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Review Paper

Failure Mechanisms and Risk-Based Mitigation of Hydrocarbon Pipeline Blockages: A Comprehensive Review

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ABSTRACT - Hydrocarbon pipelines play a vital role in ensuring the continuous transportation of oil and gas. However, pipeline blockages remain a major operational challenge because of their significant impacts on safety, environmental protection, and production reliability. This study presents a literature review aimed at identifying and classifying the hazards and risks associated with hydrocarbon pipeline blockages using a 5×5 risk matrix based on the MIL-STD-882B military safety standard. Historical incident data from 1970–2024 are collected from the Pipeline and Hazardous Materials Safety Administration of the US Department of Transportation to support the risk assessment process. The analysis indicates that environmental damage is the most significant consequence of pipeline blockage incidents (28%), followed by fire and explosion (22%), toxic gas exposure (17%), overpressure (13%), economic losses (11%), and production losses (9%). Furthermore, environmental recovery costs account for approximately 88.6% of the total financial impact, while the probability of severe incidents reaches 80%, with estimated economic losses up to USD 20 million or production disruptions of 25%. The findings highlight the urgent need for effective mitigation and prevention strategies to improve pipeline integrity, operational safety, and sustainability within the oil and gas industry .

Keywords: blockage, pipeline, failure mitigation, hazard, risk matrix

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INTRODUCTION

Pipeline systems have a long history in fluid transportation technology. Their earliest applications date back to about 500 BC in ancient Chinese civilizations using bamboo pipes to convey water, while the Babylonians and Romans used crude oil and other fluids via clay and copper pipelines. Iron pipelines were first developed for crude oil transportation in the mid-nineteenth century following the discovery of the first commercial oil well in the United States (Hemeda et al., 2018). In 1879, Standard Oil completed a pipeline for transporting oil, constructing a modern network approximately 175 km in length. Subsea pipeline systems (using high-strength steel) were developed in the 19th century and were an important breakthrough in pipeline technologies for higher pressures. Insulated pipelines, sophisticated welding methods, and newer leak detection systems connected to instrumentation and sensor technology (Samaei & Ghahfarrokhi 2023) were among the developments that progressed alongside these technologies.

The Druzhba pipeline is one of the longest crude oil pipeline systems in the world with approximately 4,000 km length that spans Russia and a number of Central European countries including Germany, Poland, Hungary, Slovakia and the Czech Republic, and was introduced first in 1964 (Roncevic et al., 2023. Other notable pipeline systems include the West–East Gas Pipeline, reaching as far as 8,700 km between China's Tarim Basin in Xinjiang and Shanghai (Zhang et al., 2020, and the Keystone Pipeline which runs for 4,324 km for crude oil from Alberta to refineries in Texas (Wood, 2019 as well as the Nord Stream, 1,224 km subsea pipeline that extends between Russia and Germany with an annual capacity of 55 billion m³ of natural gas (Harris et al., 2025. Other examples are, the Trans-Alaska Pipeline System to transport Arctic crude oil 1,287 km to the Valdez terminal (Swarz, 2016, and the Trans-Saharan Gas Pipeline, which is projected to transport natural gas to Europe over a distance of approximately 4,300 km (Voytyuk 2023).

A blockage incident in a large pipeline, such as the Druzhba pipeline, could cause the pipeline's internal pressure to rise above the Maximum Allowable Operating Pressure (MAOP), resulting in a leak or rupture. Such a scenario could lead to widespread environmental pollution, social and economic disruption, including interruptions to fuel distribution. The potential cascading effects of a large pipeline failure could impact a number of countries and regional energy security (Alifah et al., 2025; Pamungkas et al., 2025). Most existing studies focus primarily on leak-related risks and blockage detection techniques. Therefore, this paper will focus more deeply on mitigating the risk of pipe blockages and hazard control measures.

The widespread expansion of pipeline networks in the world has introduced increasingly complex operational and integrity challenges, particularly the aging of existing pipeline infrastructure. Pipeline materials continue to degrade, and flow control and instrumentation systems may fail, resulting in elevated risks of leaks and transport blockage. Pipelines are still considered one of the safest and most cost-effective means of transporting crude oil, natural gas, and refined products, yet they are not without risk. These failures could produce extensive environmental and other ecological damage, fatalities, public safety hazards, economic damage, and economic disruption for the public sector or the industries. In extreme situations, pipeline failures can also cause production and transportation operations to cease for extended periods of time (Novrianti et al., 2026).

The number of major hydrocarbon leak incidents increased significantly in 2009–2010 (85 cases), compared with 61 incidents in 2008–2009, according to reports by the Health and Safety Executive (Acheampong & Kemp 2022). During 2023–2024, a Perenco crude pipeline ran into trouble and suffered a leakage incident, which leaked around 200 barrels of petroleum hydrocarbons into Poole Harbour. The event caused intense environmental contamination along with widespread recovery and remediation as well as an emergency declaration by municipal authorities (Taylor 2021). Back in 2022, a large-scale leak event on the Nord Stream in the Baltic Sea resulted in the release of an estimated 778 million cubic meters of methane into the ocean. The event resulted in widespread ecological and environmental impacts in the Baltic region and its surrounding areas within Russia and Western Europe (Poursanidis et al., 2024).

According to Pipeline and Hazardous Materials Safety Administration, the United States has about 3.3 million miles of pipeline infrastructure, which deliver nearly 1.2 million barrels of hazardous materials each day. The pipeline system also handles approximately 64% of the national flow of energy commodities (U.S. Department of Transportation 2023). Pipeline leakage incidents have contributed to environmental contamination in both marine and terrestrial environments, while also affecting social stability, energy security, and economic activities. Even though pipeline replacement lowers the chance of failures, complete rehabilitation of the system is expensive and regarded as an economic burden.

Moreover, monitoring pipelines extending for thousands of kilometer in a routine manner poses considerable operational difficulties, especially in remote or inaccessible areas (Karono 2015; Venriza & Wahyuni 2024). Thus, a comprehensive risk assessment becomes fundamental to reduce the chances of damaging and failing pipes, enable preventative decision-making, and inform organizations about any environmental protection, human safety, and asset integrity consequences stemming from pipeline accidents. Numerous studies have examined operational risks in the oil and gas industry; however, the findings remain fragmented and are often investigated within isolated analytical frameworks. In contrast, existing research primarily focuses on production performance and the economic implications of corrosion-induced degradation of pipeline integrity throughout the service life of pipelines. Integrated evaluations in this context are limited (Sonam Mehta & Er Manisha 2023).

Nearly all risk assessments to date have focused on the degradation in pipeline integrity associated to inside and outside corrosion. Recent research done by (Woldesellasse & Tesfamariam 2025), for example, used an integrated Bayesian network model to predict the probability of failure in pipelines that experienced external corrosion. (Shabani et al., 2025) explored a different area by applying metaheuristic optimization methods, to predict the corrosion risk for performance-based pipe systems and index-based sensitivity analysis for assessing the external degree of corrosion. Simultaneously, (Yang et al., 2025) assessed the corrosion risk relating to hydrogen induced damage modes on the basis of quantitative risk assessment (QRA) and probabilistic failure analysis. Moreover, integration of economic considerations and safety performance in asset optimization has also been studied by (Bhattacharyya & Cheliyan 2019), by considering the most pertinent risk indicators within oilfield design and asset management frameworks.

The risk-based pipeline asset evaluation framework has been extensively addressed to inform the appropriate design and integrity management of offshore facilities, examining the probabilities of failure and the resulting consequences related to long-term degradation. In this construct, the monitoring techniques with regard to technical and managerial aspects, covering everything from field work and company strategy, with Key Performance Indicators (KPIs) are widely used in this context (Da Silva Alves et al., 2025).

(Zheng et al., 2025 also explored probabilistic risk models on natural gas pipelines for assessing Probabilistic-related Risk models assessment on failure probabilities such as corrosion depth and degradation severity. Their methodology assisted in supporting predictive maintenance planning in the case of corrosion risk based preventive maintenance, as these are often associated with lower long-term maintenance costs overall. Additional studies have suggested an integrated optimization approach that integrates technical, economic and safety concerns applying manifold-based pipeline risk analysis considering manifold dimensions, pipeline materials, production needs and investment strategies for worst-case operational uncertainty scenarios. An estimated 2,381 oil and gas pipeline segments were operating in 162 countries in December 2020 and the combined length reached over 1.18 million km (Inman et al., 2021).

According to the Global Energy Monitor Several large-scale hydrocarbon pipelines travel to outlying and difficult, environmentally vulnerable areas. For example, the Druzhba pipeline extends approximately 4,000 km across several countries and crosses numerous rivers, railways, and transportation corridors (Fąfara & Matuła 2024).

Previous studies on pipeline integrity have conducted extensive work, focusing almost exclusively on corrosion, third-party interferences, and natural hazards in the risk assessment studies of a pipeline, but have not systematically analysed blockage-related risks and mitigation strategies. Pipeline blockage, however, remains a comparatively underexplored failure mode. Blockage development can result in internal operating pressure exceeding allowable design constraints, which may lead to concurrent leakage along various sites. Such incidents constitute emergencies in which the timing and location of flow disturbances are difficult to predict (Kovačević & Stoiljković 2019).

Based on the foregoing, this study builds on existing literature to examine the risk of flow disruption due to pipe blockage, analysis of flow disruption risks such as mechanisms, impacts, operability, and risk mitigation through efficient mechanisms. By using a probability-severity risk matrix, this study identifies pipeline blockage as a critical hazard with potentially severe operational and environmental consequences.

METHODOLOGY

The dataset is derived from longitudinal pipeline safety statistics in the United States covering the period from 1970 to 2024, during which 650 fatalities and 5,009 injuries, 24,100 hazardous liquid incidents, and $12,034 million of current property damage. The data includes four main indicators: deaths, injuries, incidents, and property damage, which are further classified into hazardous liquid pipelines and natural gas transmission/distribution pipelines. Specifically, the dataset contains annual records of deaths and injuries caused by pipeline accidents, the total number of reported incidents for each pipeline category, and estimated property damage expressed in millions of US dollars. Overall, the data demonstrates long-term trends in pipeline safety performance, showing fluctuations in the frequency and severity of accidents, while highlighting the economic consequences associated with pipeline failures over five decades. Furthermore, data filtering was carried out specifically for blockage incidents, which serve as the basis for writing this paper.

In this regard, the 5×5 risk matrix is the most popular risk matrix for the U.S. Department of Defense, and is used to perform risk assessment and risk management based on the MIL-STD-882B standard. The framework uses five categories of probability and severity of consequence to classify hazards resulting in a 5×5 matrix that facilitates risk prioritization and supports mitigation planning (Kovačević & Stoiljković 2019. In practice, the matrix acts as a semi-quantitative and qualitative decision-support tool for applying probabilistic risk assessment concepts to estimate potential failures and their impacts. In order to enhance the accuracy in predictive ability, probabilistic models are normally combined with Bayesian statistical techniques, where risk probabilities can be updated, allowing risk probabilities to be continuously updated as additional data become available. Moreover, fuzzy logic techniques are applied for a more accurate representation of uncertainty than the traditional Boolean evaluations proposed from the previous review (University of Defense et al., 2019).

Comprehensive statistical information specifically related to pipeline blockage events remains limited. Accordingly, in this manuscript we use a probabilistic risk assessment procedure consisting of both historical incident data and statistical analysis to evaluate the probability of blockage taking account of operational, design, and environmental aspects. To further enhance the analysis, this study also presents a systematic review of blockage-detection techniques, with particular emphasis on methods for identifying blockage location and severity in pipeline systems (Li et al., 2024).

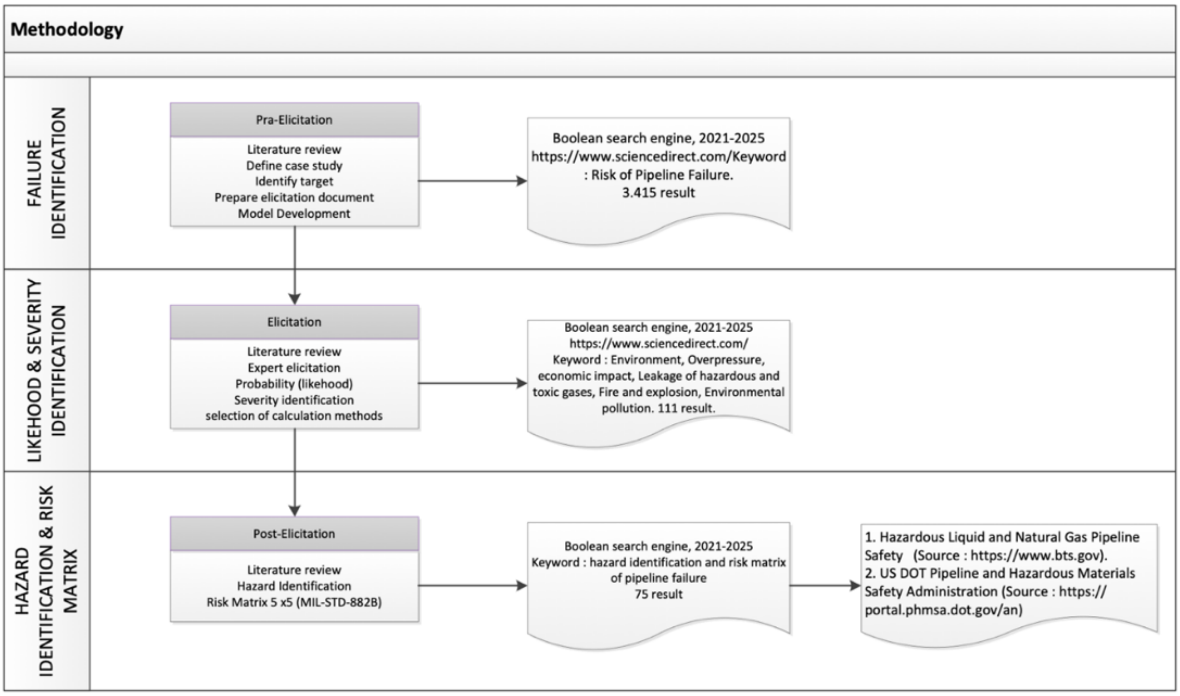

Figure 1. Methodology for hazard identification and risk matrix

Hazard identification and risk assessment are essential components of emergency management systems to assess hazardous conditions and support effective preventive planning. The first phase of hazard identification includes recognizing all potential sources capable of causing accidents, operational disruption, human injury, asset damage, or environmental impacts, including physical, chemical, biological, ergonomic, and psychosocial hazards (Badida et al., 2019).

Hazard identification can be achieved through multiple means such as direct observations of operational activities, equipment conditions, and the surrounding environment, as well as interviews to gather information related to potentially hazardous conditions. Historical incident records, inspection reports, and maintenance histories can also be reviewed to recognize recurring failure patterns and hazardous conditions. After the hazard is identified, the next stage involves evaluating the associated risks by considering both the probability of occurrence and the severity of the resulting consequences.

The probability assessment is primarily based on the frequency at which a particular hazard is expected to occur. This evaluation is generally derived from historical incident data and categorized into five likelihood levels: 1). Namely very unlikely; 2). Unlikely; 3). Possible, 4). Likely, and 5). Very likely, as presented in Table 1.

Likelihood probability scoring is used to estimate the possibility of an event occurring based on available data. This analysis seeks to estimate the probability of similar incidents occurring under similar conditions. In the evaluation process, events

Table 1. Likelihood probability score assessment (Aydin et al., 2022)

Score value	Opportunity description	Estimated percentage	Description
1	Very rarely	< 5%	Almost never happens; it's very unlikely.
2	Seldom	5% – 20%	It could happen, but the chances are slim.
3	Quite often (maybe)	20% – 50%	This can happen under certain conditions.
4	Often	50% – 80%	Tends to occur periodically.
5	Very often (almost certainly)		

likely to have major impacts are identified and data from historical records, operational trends, environmental conditions, and other relevant data sources related to probability estimation are usually considered for the initiation and subsequent assessment of the events. Then a suitable method for the likelihood assessment is chosen, qualitative or quantitative, in turn. In this process, the reliability and accuracy of the gathered data are vital. Experts' judgment and structured interviews are most often used to address uncertain or scarce data to help reduce personal bias in the assessment process (Aydin et al., 2022).

The probability of hazardous events can be estimated through historical data analysis by examining previous incidents and evaluating the likelihood of similar failures occurring in the future. In addition, expert-based assessments may be used when direct operational experience is available. Simulation-based prediction models are also applicable in cases where historical data and expert information are insufficient. Furthermore, environmental conditions are considered important external variables influencing the probability of hazardous events. Meanwhile, consequence severity is evaluated according to the magnitude of potential impacts and classified into five levels: 1). Negligible; 2). Minor, 3). Moderate, 4). Severe, and 5). Critical or catastrophic, as summarized in Table 2.

Table 2 provides the criteria used to evaluate hazard severity based on several key aspects, including occupational health and safety, environmental consequences, reputational impact, and property or asset damage. Each category is assessed using a five-level scale according to the magnitude of the impact and the extent of corrective actions required.

After determining the likelihood of occurrence and consequence severity, the values are mapped into a 5×5 risk matrix to evaluate and prioritize operational risk conditions within the production system. The matrix, illustrated in Table 3, consists of five rows and five columns categorized using numerical ratings and corresponding color classifications as shown in Figure 2:

The probability and severity values are subsequently combined to determine the overall risk level using Equation 1 (Makajić-Nikolić 2023), in which, R, P and C are total risk score, probability or likelihood of occurrence, and consequence, respectively.

$$R = P \times C \tag{1}$$

The risk matrix assessment is the most popular method for determining risk levels and magnitude in safety engineering, as well as risk management. The likelihood parameter indicates the frequency or probability of occurrence of the hazardous event and the consequence parameter evaluates how that event will impact people, environment, the continuation of operations and economic loss. The risk classification framework is standardized by a five-level scale ranging from very low to very high for both the variables.

		Probability				
		1	2	3	4	5
Severity	1	Acceptable	Acceptable	Acceptable	Acceptable	Moderate
	2	Acceptable	Acceptable	Moderate	Moderate	Serious
	3	Acceptable	Moderate	Moderate	Serious	Critical/Major
	4	Acceptable	Moderate	Serious	Critical/Major	Critical/Major
	5	Moderate	Serious	Critical/Major	Critical/Major	Critical/Major

Figure 2. Risk matrix (International Electrotechnical Commission 2019)

Table 2. Severity assessment parameters (Aydin et al., 2022

everity	Low (1)	Minor (2)	Moderate (3)	Serious (4)	Major (5)
ealth and afety	First Aid.	Medical Treatment Case. Restricted Work Case. Lost Time Injury (LTI) ≤ 3 days.	LTI > 3 days. Severe health effects are not permanent.	Resulted in a single fatality. Caused permanent injury or life-threatening illness. Led to temporary suspension of production operations.	Resulted in multiple fatalities. Impacts extended beyond the op site to surrounding areas. Exposure to hazardous toxic sub caused loss of life.
nvironment impact	Oil spill < 1 barrel. Dispersant control.	Oil spill volume ranging from 1 to 15 barrels. Incident can be controlled and managed directly by on-site personnel.	Oil spill volume ranging from 15 to 100 barrels. Incident response managed by the oil spill response team (osrt). Moderate environmental impacts requiring remediation and recovery measures.	Uncontrolled oil release exceeding 250 barrels. Severe and potentially irreversible environmental degradation. Incident mitigation requires specialized external response teams. Compensation and recovery measures must be provided to affected communities and environmentally sensitive areas.	Uncontrolled hydrocarbon relea exceeding 500 barrels. Caused severe and irreversible environmental impacts. Emergency response required sp external intervention teams. Compensation and remediation were necessary for affected com and environmentally sensitive re
eputation	Not in the media spotlight	Incident received coverage from local media outlets. Generated significant concern among relevant stakeholders. Environmental restoration measures may require government involvement and rehabilitation programs.	Received widespread attention from national and regional media, negatively affecting organizational reputation. Resulted in violations of applicable legal and regulatory requirements. Created the possibility of government-led environmental rehabilitation claims or legal prosecution.	Exposed by international and national media. Disturbing reputation. Violating legal aspects. Disturbing surrounding communities. Subject to government-mandated environmental restoration and remediation requirements.	Exposed by international and na media. Damaging reputation. Violating legal aspects. Disturbing surrounding commun Negative public perception led t suspension of operational activi Government authorities required environmental remediation and rehabilitation measures.
operty mage	Financial losses not exceeding usd 100,000. Production reduction limited to ≤ 5%. Partial operational shutdown lasting less than one day.	Financial losses ranging from usd 100,000 to usd 1,000,000. Production decline estimated between 5% and 10%. Complete production shutdown with a duration of less than 24 hours.	Financial losses estimated between usd 1 million and usd 5 million. Production reduction ranging from 10% to 25%. Complete operational shutdown lasting between 1 and 7 days.	Financial losses estimated between usd 10 million and usd 20 million. Production capacity reduction ranging from 50% to 75%. Complete shutdown of production operations lasting approximately 15–30 days.	Financial losses exceeding usd 2 million. Production reduction greater tha Total operational shutdown exte beyond 30 days.

Meanwhile, the risk assessment method used is the Risk Priority Number (RPN), which is a quantitative risk assessment method commonly applied in Failure Mode and Effects Analysis (FMEA) to identify and prioritize potential system failures. The RPN value is calculated using Equation 2,

$$RPN = S \times O \times D \quad (2)$$

where is severity, occurrence, and is detection ability. Severity is the magnitude of consequences of a failure, occurrence is the likelihood or frequency of a failure event, and detection is the ability to detect a failure before it produces a significant impact. Normally, each one of the parameters is assessed on a numerical scale from 1 to 10, and the multiplication of these variables produces a risk priority value that can be used to systematically rank potential hazards.

The risk matrix is widely used as a systematic tool for identifying, evaluating, and managing risks associated with operational activities, equipment performance, and hazardous conditions. This framework supports hazard identification, assessment of risk magnitude based on potential consequences, and prioritization of mitigation measures according to the significance of the identified risks. In addition, the matrix enables continuous monitoring, periodic evaluation, and the management of emerging risks within operational systems.

Risk levels are classified into several categories represented by different color codes, where each category reflects a specific hazard condition and corresponding response priority, as summarized in Table 3.

Risk scores ranging from 1–4, represented by Risk scores ranging from 1–4, represented by the green category, indicate low-risk conditions that are generally acceptable without requiring additional mitigation measures. Scores between 5–9, shown in yellow, correspond to moderate-risk conditions where supplementary controls and long-term mitigation strategies are recommended. Risk levels of 10–12, identified by the orange category, represent significant hazards requiring immediate attention and the implementation of short-term control measures. Meanwhile, risk scores between 15–25, indicated in red, classify critical or intolerable risks that demand urgent corrective actions and comprehensive hazard control planning (Hao & Nie, 2022.

RESULT AND DISCUSSION

To comprehensively understand pipeline blockage phenomena, the analysis should not focus solely on observable operational symptoms but also on the underlying causes of blockage formation. Accordingly, this section systematically evaluates the primary failure mechanisms that directly or indirectly contribute to the initiation and progression of flow restrictions in crude oil pipeline systems. Flow rate, temperature, pressure, and other operational parameters play crucial roles in pipeline performance; however, their effects are ultimately governed by underlying physicochemical and hydrodynamic mechanisms.

Table 3. Risk level (Qi et al., 2024)

1-4	**5-9**	**10-12**	**15-25**
Acceptable	**Moderate**	**Serious**	**Critical/Major**
Under normal circumstances, the condition is considered acceptable and does not require additional control measures.	Hazard conditions are considered acceptable provided that appropriate safeguards and long-term risk reduction measures are implemented.	Unanticipated risk conditions may be tolerated subject to management approval, while risk reduction should be pursued through short-term control and mitigation planning.	The identified risk is considered unacceptable and requires immediate corrective action to minimize its potential impact. Preventive control measures should be implemented before the hazardous event occurs.

Pipeline blockage does not occur solely because of crude oil properties, such as wax formation tendencies, but rather results from complex failure mechanisms governing deposit nucleation, precipitation, adhesion, and accumulation under specific operating conditions. Thus, in this part we critically analyze these mechanisms to illustrate how the interaction of fluid properties and operating conditions drives blockage initiation and progression as the final stage of a complex multi-physics and multistage process.

Analysis of failure mechanisms

For ideal fluid flow, in which frictional effects and energy losses are neglected, the total mechanical energy—comprising pressure, kinetic, and potential energy—remains constant along the flow path (Hasnizam et al., 2025, as illustrated in Figure 3. The reduction of pipeline diameter typically begins with the gradual adhesion and accumulation of deposits along the internal pipe wall, leading to progressive narrowing of the effective flow area (Figure 4). Under prolonged deposition conditions, the flow passage may eventually become partially or completely obstructed.

As deposit accumulation increases, the pipe cross-sectional area decreases *($A_1 > A_2$)*, resulting in higher fluid velocity *($V_1 < V_2$)* and a corresponding pressure reduction in the downstream section *($P_1 > P_2$)*. These hydrodynamic changes significantly affect flow stability and pipeline operating performance.

The deposited material generally consists of hydrocarbon compounds containing approximately 85.5% carbon, 13% hydrogen, and smaller fractions of sulfur, nitrogen, oxygen, metals, and salts. Crude oils with API gravity values ranging from 30–47°API are particularly susceptible to solidification and deposition on pipe walls when the operating temperature approaches the pour point temperature (Barros et al., 2022; Cauduro et al., 2024).

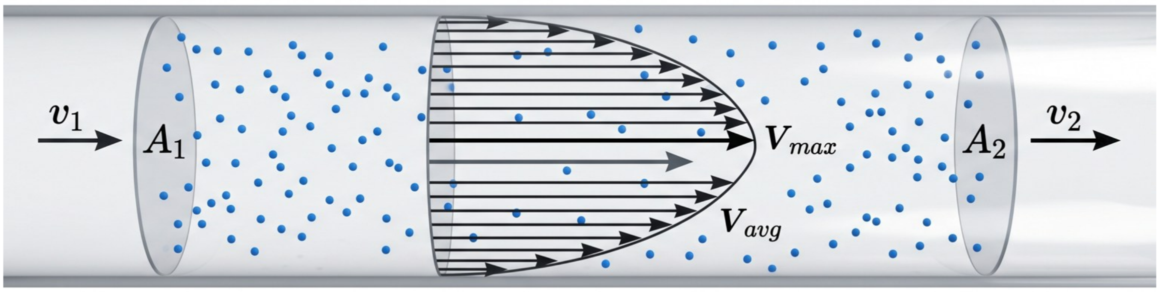

Figure 3. Pipeline flow behavior under normal operating conditions based on Bernoulli's principle

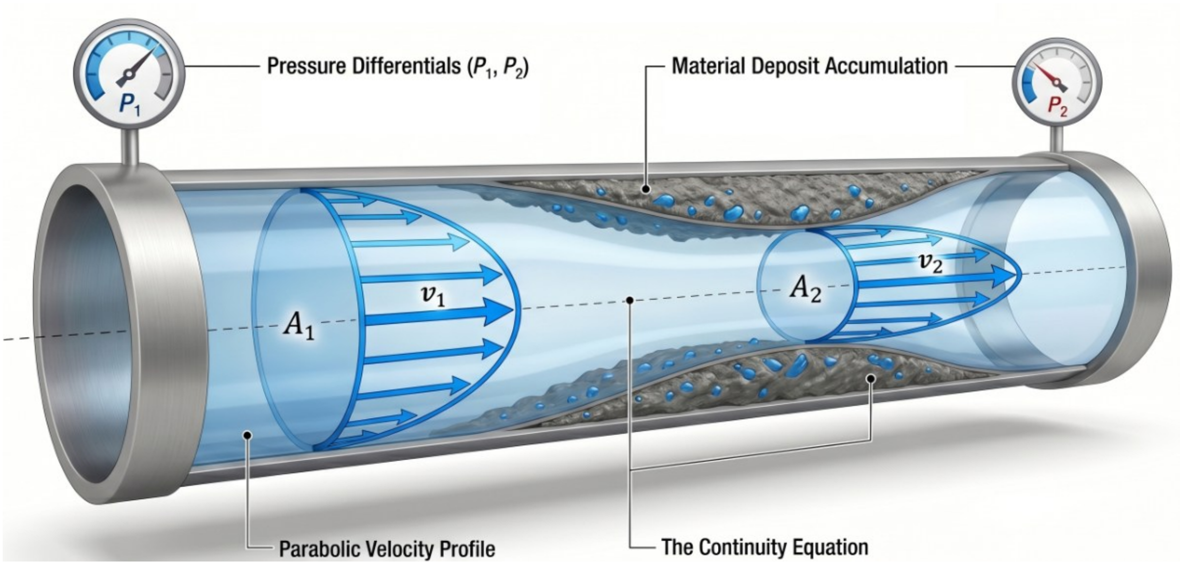

Figure 4. Initial stage of deposit accumulation on the internal pipe surface (Elkatory et al., 2022)

Hydrocarbon fluids consist of complex mixtures of chemical compounds, including aromatic hydrocarbons, paraffins, iso-paraffins, naphthenes, sulfur compounds, nitrogen-containing compounds, asphaltenes, and oxygenated components. These constituents are commonly classified according to their polarity and solubility characteristics, which strongly influence the rheological behavior and viscosity of crude oil. Increased viscosity leads to greater resistance to flow and consequently reduces fluid velocity within the pipeline system. The viscous nature of crude oil is primarily associated with heavy hydrocarbon fractions such as paraffin waxes and asphaltenes.

The American Petroleum Institute (API) classifies crude oil density using the API gravity standard. Crude oil with API gravity below 10°API is categorized as extra-heavy oil, while values between 10°API and 22.3°API are classified as heavy oil. In contrast, crude oils exceeding 31.1° API are generally considered light oil. Viscosity, commonly measured in centipoise (cP), represents the resistance of a fluid to flow or deformation. Higher centipoise values indicate increased viscosity and stronger flow resistance (Arham et al., 2025). The interaction among hydrocarbon components such as paraffins, iso-paraffins, asphaltenes, sulfur-containing compounds, and other heavy fractions significantly contributes to viscosity enhancement, thereby affecting flow behavior and increasing the tendency for deposit formation and pipeline blockage (Figure 5a).

Paraffin wax is one of the primary hydrocarbon compounds responsible for deposit formation on internal pipeline surfaces. Wax crystallization occurs when the operating temperature falls below the cloud point or Wax Appearance Temperature (WAT), typically ranging from 14.2°C to 37.83°C (Wang et al., 2024. Under these conditions, wax molecules precipitate and adhere to the pipe wall, initiating deposit accumulation (Figure 5b).

Crude oils containing high concentrations of wax and asphaltene generally exhibit poor flowability due to elevated viscosity and strong deposition tendencies. Continuous accumulation of these deposits progressively reduces the effective pipe cross-sectional area, eventually leading to partial or complete blockage, which represents a critical challenge in hydrocarbon transportation systems.

The phenomenon of wax deposition has been extensively investigated using theoretical and computational models based on thermodynamics, heat transfer, mass transfer, fluid dynamics, and petrochemical principles to support pipeline design optimization and maintenance planning.

(a) (b)

Figure 5. (a). Wax deposits extracted from the internal surface of the pipeline. (b). Wax deposits extracted from the internal surface of the pipeline.

Nevertheless, accurately predicting deposition rates, identifying deposition locations, and quantifying deposit thickness, distribution, and accumulation volume remain highly challenging due to the complex and dynamic nature of multiphase hydrocarbon flow systems. The phenomenon of wax deposition has been extensively investigated using theoretical and computational models based on thermodynamics, heat transfer, mass transfer, fluid dynamics, and petrochemical principles to support pipeline design optimization and maintenance planning. Nevertheless, accurately predicting deposition rates, identifying deposition locations, and quantifying deposit thickness, distribution, and accumulation volume remain highly challenging due to the complex and dynamic nature of multiphase hydrocarbon flow systems.

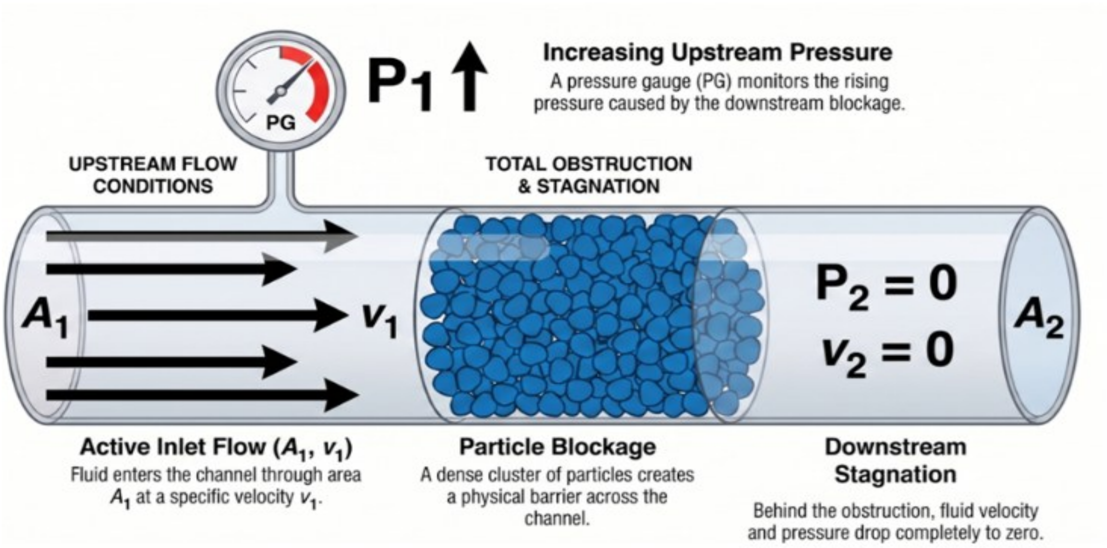

Figure 6. Complete flow obstruction condition *(P_2=V_2=0)*

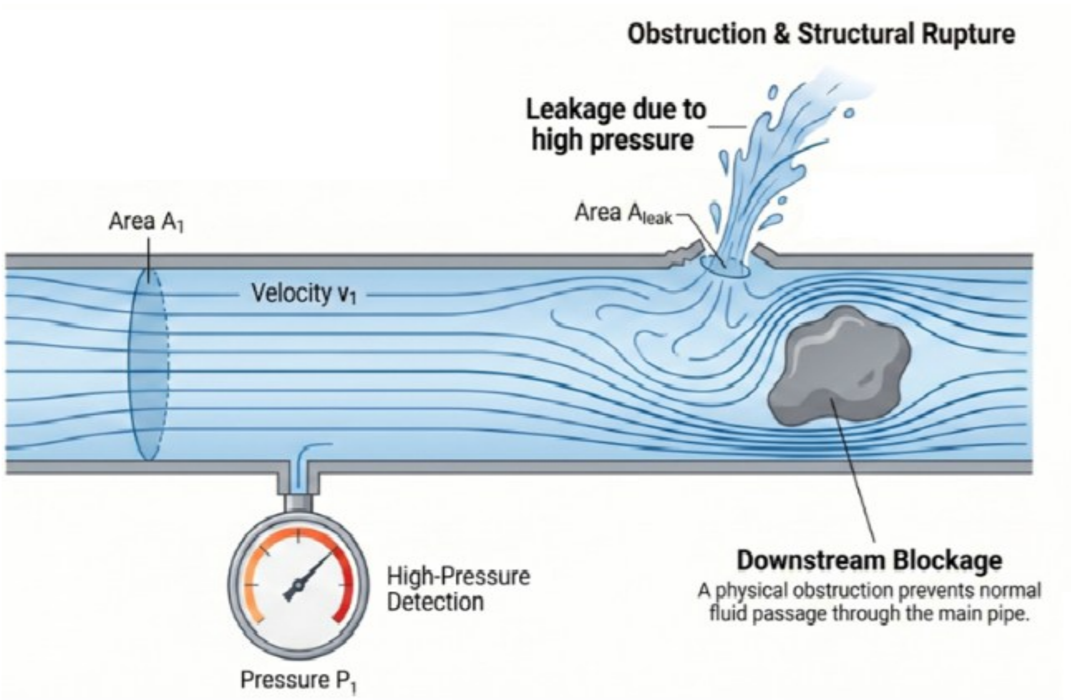

Figure 7. Increase in upstream pressure leading to pipeline rupture when MAOP > MAWP

Operational impacts

Continuous accumulation of deposits along the internal pipe wall progressively reduces the effective flow diameter of the pipeline. Under critical conditions, the flow passage may become suddenly and completely obstructed without precise knowledge of the blockage location, extent, or affected area (Figure 6). Such total blockage disrupts normal fluid transport and causes a significant pressure increase in the upstream section of the pipeline. When the internal pressure exceeds the maximum allowable working pressure, failure is likely to occur at structurally weaker regions or sections with minimum wall thickness, potentially resulting in pipeline rupture or leakage (Figure 7).

In complex and extensive pipeline networks, identifying leakage points caused by blockage-induced overpressure is highly challenging and often requires considerable time for detection and mitigation (Figure 8). Until the blockage location is identified and removed, the upstream pressure buildup remains uncontrolled, increasing the possibility of leakage or rupture at multiple locations throughout the pipeline system.

Pipeline leakage caused by blockage-induced overpressure may occur unexpectedly at multiple locations along the pipeline network, making rapid detection and emergency response highly challenging. Under such conditions, both the leakage flow rate and the released fluid pressure are often difficult to control within a short period. Early indications of abnormal operating conditions generally include a significant pressure increase in the upstream section, excessive pressure drop downstream of the blockage location, and abnormal thermal losses within the pipeline system. If these anomalies continue without corrective intervention and the system remains in operation under unstable conditions, the probability of pipeline failure and structural damage will increase progressively over time.

The estimation of pipeline failure probability and consequence severity constitutes a fundamental component of blockage risk assessment. Evaluation of blockage-related risks typically begins with analyzing deposit formation rates and identifying potential damage mechanisms associated with sediment accumulation, from the initial deposition stage to the predicted failure condition leading to leakage.

Probabilistic assessment methods are commonly applied to estimate the likelihood of failure using limit-state approaches to improve evaluation accuracy and reduce uncertainty. These limit states are influenced by random and uncertain variables that can be represented using probabilistic theory. Furthermore, risk evaluation associated with the release of hazardous and toxic gases, which may trigger fires, explosions, or respiratory hazards, can be determined based on the physicochemical characteristics of the hydrocarbon mixtures transported within the pipeline system.

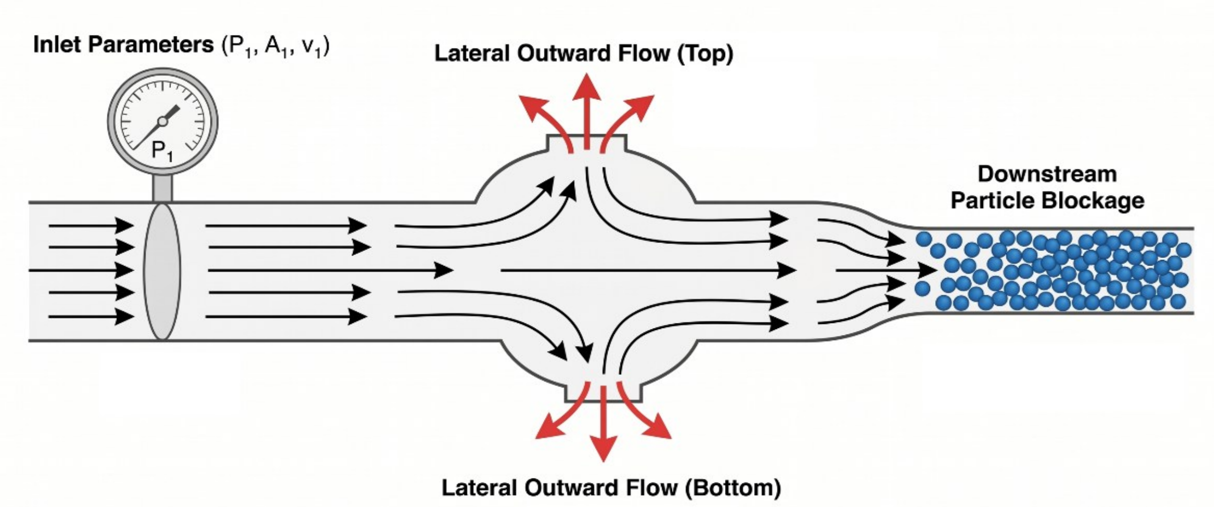

Figure 8. Leakage occur simultaneously at multiple locations that are difficult to identify (Huang et al., 2025).

Environmental pollution risk assessment is generally determined based on the geographical characteristics and ecological sensitivity of areas traversed by the pipeline network, including forests, rivers, coastal regions, agricultural land, marine ecosystems, and other environmentally sensitive zones. The complexity of the terrain, combined with the ecological importance of vegetation and wildlife habitats, significantly increases the severity and consequence level of potential environmental impacts.

From an operational and organizational perspective, social risk assessment evaluates the potential impacts of pipeline incidents on surrounding communities, particularly regarding public health, safety, and daily activities. In cases involving casualties, the relationship between incident severity and the number of fatalities is often non-linear, resulting in substantial social disruption risks. Such consequences may adversely affect corporate reputation and lead to major financial liabilities, including compensation for fatalities and medical recovery costs. In severe cases, regulatory sanctions, suspension of operating licenses, or government-mandated shutdown of operations may also occur.

Identifying pipe blockage hazard

Pipeline blockage represents one of the most critical operational challenges in crude oil transportation systems because it can trigger a cascade of safety, environmental, and economic consequences when not detected and mitigated at an early stage. One of the most significant hazards associated with blockage formation is the progressive accumulation of pressure upstream of the obstructed section. As the flow passage becomes increasingly restricted by wax deposition or other solid accumulations, the hydraulic resistance within the pipeline rises substantially, forcing the operating pressure to increase in order to maintain the desired flow rate. If the blockage continues to develop without intervention, the internal pressure may eventually exceed the maximum allowable working pressure (MAWP) specified in the pipeline design. Under such circumstances, the structural integrity of the pipeline can be severely compromised, potentially resulting in pipe deformation, mechanical failure, or catastrophic rupture due to the inability of the pipe wall to withstand the excessive stress generated by the elevated internal pressure.

The occurrence of blockage-induced overpressure can also lead to pipeline leakage, creating a direct pathway for the uncontrolled release of crude oil, toxic gases, and flammable hydrocarbon compounds into the surrounding environment. Such releases are particularly hazardous because they often occur suddenly and may remain undetected for a period of time, allowing contaminants to spread beyond the immediate vicinity of the failure location. Crude oil spills can penetrate soil layers, alter soil properties, and contaminate surface water and groundwater resources, thereby causing long-term ecological degradation and disrupting local ecosystems. Furthermore, environmental remediation following major spill incidents typically requires extensive cleanup operations, significant financial expenditures, and prolonged restoration efforts, making pipeline blockage not only a technical issue but also a substantial environmental liability.

In addition to environmental impacts, the release of hazardous gases associated with crude oil transportation presents serious risks to human health and occupational safety. Toxic gases such as hydrogen sulfide (H_2S), which may be present in certain crude oil streams, can rapidly accumulate in the surrounding area following a leak or rupture event. Exposure to elevated H_2S concentrations can result in severe respiratory distress, neurological impairment, loss of consciousness, and, in extreme cases, fatality. Moreover, the displacement of oxygen by released gases can create localized oxygen-deficient atmospheres, increasing the likelihood of asphyxiation among personnel working near the affected area. Beyond human health concerns, prolonged exposure to toxic gas emissions may also adversely affect surrounding vegetation, wildlife habitats, and ecological balance within the impacted region.

Another critical consequence of blockage-related failures is the increased potential for fire and explosion incidents. The release of flammable hydrocarbons into the atmosphere can generate combustible vapor clouds that may ignite when exposed to ignition sources such as electrical equipment, hot surfaces, static electricity, or mechanical sparks. Once ignition occurs, the resulting fire or explosion can cause extensive damage to pipeline infrastructure, processing facilities, and nearby assets while posing severe threats to workers and surrounding communities. From an operational and economic perspective, such incidents frequently necessitate emergency shutdown procedures, resulting in unplanned production interruptions, reduced throughput, loss of revenue, and increased maintenance and repair costs. Consequently, the early detection and prediction of pipeline blockage formation are essential not only for maintaining flow assurance but also for safeguarding personnel, protecting the environment, preserving asset integrity, and ensuring the long-term reliability and sustainability of pipeline transportation systems.

The probability values applied to evaluate the likelihood of these identified hazards are summarized in Table 4.

Environmental damage is considered a highly probable consequence of pipeline blockage events that result in leakage, with an estimated likelihood exceeding 80%. Meanwhile, the risk of overpressure conditions is projected to occur within a probability range of 50%–80%, similar to the potential occurrence of fire, explosion, and production loss incidents. In contrast, hazards associated with hazardous and toxic gas release, including respiratory exposure risks, are generally condition-dependent and may occur under specific environmental circumstances, such as elevated ambient temperatures and multidirectional wind dispersion, resulting in an estimated probability of approximately 20%–50%.

Figure 9 clearly indicates that environmental pollution represents the most probable consequence among the identified hazards associated with pipeline blockage events. Regardless of the spill volume, crude oil leakage inevitably leads to contamination of terrestrial and aquatic environments, with the primary difference being the extent of the affected area depending on the magnitude of the release. The risks associated with overpressure, fire, explosion, and production loss exhibit relatively similar probability levels because delayed identification of pipeline blockage can still be mitigated through emergency operational measures, such as production shutdown and flow isolation within the affected pipeline segment.

The severity level of each identified hazard was subsequently evaluated using the severity assessment criteria presented in Table 2, as summarized in Table 5.

The severity of hazardous and toxic gas leakage is strongly influenced by the chemical composition of the transported hydrocarbons. Light hydrocarbon gases such as methane, ethane, propane, and butane may induce dizziness, nausea, and neurological disturbances, while simultaneously forming highly flammable and explosive mixtures in the atmosphere. In addition, exposure to high concentrations of hydrogen sulfide *(H_2S)* can result

Table 4. Pipeline blockage likelihood (U.S. Department of Transportation 2023)

Ident. No	**Hazard identification**	**Likelihood (1 – 5)**	**Description**
1	Overpressure	4	Occurs with relatively high frequency and shows a recurring tendency (50%–80%).
2	Leakage of hazardous and toxic gases	3	May occur under specific operating or environmental conditions (20%–50%).
3	Fire and explosion	4	Has a recurring occurrence pattern with an estimated probability of approximately (50%–80%).
4	Environmental pollution	5	Has a very high likelihood of occurring in the near future (>80%).
5	Economic Losses	3	Has a limited but plausible probability of occurring in the near future (5%–20%).
6	Potential loss of production	4	Demonstrates a recurring occurrence trend with a probability ranging from (50%–80%).

in unconsciousness, respiratory paralysis, and fatality. Other gaseous compounds commonly associated with hydrocarbon systems, including carbon monoxide *(CO)*, carbon dioxide *(CO_2)*, nitrogen oxides *(NO_x)*, and sulfur oxides *(SO_x)*, may cause respiratory irritation, headaches, and severe breathing disorders, with elevated exposure levels potentially leading to respiratory failure.

Hazard severity was evaluated based on four principal criteria: occupational health and safety, environmental consequences, reputational impact, and asset or economic losses. From the health and safety perspective, nearly all identified hazards, except production loss, were classified at the highest severity level due to their potential to cause multiple fatalities and widespread impacts on surrounding areas, including smoke propagation and fire escalation.

Regarding environmental consequences, hazardous gas releases, fire and explosion events, and oil spill incidents were assigned the highest severity rating because they may generate uncontrolled hydrocarbon releases exceeding 500 barrels and result in irreversible environmental degradation. Such events may require extensive remediation activities, involvement of specialized emergency response teams, and compensation programs for affected communities, thereby contributing to significant economic losses.

From the corporate reputation perspective, hazardous gas releases, fires, explosions, and environmental pollution were also categorized at the highest severity level because these incidents may attract widespread national and international media attention, generate public concern, violate environmental regulations, and potentially lead to legal claims, mandatory environmental rehabilitation, suspension of operations, or revocation of operating permits.

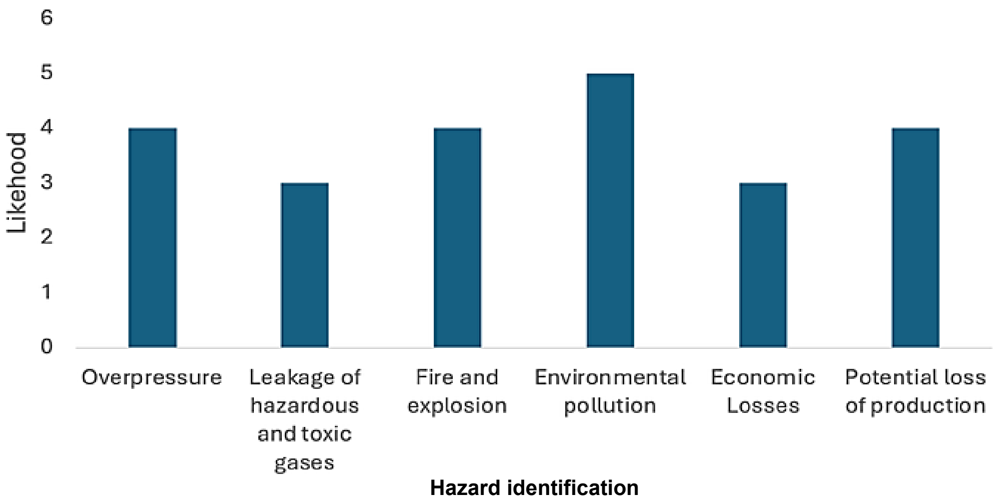

Figure 9. Graphical of hazards associated with pipeline blockage events (U.S. Department of Transportation 2023)

Table 5. Severity evaluation of hazards pipeline blockage (U.S. Department of Transportation 2023)

Id no	Hazard identification	Health and safety	Env. Impact	Reputation	Property damage	Average	Description
1	Overpressure	1	1	1	3	3	Moderate
2	Leakage of hazardous and toxic gases	5	5	5	4	5	Critical/Major
3	Fire and explosion	5	4	5	5	5	Critical/Major
4	Environmental pollution	5	5	5	5	5	Critical/Major
5	Economic Losses	4	5	4	4	4	Critical/Major
6	Potential loss of production	2	2	2	2	2	Moderate

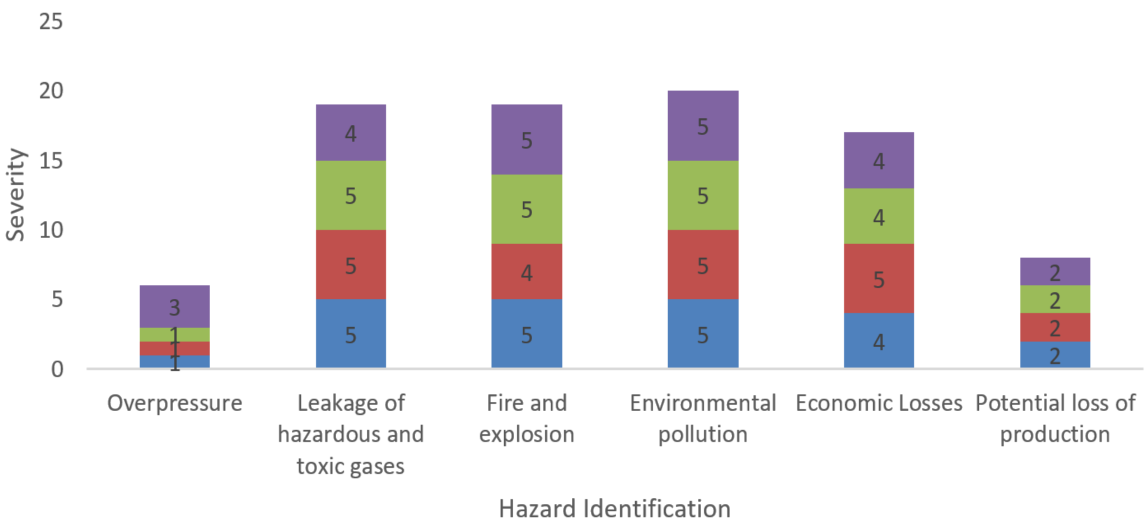

Figure 10. Severity of consequences pipeline blockage (U.S. Department of Transportation 2023)

From an environmental impact perspective, hazardous and toxic gas releases, environmental contamination, and respiratory exposure hazards are ranked at the highest severity level due to the significant time and resources required for environmental recovery and remediation processes as shown in the hazard identification chart (Figure 10). In terms of corporate reputation, toxic gas leakage, fire and explosion incidents, and environmental pollution were also classified at the maximum severity level because such events may result in government sanctions, revocation of operating permits, or termination of hydrocarbon sales agreements with business partners, thereby negatively affecting corporate financial performance.

Regarding asset integrity, fire and explosion hazards as well as environmental damage were categorized at the highest severity level because these incidents can lead to major destruction of operational facilities and hydrocarbon production infrastructure. Economically, these consequences are expected to generate financial losses exceeding USD 20 million, reduce production capacity by more than 75%, and cause operational shutdowns extending beyond 30 days.

Based on the combined evaluation of occurrence probability and consequence severity, the corresponding risk levels associated with pipeline blockage hazards can be identified and determined by integrating the likelihood and severity assessments presented in Table 6. The highest risk score, classified as 25, was identified for environmental pollution, fire and explosion events, and hazardous or toxic gas releases. These categories represent intolerable risks that require immediate implementation of preventive and mitigation measures before hazardous incidents occur.

Table 6. Pipeline blockage risk level

Ident. No	Hazard Identification	Likelihood (L) (1 – 5)	Severity (S) (1 – 5)	Risk Level (L x S)
1	Overpressure	4	3	12
2	Leakage of hazardous and toxic gases	3	5	15
3	Fire and explosion	4	5	20
4	Environmental pollution	5	5	25
5	Economic Losses	3	5	15
6	Potential loss of production	4	2	8

In the event of an incident, rapid emergency response actions involving all relevant stakeholders, including internal response units and external emergency teams, must be immediately activated. In addition to technical mitigation efforts, comprehensive improvements in administrative and management systems are also necessary, including revisions to safety and environmental protection designs, operational procedures, emergency response documentation, and critical risk management practices.

Figure 11 illustrates the relationship between the probability of occurrence and the severity level of the identified hazards, including overpressure, hazardous and toxic gas release, fire and explosion, environmental pollution, economic loss, and production interruption. Environmental pollution exhibits both a very high likelihood of occurrence and a high severity level, comparable to the risks associated with fire and explosion incidents.

In contrast, the occurrence of hazardous and toxic gas release is strongly influenced by the chemical composition of the transported hydrocarbons. Although this hazard possesses the highest severity classification, its probability of occurrence is relatively lower than that of fire and explosion events. Production loss is also considered a probable consequence; however, its severity rating is comparatively lower because it is generally interpreted as a temporary interruption or delay in hydrocarbon production rather than a permanent operational loss.

Based on the calculated probability and severity values, the resulting risk levels can subsequently be mapped onto the risk matrix, as presented below.

The risk matrix indicates that the highest-risk categories, represented by the red zone, include environmental pollution, fire and explosion incidents, and hazardous or toxic gas leakage. Through this matrix, companies can systematically identify, evaluate, and prioritize risks associated with operational conditions and equipment integrity, enabling structured risk management and effective allocation of organizational resources to prevent hazardous events.

Preventive strategies include the implementation of administrative controls, routine inspection and monitoring programs, periodic revision of operational procedures, development of effective blockage prevention and detection techniques, and compliance with applicable standards and regulatory requirements. All mitigation measures should be prioritized according to the identified hazard level and associated risk severity.

Furthermore, the matrix supports rapid and informed decision-making by facilitating efficient resource management, continuous risk monitoring and evaluation, and organizational awareness

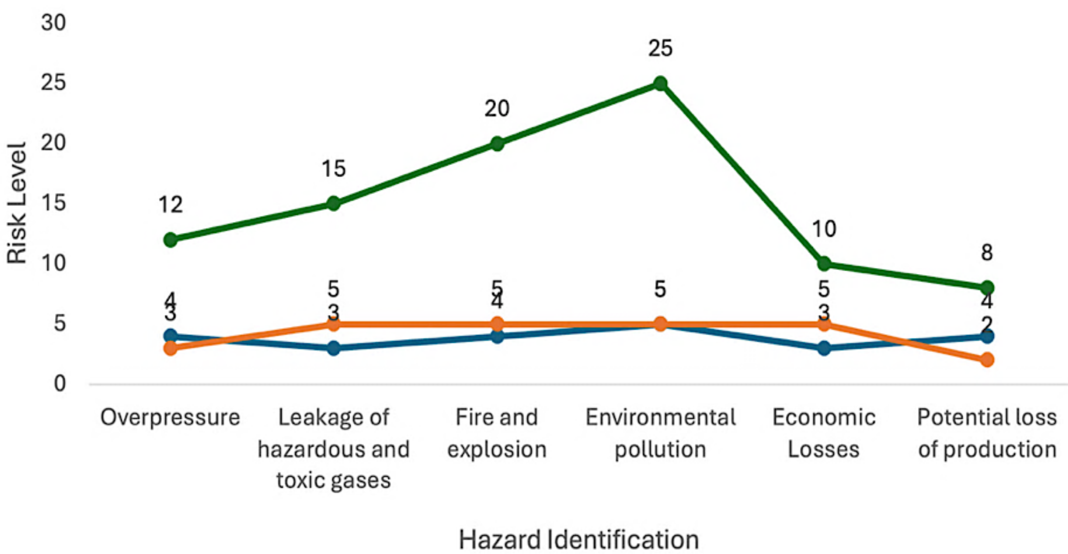

Figure 11. Representation of pipeline blockage risk levels (U.S. Department of Transportation 2023)

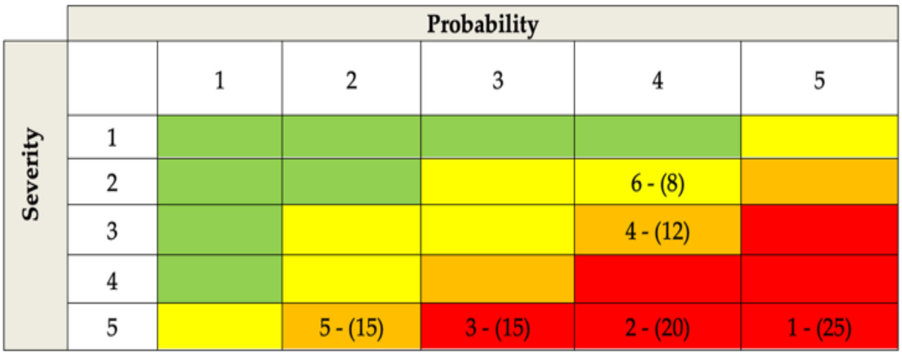

Figure 12. Pipeline blockage risk matrix (Makajić-Nikolić 2023; University of Defense et al., 2019)

Table 7. Recovery cost estimate

Risk level	Hazard identification	Recovery cost estimate	References
1	Environmental pollution	USD 65 billion	Deepwater Horizon, 2010 (Kwok et al., 2022)
2	Fire and explosion	USD 3.4 billion	Piper Alpha incident, 1988 (Drysdale & Sylvester-Evans 1998)
3	Leakage of hazardous and toxic gases	USD 3 billion	Bhopal incident, 1984 (Saraf & Karanjikar 2005).
4	Overpressure	USD 1 billion	San Bruno incident, 2010 (Davidson et al., 2012).
5	Economic Losses	USD 54 billion	Crude oil pipeline blockage – Nigeria (Apuke 2017) .
6	Potential loss of production	478.000-ton CH_4	Nord Stream Gas Pipeline, 2022 (Poursanidis et al., 2024).

programs aimed at strengthening safety culture and long-term sustainability. These findings are consistent with the recovery and remediation costs reported in previous pipeline incident cases, which generally increase according to the corresponding severity and risk classification levels, as discussed below.

Several major pipeline and hydrocarbon-related incidents demonstrate the severe consequences associated with operational failures and leakage events. The Deepwater Horizon oil spill in the Gulf of Mexico caused extensive damage to marine and coastal ecosystems following the release of approximately 4 million barrels of crude oil over a three-month period, with estimated recovery and remediation costs reaching USD 65 billion. Similarly, the Piper Alpha disaster in northeastern Scotland resulted in 167 fatalities and generated economic losses of approximately USD 3.4 billion associated with compensation payments and infrastructure recovery.

Another catastrophic event was the Bhopal disaster in India, where the release of hazardous and toxic gases caused thousands of deaths and resulted in long-term environmental and public health impacts, with total compensation and recovery costs estimated at USD 3 billion. Overpressure-related pipeline failure was also observed in the San Bruno pipeline explosion involving the Pacific Gas and Electric Company (PG&E) pipeline system, which caused severe damage to nearby residential areas and multiple fatalities.

Substantial economic losses, estimated at USD 54 billion, have also been reported in crude oil pipeline blockage incidents in Nigeria. In addition, the Lake Nyos disaster in Cameroon caused numerous fatalities due to toxic gas exposure and respiratory failure. Furthermore, the Nord Stream incident resulted in methane emissions estimated at approximately 478,000 tonnes of CH_4.

Risk mitigation strategies

Pipeline leakage and blockage events can have severe environmental, social, and operational consequences. Therefore, the implementation of comprehensive risk mitigation strategies is essential to minimize their impacts. Effective mitigation begins during the planning and design stages of pipeline development by considering environmental conditions, flow characteristics, terrain conditions, and the physicochemical properties of transported hydrocarbons. Accordingly, pipeline design, operation, inspection, maintenance, and repair activities should be integrated into a comprehensive pipeline integrity and risk management framework.

Corrosion-resistant coatings, thermal insulation systems, pipeline heating facilities, and chemical injection technologies are effective preventive measures, particularly for pipelines operating in environmentally sensitive, disaster-prone, or densely populated areas. Furthermore, the integration of advanced monitoring technologies, emergency response systems, and operational control measures facilitates the early detection and rapid mitigation of blockage events. For continuous blockage monitoring and operational inspections, real-time technologies such as Fiber Bragg Grating (FBG) sensors have been proposed. However, the effectiveness of these technologies depends heavily on the availability of reliable field data, robust analytical capabilities, and rapid decision-making processes. In addition, their implementation should be evaluated through cost-benefit analyses and operational performance assessments to ensure effective risk reduction and sustainable asset management.

Continuous monitoring of pressure, temperature, and flow conditions should be implemented to facilitate the early detection of abnormal operating conditions. Preventive maintenance programs should include routine internal cleaning operations, integrity assessments using intelligent pigging technologies, and drone-based inspections. Recent advances in deep learning-based monitoring systems also offer significant potential for reducing the operational costs associated with conventional pipeline flow simulation and monitoring systems.

Emergency preparedness is another critical component of risk mitigation. Dedicated emergency response teams equipped with trained personnel, specialized equipment, and standardized emergency procedures should be established to manage leakage incidents effectively. Containment booms and absorbent materials should be deployed promptly to limit spill propagation, minimize environmental contamination, and reduce ecological damage. In parallel, periodic audits, risk assessments, inspection records, and maintenance histories should be systematically reviewed to evaluate pipeline integrity and predict potential future failures.

Accurate identification of blockage locations, including the length, thickness, and extent of the obstruction, is essential for effective remediation and operational recovery. Therefore, standardized procedures for blockage detection, assessment, and response should be incorporated into operational guidelines to prevent the recurrence of similar incidents. Most importantly, compliance with national regulations and internationally recognized standards established by the American Petroleum Institute (API) remains fundamental to ensuring operational safety, environmental protection, emergency preparedness, and the long-term sustainability of oil and gas operations.

CONCLUSION

This study identified and evaluated the major hazards and risks associated with hydrocarbon pipeline blockage events using a 5×5 risk matrix approach based on the MIL-STD-882B framework. The analysis revealed six principal hazard categories, namely environmental damage, fire and explosion, hazardous and toxic gas releases, overpressure incidents, economic losses, and production losses. Among these, environmental damage emerged as the most significant consequence, accounting for 28% of all identified impacts and approximately 88.6% of the total recovery and remediation costs.

The findings indicate that pipeline blockages represent a critical operational hazard capable of triggering severe environmental, safety, and economic consequences. Environmental contamination was identified as the most probable and severe impact due to its extensive ecological effects, high remediation costs, and long-term socio-economic implications. In addition, blockage-related incidents may lead to substantial production disruptions, asset losses, legal liabilities, and reputational damage.

From a practical perspective, the results highlight the importance of implementing integrated risk management strategies throughout the pipeline lifecycle, including appropriate design considerations, continuous monitoring, preventive maintenance, early blockage detection, and effective emergency preparedness. The adoption of advanced monitoring technologies and risk-based integrity management approaches can significantly improve operational safety, environmental protection, and asset reliability.

Although this study provides a comprehensive assessment of blockage-related hazards based on historical incident data and literature analysis, future research should focus on developing quantitative predictive models for blockage formation and evaluating the effectiveness of emerging detection and mitigation technologies under various operational conditions. Such efforts would further support the development of safer and more sustainable hydrocarbon transportation systems.

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DECLARATIONS

Author contribution

H. Wahab: conceptualization, methodology, investigation, data curation, formal an alysis, visualization, writing original draft, writing review & editing. A. Martin: Supervision (co), methodology, validation, writing review. Asral: Supervision (co), methodology, writing review.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

The use of AI or AI-assisted technologies

The author(s) used Gemini AI Copilot to assist in generating illustrative images from textual descriptions After using this tool, the authors review and edit the content as needed and take full responsibility for the publication's content.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
RPN	Risk priority number	Dimensionless index
S	Severity	Dimensionless
O	Occurrence	-
D	Detection ability	-
R	Total risk score	Dimensionless
P	Probability or likelihood of occurrence	%
C	Consequence	-

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