and GPS (Global Positioning System), to expand on the value-added by technology to address the main research gap of proactively identifying the possible cause and location of spillage which was not addressed by previous studies. This study's outcome could improve the environmental, health, social, and economic welfare of Niger Delta residents by facilitating proactive pipeline monitoring and informing action against vandals.

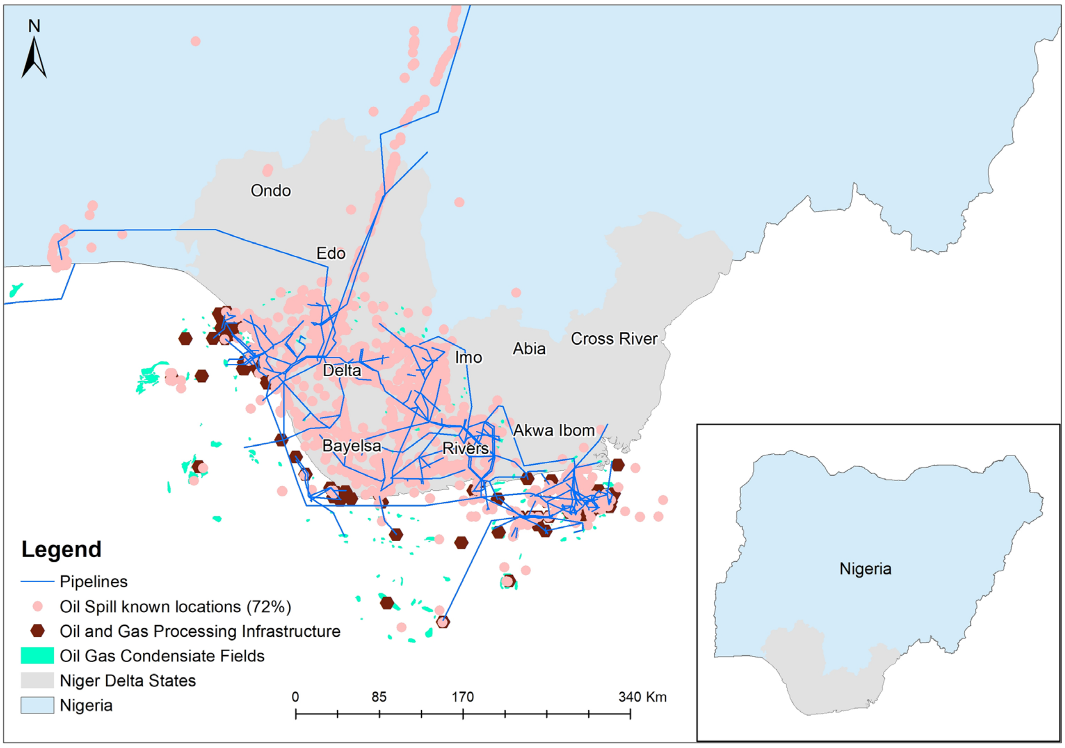

Figure 1. Oil and gas pipeline network and oil spill distribution (Map plotted from the Nigerian National Petroleum Company (NNPC) and National Oil Spill Detection and Response Agency (NOSDRA) data).

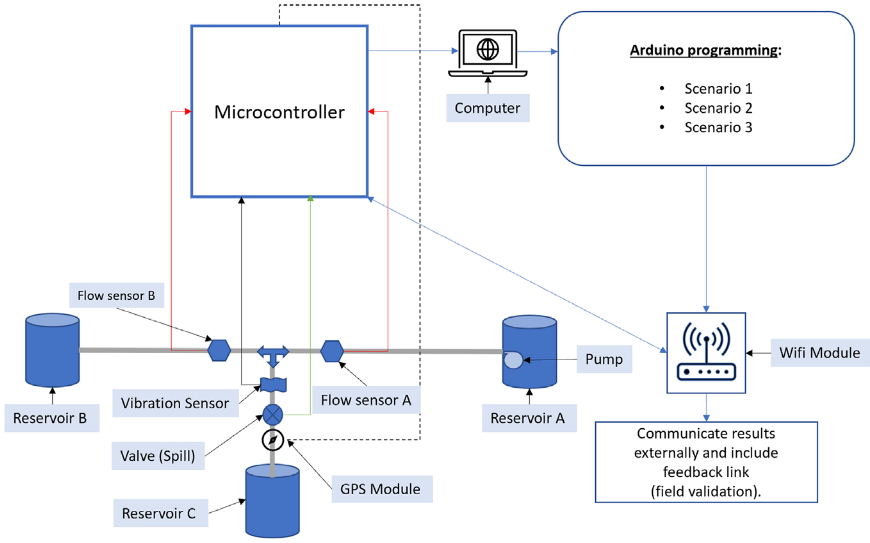

Figure 2. Conceptual block diagram and idealization of the proposed project (Adapted from Che *et al.*, [24]; Tina *et al.*, [25]).

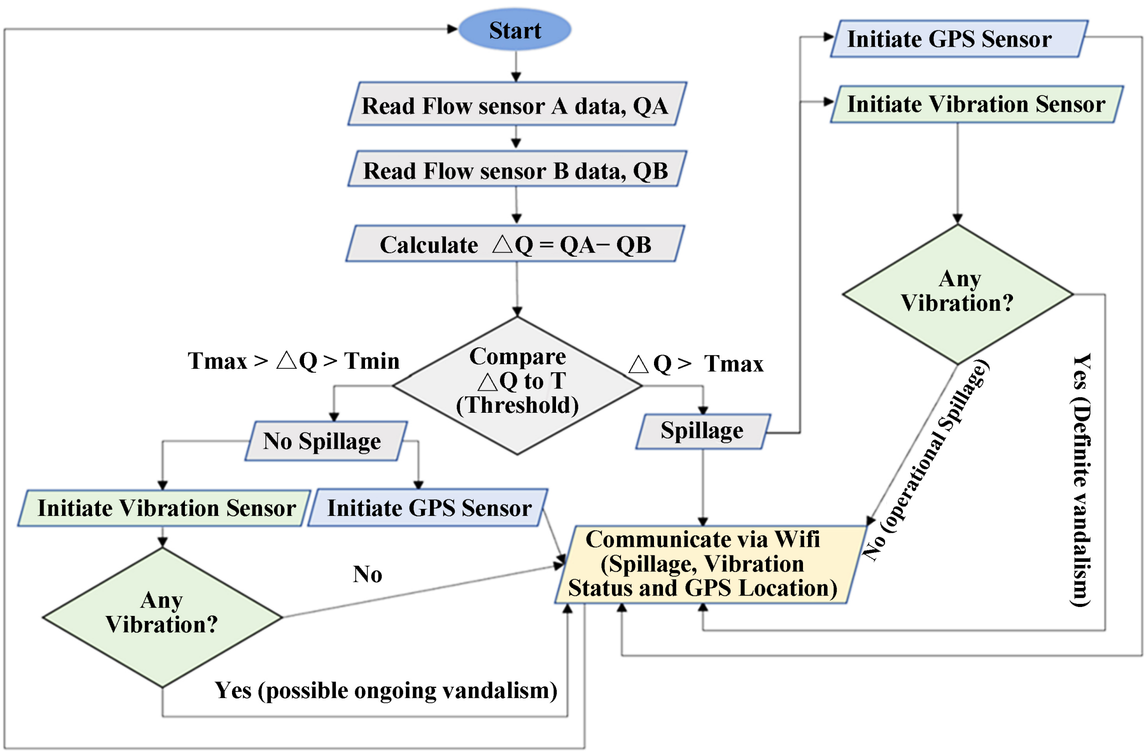

Figure 3. Flowchart for oil spillage and vandalism detection system.

Aim and Objectives

This study aims to develop a low-cost prototype system for operational and vandalism spillage monitoring for oil pipelines. The specific objectives are:

1) To design and develop a low-cost system to monitor pipeline spillage.
2) To identify the possible cause, location, and time of spillage.
3) Develop a framework for spillage verification and action.

2. Methodology

2.1. Conceptual Design and Prototype Development

This study will rely on a data acquisition method comprising of integrated sensors, hardware, computer, and software systems and a plumbing system setup depicting a prototype crude oil pipeline network. **Figure 2** shows the conceptual diagram used to build the methodology for this study. The prototype oil pipeline-network component comprises three reservoirs (A = source (initiated by a pump), B = destination/receiver and C = syphoned) connected at a Tee-junction and a ball valve connected to the reservoir "C", which, when turned on will depict spillage. Flow sensors A and B estimate the flows from the source to the destination reservoirs. The difference in flow between flow sensors A and B about a defined threshold determines the presence or absence of spillage. The sabotage/vandalism scenario was achieved by intermittently sticking and sawing the pipeline, consistent with vandalization scenarios (2 and 3 disclosed below) sensed by the vibration sensor. In addition, a GPS (Global Positioning System) Module (NEO-6M) attached to the piping network collects data information on the system location (coordinates: latitude and longitude) and all other data, including flow rate, vibration, and location are harmonized by Wifi-module (ESP8266 NodeMCU) to transmit data via the internet to an analytical platform (ThingSpeak). All sensors and modules connected to the microcontroller are programmed on the Arduino Integrated Development Environment (IDE) for digital/analogue signal exchange. Furthermore, sensor-specific libraries were adopted and modified in Arduino IDE to gain extra functionality for hardware or data manipulation.

This study adopted three programming scenarios consistent with the spillage scenarios in the Niger Delta Region, *i.e.*, operational spillage and vandalism [23].

- **Scenario 1:** Operational spill detection based on the difference in flow between reservoirs A and B.
- **Scenario 2:** Definite vandalism, based on vibration detection following scenario 1.
- **Scenario 3:** Possible ongoing vandalism based on repeated pipeline vibration but no spillage.

Figure 3 shows the flowchart programmed in Arduino IDE to achieve the three stipulated scenarios. The programming starts with the flow sensor reading data from reservoir A as it transits to reservoir B, and the difference in flow (*i.e.*, the rate of change of velocity) depicts "Spillage" or "No Spillage". Since velocity relies on the pressure of fluid flowing through the pipeline and the cross-section of the pipe is known and constant, normal speed suggests a steady stream rate [22]; thus, Flowrate (Q) = V (Velocity) × A (Area) [26]. Subsequently, the change in flow ($\Delta Q = |QA - QB|$) is analyzed, and the system detects "spillage" when ΔQ exceeds the threshold determined for normal flow ($\Delta Q > Tmax$) and "no spillage" when ΔQ is below the threshold determined for normal flow ($Tmax > \Delta Q > Tmin$). Whether spillage is detected or not, the system initiates location data collection via the GPS module and the vibration sensor to detect definite or possible vandalism.

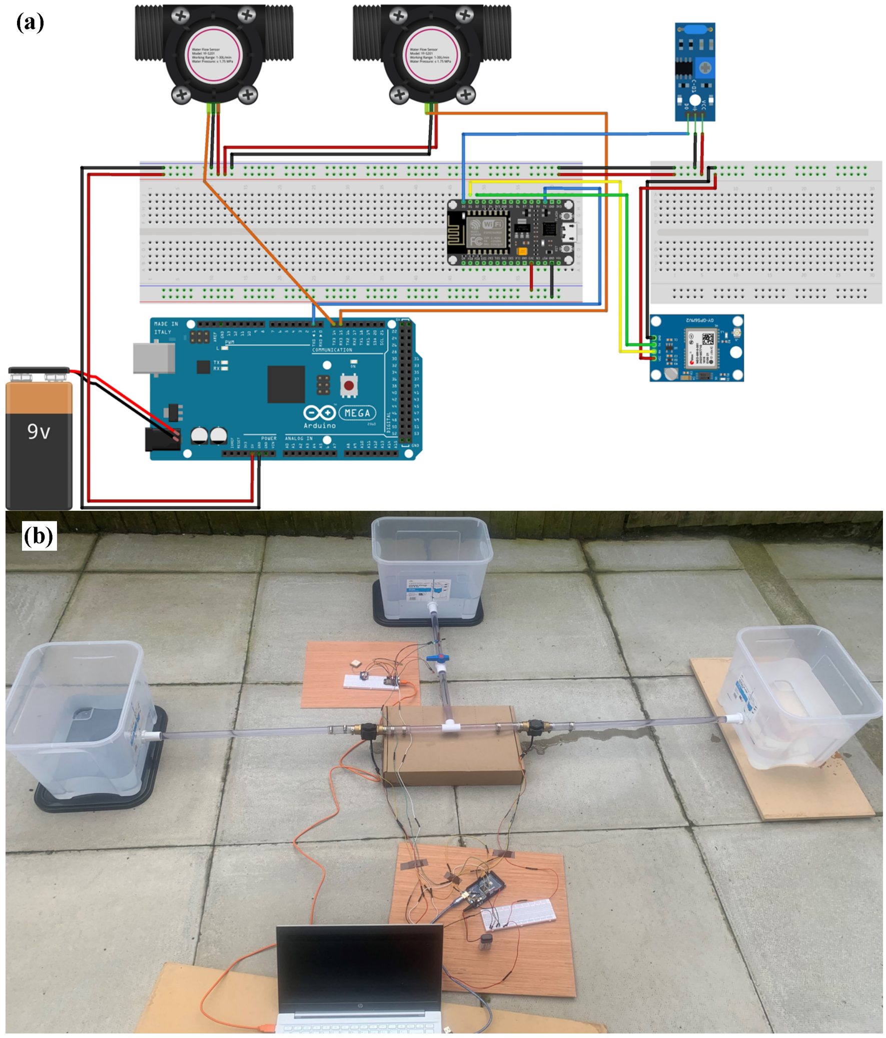

Figure 4. (a) Schematics diagram of GPS, Vibration, Flow Sensor, Wifi module and Microcontroller; (b) Physically connection of GPS, Vibration, Flow Sensor, Wifi module, Microcontroller.

2.2. Prototype Configuration and Components

Figure 4(a) and Figure 4(b), respectively, show the configuration of the connection diagram and physical connection of components for an integrated system containing the GPS module, Vibration sensor, Flow Sensor, Wifi module and Arduino Microcontroller. The flow sensors are connected to reservoirs A and B, while the vibration module is attached to the pipe connected to Reservoir C using a Sellotape. Figure 4(a) presents the connection diagrams a schematic showing the relationship between circuit components for individual and integrated components of the oil spillage detection system. The connection diagram comprises a GPS Module (NEO-6m) module and SW-420 Vibration Sensor interfacing with the NodeMCU ESP8266 Wi-Fi module. The GPS module is connected to the NodeMCU micro-controller through 1) the TxD (Transmitter) pin for serial communication, 2) RxD (Receiver) pin for serial communication, and VCC for power supply (3V), 3) VCC for power supply and 4) the GND (ground) that connects the module to ground.. The Vibration Sensor is also connected to the NodeMCU ESP8266 Wi-Fi module via three pins, VCC, GND and D0 (Digital Output). Then the pipeline is subjected to a physical disturbance, and the red LED light switches on, indicating an active response of the vibration sensor to the cutting effect, such as a hacksaw used for vandalism. **Figure 4(b)** portrays the physical interpretation of the connection diagram. The connection diagram also shows the two Water Flow Sensors interfacing with NodeMCU ESP8266 Wifi Module/microcontroller, where the red wire draws power from the 9V battery through the breadboard, the orange wire delivers output signals to the NodeMCU, and the black wire connected to the ground. **Figure 4(b)** also shows the physical interpretation of the connection diagram and a cross-section of the pipeline assembly attached to the flow sensors.

2.3. Conceptual Framework for Field Verification and Feedback Mechanism

Upon promptly identifying the location and potential status of spillage, objective three was achieved by adopting a simplified JIV questionnaire disclosed in the introduction section. The early spill detection system developed in this study will facilitate prompt dispersion of the JIV team, thereby bridging the gap between the time from the spill incident to the JIV visit to execute spill management. We recommend adopting digital forms developed using KoboToolBox for field validation. Kobo Toolbox is an open-source data collection tool available on smart devices such as phones, tablets, and computers [27] and is widely applied in remote areas with limited internet coverage.

3. Results and Discussion

3.1. Experimental Results from Sensors and Modules

The individual and integrated systems presented in section 2.2 were programmed on Arduino IDE to generate the results presented in this section. These include GPS coordinates, vibration signals and differences between the two flow sensors that depict pipeline leakage. The GPS coordinates (latitude: −2.7259; longitude: 53.7675) generated can be visualized via the link: https://goo.gl/maps/pJFV7iR6U6zW3yd77. The coordinates can help field teams navigate leakage locations in the remote and difficult terrain of the Niger Delta (e.g., mangroves and swamps) and facilitate the geofencing of field surveys to ensure quality assurance [28].

The result of the vibration signals generated by the sensor and programming are presented in **Figure 5**. The spikes in vibration pulses depict possible vandalism. The consistent spikes observed between 15:43 pm and 15:51 pm indicate definite vandalism if followed by a reduction in flow captured by the flow sensor system. **Figure 6** shows additional results of vibration readings communicated to ThingSpeak for remote visualization and the serial monitor outputs detecting vandalism and leakage.

The programming results from the difference in flow rate between flow sensors

A and B are shown in Figure 7. The area in diagonal stripes displayed in Figure 7 depicts the difference in flow (*i.e.*, leakage) captured by flow sensors A and B between the source (A), receiving (B) and leakage (C) reservoirs. Furthermore, the volume of flow (oil spilt) is calculated using the continuity equation,

$$\text{Volume}(V) = \text{Flowrate}(Q)/\text{Area}(A) \tag{1}$$

Q is derived by computing the sum of the positive (+ve) and negative (−ve) differences in flowrate between flow sensors A and B, and Ar of the pipeline is derived from πr^2 (where $\pi = 3.142$ and radius (r) = 7.5 mm or 0.0075 m). The flow rate was converted from litre per minute to cubic meter per second using a conversion factor of 1.6667×10^{-5}. The analysis reveals that from the 20L of water stored in the source reservoir, 11.31 L (+ve) was spilt due to vandalism, and 0.58L (−ve) leaked from joints, suggesting operational spillage (equipment failure). In a practical situation, using a scaled-up factor of 13.5 based on the actual diameter of an oil pipeline in Nigeria [29], which is 8-inches (203.2 mm), the quantity of oil spilt in the 7 minutes flow regime is approximately 153 L (the equivalent of 1.52 barrel) and would create an economic loss of $116.9 (at an average rate of $76.9 per barrel).

Based on JIV data from the NOSDRA Oil Spill Monitor, the average delay between the oil spill occurrence and the JIV visit was 21 days, and the maximum delay was 101 days. In practice, these delays would have resulted in an economic loss of around $544,987 and $2,428,822, respectively, in addition to the cost of remediation, rehabilitation and loss of livelihood.

The results from several programming of integrated individual sensors to achieve the desired spillage scenarios conceptualized in section 2.1, *i.e.*, Operational spill detection (Scenario 1), Definite vandalism (Scenario 2) and Possible ongoing vandalism (Scenario 3) are shown in Figure 8. It shows a screenshot of the Arduino IDE interface code and a serial monitor displaying a typical leakage detection situation at a location. For instance, when a 2-litre flow difference is observed by 12:15:33.773, the serial monitor notes that leakage is detected at position: Latitude: −2.725936 and Longitude: 53.767614. Figure 8 presents a cross-section of the three spillage scenarios and the corresponding vibration signals visualized on ThingSpeak. For instance, in the simulated scenarios, the serial monitor prompts that at 21:45:14.433, operational leakage is detected, which corresponds with the time between 21:44 and 21:16 when the vibration signal is consistently 1 on ThingSpeak, and reduced flow is observed between flow sensors A and B. Definite vandalism is observed on the serial monitor between 21:45:36.372 and 21:47:20.197, which corresponds to constant vibration signals of 3 displayed on ThingSpeak, which was caused by a deliberate action of sawing the pipeline to demonstrate vandalism.

Data from the vibration and flow sensors provide timestamps that can help track when an external force is sensed (vandalism) and when the difference in flow is observed (spillage). Understanding the time of vandalism or operational spill is essential to inform prompt management measures.

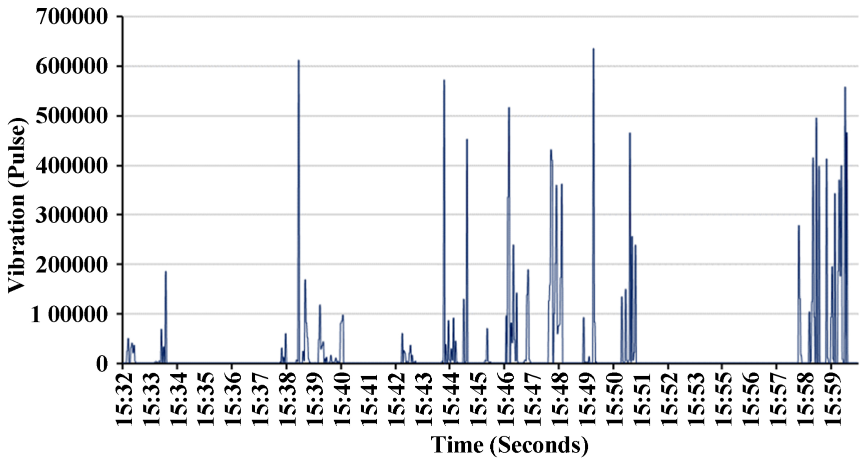

Figure 5. Time series of Vibration Sensor Outputs.

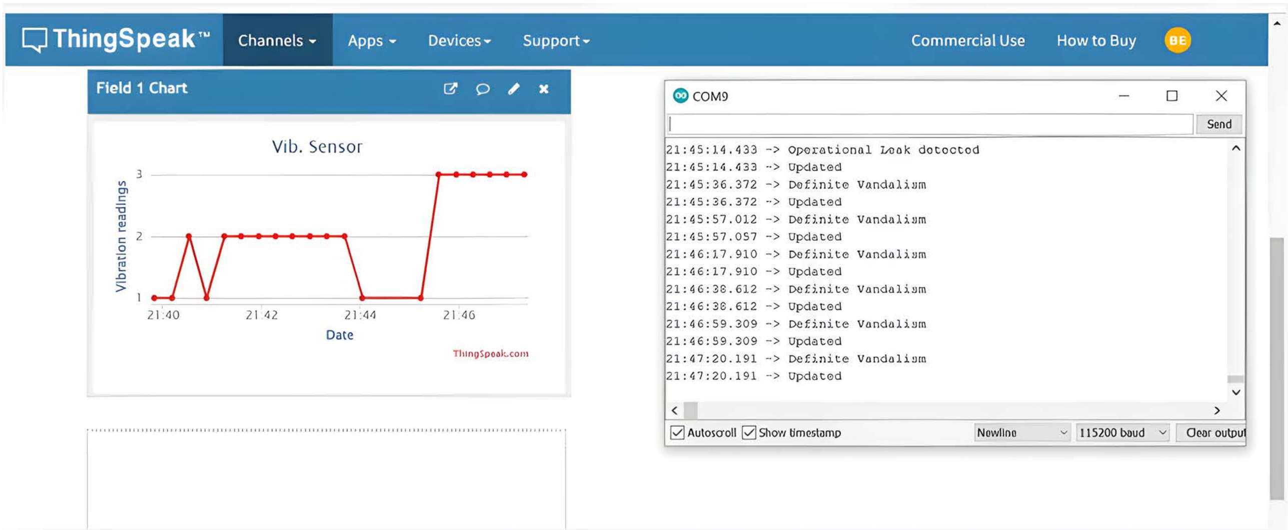

Figure 6. Cross-section of flow and vibration sensor transmitted to ThingSpeak.

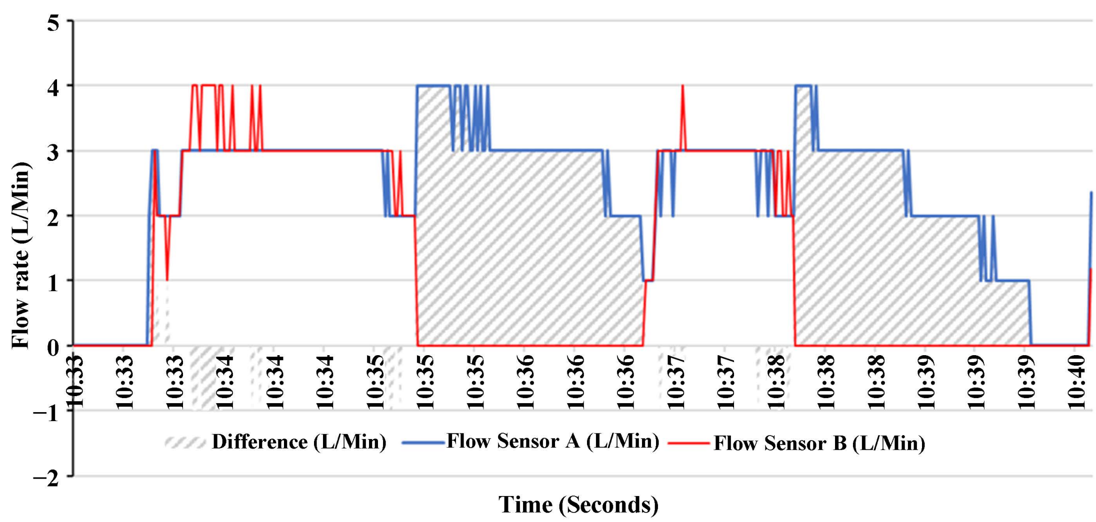

Figure 7. Timeseries of results from the two flow sensors and the difference.

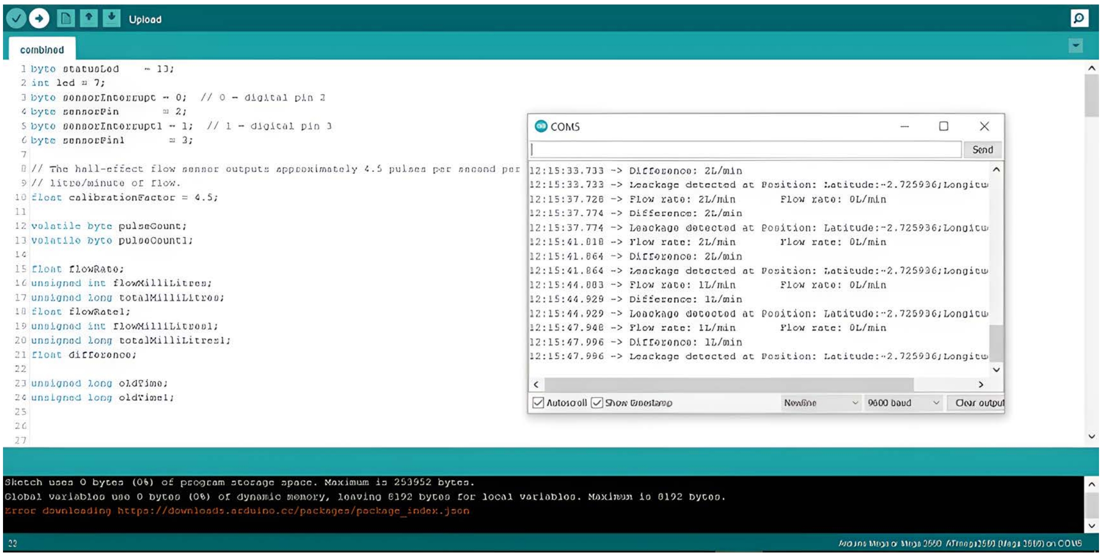

Figure 8. Arduino code and Serial Monitor results for integrated flow sensor and GPS.

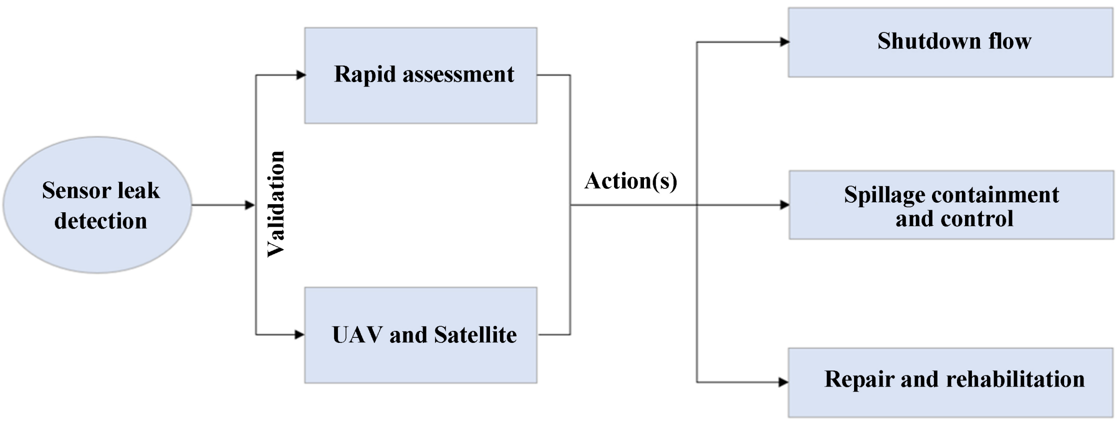

Figure 9. Proposed framework for pipeline leakage validation and action.

3.2. Discussion: Model Validation and Action Framework

Figure 9 shows the proposed framework for pipeline leakage validation and action that will rely on rapid assessment, to be facilitated by citizens [30] and technology such as UAVs and satellite technology [31]. This framework bridges the research gap identified by Zabbey *et al.*, [32], which recognizes that integrating technology (e.g., alarms, acoustic microphones, sensors, and infrared radiometers) and citizen science could improve oil spill monitoring in Nigeria. Zabbey *et al.*, [30] proposed a citizen-led approach for oil spill monitoring implemented on the WhatsApp platform and managed by the Center for Environment, Human Rights and Development (CEHRD). Our proposed framework would leverage the CEHRD network of volunteers and complement the JIV approach, thereby compensating for compliance and transparency deficiencies in the JIV [15] and reducing the time from spillage incident to action, therefore decreasing the health and environmental and socio-economic impacts of oil spillage.

The rapid pipeline leakage validation approach proposed in **Figure 9** will be curated, allowing selected and trained citizens living in and around pipeline areas to be deployed for field validation after sensor notification. The sample questionnaire adopted from the JIV form and developed in KoboToolBox to support citizen feedback collection to validate sensor is accessible via:

https://kf.kobotoolbox.org/#/forms/aJB6GhwzTm4ak3LXq3VMc2.

Citizen science has been widely adopted for curated data collection for environmental monitoring [33], including being used for hydrological data collection by river basin authorities in Nigeria since the 1980 s [34]. This study has identified 95 Local Government Areas (LGA) where oil pipelines pass through and recommends that an equivalent number of volunteers or more can be trained in each LGA, consisting of Abia (7), Akwa-Ibom (11), Anambra (1), Bayelsa (8), Cross Rivers (2), Delta (18), Edo (9), Imo (10), Kogi (2), Ogun (1), Ondo (3), and Rivers (23). The framework further suggested deploying Unmanned Aerial Vehicles (UAVs) or satellite technologies for remote monitoring and mapping [2]. Through this rapid validation and action approach, citizen feedback will be available in near real-time on the KoboToolBox web-based monitoring platform, consequently informing actions such as 1) shutdown of flow to reduce spillage, 2) spillage containment and control to minimize spread and impact, and 3) repair and rehabilitation to correct equipment failure and rectify vandalization points.

4. Conclusions

This study provides integrated technology and citizen science solutions to facilitate proactive oil spillage monitoring and reduce the overall response time compared to traditional approaches such as the JIV. This reduction in response time and, consequently, action would improve the environmental, health, social, and economic welfare of Niger Delta residents by informing action against vandals to minimize the quantity of oil spilt and economic loss and reduce bioaccumulation and exposure of plants, animals, and humans to oil contamination.

All sensors and modules worked properly and collected the required data on flow differences (leakage detection), vibration signals (vandalism detection), GPS coordinates (location identification) and time of occurrence. Therefore, the design fulfilled the research objectives to 1) design and develop a low-cost pipeline spillage monitoring system, 2) identify the causes and location of oil spills (*i.e.*, operational and vandalism) and 3) establish a framework for sensor results validation and action. Furthermore, acquired data was transmitted via Wifi to an IoT platform for data visualization over the internet, as demonstrated by vibration signals presented in **Figure 6**. Moreover, the volume of oil spilt was also quantified, and the economic loss was estimated. Overall, the system developed from this study provided real-time data required to quickly detect and report oil spillage occurrences and causes, and a platform for rapid validation of sensor reports was developed to ensure integrated oil spillage detection and response.

Some of the limitations envisioned regarding the adoption of the proposed leakage and vandalism system in practice include potential theft, sabotage, lack of an energy source in remote areas and damage due to environmental exposure in swampy areas of the Niger Delta. Thus, implementing such a system will require stakeholder consultation to deter theft and sabotage, as well as integrating an off-grid power source (such as solar PV or battery) and sealing the sensor system in a water-proof case and camouflaging its installation [35]. Future study areas may include initiating an automatic system shutdown using a solenoid valve at the source reservoir [36], enabling the rapid shutdown of flow during spillage occurrence to avert irreversible consequences, such as an ecological disaster or loss of lives. In remote areas where internet access is limited, using a Wifi module could limit the system's functionality. Thus, integrating GSM/GPRS modules could further enhance data transmission and communication [37] [38].

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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