Journal of Scientific Reports 2024, 7(1), 72-99
ISSN: 2708-7085
Journal: ijsab.com/jsr

Understanding Oil Production: Investigating Factors Affecting the Oil Production Decline in Blocks 3 & 7 of South Sudan (2017-2022)

Jacob Dut Chol Riak [1]

[1] Associate Professor, Department of Political Science, University of Juba, Juba, South Sudan.
Email: dutsenior@yahoo.com

Abstract

The study has comprehensively examined factors that have led to oil production decline in block 3 & 7 in Paloch of South Sudan from 2017-2022 as well as appraising solutions to the oil production decline. The study objectives were subjected through rigorous empirical literature review and the gaps in the literature were filled through field research. During fieldwork, mixed research methodology was deployed. This includes qualitative and quantitative research design. Research instruments such as questionnaires and interview guides were used to collect the data with a target population of 100 people that was later determined via Yamane's formula to end up with a sample of 80 respondents. The study found systematic and drastic oil production decline of block 3 & 7. From 2017, the average daily production was 131,000 barrels per day (bpd). However, in 2022 the average daily production was 97,267 barrels per day (bpd). The study findings indicate that the causes of oil production are high water cut (produced water), too much sand produced, floods, poor & obsolete technologies and wars & conflicts in block 3 & 7 of Paloch. The study found the solutions to this oil production decline as re-injection of the water to the reservoir, proper reservoir management, laboratory testing for the sand before it accumulates, use of dykes and river Nile dredging for floods prevention, use of modern and relevant technologies and finally maintenance of genuine peace and security across the country. The study concludes with immediate implementation of the solutions to the oil production decline and carrying out more explorations as most of the oilfields are still green fields for new discoveries.

ARTICLE INFO

Research paper
Received: 14 July 2024
Accepted: 16 September 2024
Published: 18 September 2024
DOI: 10.58970/JSR.1045

CITATION

Riak, J. D. C. (2024). Understanding Oil Production: Investigating Factors Affecting the Oil Production Decline in Blocks 3 & 7 of South Sudan (2017-2022), *Journal of Scientific Reports*, 7(1), 72-99.

***Keywords**: Oil production, Decline, Water-cut, Sand, floods, Technologies, Wars and peace.*

1. Introduction

Oil production decline has surfaced as a global, regional and national concern. Globally, countries are experiencing production decline. Russia, Venezuela, Saudi Arabia, Iran, Kuwait, United Arab Emirates (UAE), United Kingdom (UK), United States of America to mention but a few are struggling to raise their production to peak levels. At the regional level of continental Africa, crude oil production decline is seen in Nigeria, Algeria, Libya, Angola, Equatorial Guinea and Sudan to mention but a few. At the national level in South Sudan, oil production decline is evident in blocks, 1,2, & 4, 5A and 3 & 7. While these oil production declines could be attributed to the global pandemic of Covid-19, these declines had occurred as early as 2017. Production decline refers to the annual reduction in the rate of crude oil production from single field or from a group of fields, particularly, after a peak in production (Hook et al, 2013). These oil production declines could be caused by factors such as the aging of the fields, war & conflicts, sand production, poor reservoir characterization, high water cuts, floods and poor technologies.

To be sure, the problem is that oil production decline has remained a worry trend for governments, corporate oil organizations, investors and those working in oil and gas industry (Minjing etal, 2024). With decline of production, then governments' loss revenues, corporate oil organizations loss profits and the staff working in the oil companies are retrenched. At the block 3 & 7, oil production drastically declined from 135,000 in 2016 bpd to average of 119,309 bpd in 2017-2022. The problem is high water cut, sand production, floods, poor technologies and conflicts in the oil fields. Yet, what cause high water cut, sand production, floods, poor technologies and conflicts in block 3 & 7 is not known and this is the problem. Indeed, this area has been understudied in deeply understanding the factors that cause oil production decline as well as pointing out remedies in preventing or treating oil production decline. While scholars such as Weyler (2020) studied the first decline of oil production, Hossein, et al (2013) noted the effects of sand production in oilfields, Veil, et al (2004) studied the effects of produced water in oil production, Khulud, et al (2013) noted the prediction of reservoir performance, Hook et al, (2013) studied the depletion rates of oil production, Markus (2015) noted the business and politics of oil production, Johnson (2013) studied the international exploration economics & risks and Inkpen and Moffet (2011) explored the management, strategy and financing of oil production, none of the above scholars has studied factors that have led to oil production decline in block 3 & 7 of South Sudan. Inspired by this pedagogical gap, the study is set to fill this gap of knowledge.

This study is significant because decline of oil production in the context of South Sudan is suicidal for the nascent economy as the country relies on oil revenues by 88% to run the state (Riak, 2021). Studying the factors that have led to the decline of oil production in block 3 & 7 shall help the government to role out a policy to ascertain these factors and more importantly, address this decline. Besides, the study shall assist the oil companies to detect the reasons for decline early and most essentially put resources together to halt this decline. The study shall be a source of knowledge and empirical literature in the context of South Sudan, particularly; political economy and oil & gas field and many academics and researchers shall find it useful to reference.

2. Literature review

The literature review is based on the specific research objectives, problem statement and theoretical framework. Oil production decline has remained a topical issue in the world today. From North Africa, Europe, South America, Asia, Oceanic and Africa, oil productions are declining due to various factors. Oil production decline refers to the diminishing or reduction in the quantity of the crude oil produced (Iruoghene, 2024). While production can occur, it has always remained a matter of concern for both the government and the oil companies. Thus, the concept and origin of oil production decline, factors responsible for oil production decline and solutions to the oil production decline should be situated through empirical literature and gaps in the literature should be filled through field research.

2.1. The Concept and Origin of Production Decline

Production decline of oil and gas is a very crucial concept since it signposts the production outcome of any investment in the hydrocarbons industry. It refers to the steady experiencing of low production of oil and gas in the oilfields (Hook, et al, 2013). While the production decline may be systematic, it sometimes occurs abruptly. The etymology of the production decline commenced early as 1800s and later on came to full limelight during second war period in 1940s (Markus, 2015). This was then attributed to the much destruction that occurred due to the war of superiority known best as the World War II. Europe was very much devastated by the war. That is why a Marshall Plan was established and enacted in 1948. This plan, though an American initiative, was meant to recover the economies of Europe by providing foreign aid to Western

Europe (Bradford, 1991). Because of the war, production of oil and gas in Northern Africa, Europe and former United Socialist Soviet Republic (USSR) plummeted affecting the entire world.

2.1.1. Types of Production Declines

There are three types of production declines and they are argued as follows:

Firstly, there is hyperbolic type. The hyperbolic type functions are analogs of the circular function or the trigonometric functions (Rapor, 2015). While the hyperbolic function occurs in the solutions of linear differential equations, calculation of distance and angles in the hyperbolic geometry helps in determining production decline in a reservoir. The hyperbolic production decline indicates a general estimation of production for a specific period such as a month, a year as the initial production rate, parameter, and initial decline rates are projected from observed well-level production data. Secondly, there is harmonic type. Harmonic type decline argues the production decline in oil and gas as nominal decline in production rate per unit of time expressed and defined as a fraction of the production rate which is proportional to the production rate itself (Weyler, 2020). Unless accumulated, harmonic production decline is always measured in unit of any time series and it is always negligible. Thirdly, there is exponential decline that refers to production rate that declines by the same percentage each time a period is known and it is widely noted as exponential decline (Hook et al, 2013). If the exponential decline rate is 8% per year, it means that the production rate at the end of the year is 8% less than at the beginning of the year (Weyler, 2020). It can be demonstrated that under conditions such as constant well-back pressure and thinning of wellhead, equation of fluid flow through porous mediums under boundary-dominated reservoir flows are equivalent to exponential decline. However, for the purpose of this study, the empirical nature of this term has a greater significance since it allows the technique to be applied to multiple fluid streams percent ratios.

2.1.2. Decline Rate Analysis

The decline rate refers to the decrease in petroleum production over a period of time (Hook, 2009). In many cases, the decline rate is calculated on annual basis, yielding the change in extracted volume of oil produced from one year to another. From a general definition, it should be understood that the decline rate can be positive in some cases, representing a decreasing of production base on natural factors such as high water cut and aging of oilfields or negative in some cases, representing a decreasing production base on man-made factors such as poor management of reservoir and poor and obsolete technologies (Hui-Ying, 2024). Here is its equation:

$$\text{Decline rate}_n = \frac{\text{Production}_n - \text{Production}_{n-1}}{\text{Production}_{n-1}}$$

Globally, decline may be caused by socio-economic factors and political factors as well as security factors. These are man-made factors that lead to restrictions on the utilization of a reservoir. It can be caused by natural factors such as depletion of recoverable volumes within a reservoir and the resulting decline in reservoir pressure that diminish the flow rates. This can be caused by technical factors such as errors during production as well as poor management of reservoir.

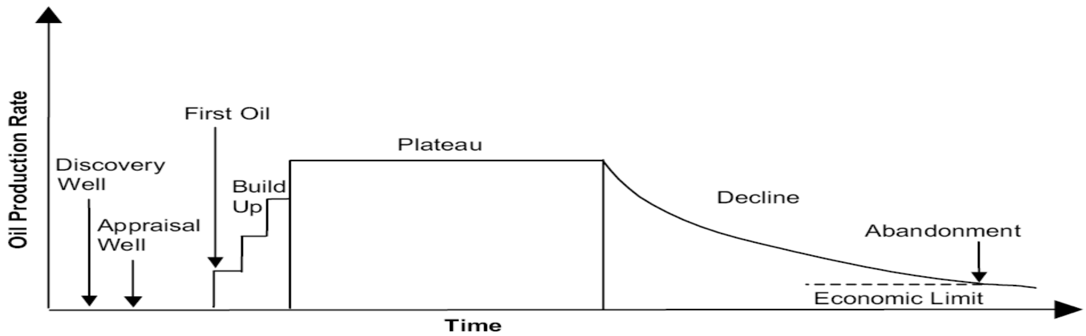

Figure 1: Example of Global Oil Production and Decline. Production curve descriptions of various stages of production maturity at any field are demonstrated below.

Source: *Robelius (2007)*

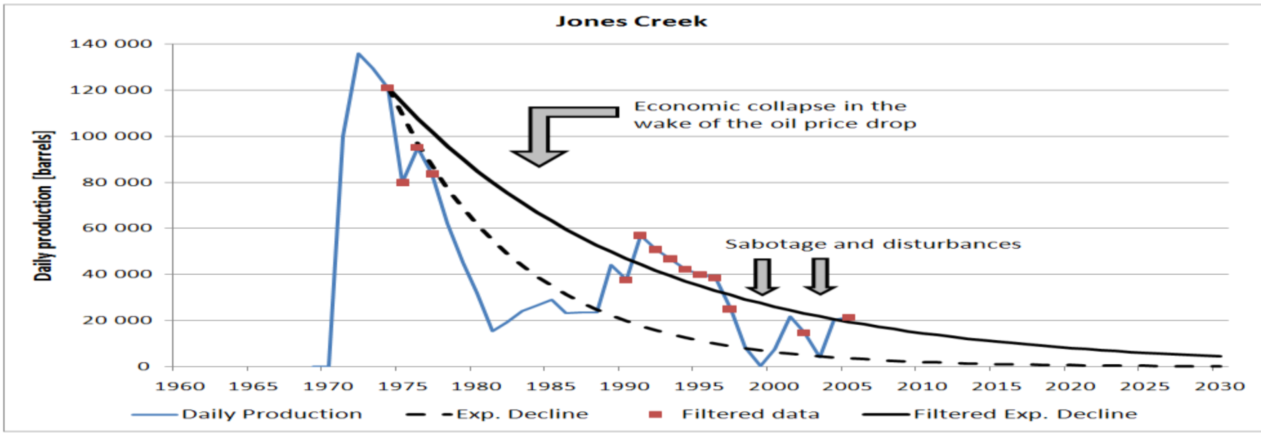

Figure 2: Example of Global Oil Production Decline in Nigeria. Jones Creek, a giant oilfield in Sub-Saharan Africa, demonstrates several production disruptions caused by the economic collapse of the Nigerian economy in the wake of the oil price drop in the 1980s along with rebels' sabotages

Source: *Hook (2009)*

2.1.3. Traditional Decline Analysis Theory

The study deploys traditional decline analysis theory. Advanced by J.J. Arps in 1945, the theory argues that all production can be depicted as having an initial transitory flow period trailed by a boundary-dominated flow epoch. During the transitory epoch, the reservoir pressure at the flow boundary stays constant at the initial reservoir pressure and the flow boundary passes outward from the well through the reservoir. This portion of a well's flow is depicted by very high decline rates. When the flow boundary touches an actual reservoir boundary, or meets with a flow boundary of another well, the reservoir pressure commences to decline and the well enters the boundary-dominated flow epoch. It is in this period that traditional decline analysis can be applied. While traditional decline theory is ancient, it is also known as decline curve analysis (DCA) method which is a non-linear regression method for production history matching as well as prediction and its historicity is very imperative (Yahya, 2024). Indeed, the purpose of traditional decline analysis is to demonstrate the actual decline levels and create a forecast of future production rates to ascertain the possible average production (Hui-Ying, 2024). Hence, traditional decline analysis theory depict through forecast tools how oilfields in block 3 & 7 have experienced oil production decline and forecast on the future to avoid this decline.

2.2. Factors Responsible for Oil Production Decline in Block 3 & 7

Several factors such as high water cut, sand production, floods, poor reservoir performance, poor technologies and wars and conflicts are responsible for oil production decline.

2.2.1. High Water Cut (Produced Water)

High water cut or produced water is a serious matter that has led to the decline in oil and gas production. Produced water is water trapped in underground formations that is brought to the surface along with oil or gas and causes failure to optimize wells production within the capacity constraints of production facilities (Busaidi and Bhaskaran, 2023). It is by far the largest volume byproduct or waste stream associated with oil and gas production. It is worthwhile recalling, in subsurface formations; naturally occurring rocks are generally permeated with fluids such as water, oil, gas or some combination of these fluids (Veil et al, 2004). It is believed that the rock in most oil-bearing formations is completely saturated with water prior to the invasion and trapping of petroleum (Amyx et al. 1960). According to Busaidi and Bhaskaran, 2023, produced water or high water cut results from too much water being produced from the reservoirs (Busaidi and Bhaskaran, 2023). The production of too much water could emanate either from the aging of the fields or from poor reservoir characterization. Also, when petrophysical tools such as logging and casings of the reservoirs to diagnose the waters are not utilized well, then high water cut can occur spontaneously (Hook, 2009). During the drilling time, reservoir beds should be prepared in away that they suck and separate oil from water underneath and allow oil to float to ensure that it is easily pumped to the field service facility (FSF) (Hook et al, 2013). The high water cut in block 3 & 7 in Paloch stands between 70-90 percent, making it the highest in the world (Pitia, 2022).

2.2.2. Sand Production

Sand production is one of the hurdles that have continued to lead to oil and gas production decline. Sand is too severe and it reduces oil production levels and more importantly production of associated gases. Too much sand production blocks the reservoir waves and prevent the flow of oil into the surface to oil gathering manifold, field service facility (FSF), wells and field processing facility (FPF) (Zoback and Mastin, 1985). Besides, Rapor (2015) confirms that sand production can be detrimental if it keeps building in the reservoirs as it can lead to the blockage and possible explosion of the reservoirs due to pressures (Rapor, 2015). Hossein et al, (2013) emphasizes:

> *Sand production in oil and gas wells can occur if fluid flow exceeds a certain threshold governed by factors such as consistency of the reservoir rock, stress state and the type of completion used around the well. The amount of solids can be less than a few grams per cubic meter of reservoir fluid, posing only minor problems, or a substantial amount over a short period of time, resulting in erosion and in some cases filling and blocking of the Wellbore (Hossein et al, 2013).*

However, Rapor (2015) argues that sand production can completely block the flow of the fluid in the reservoir beds and no any fluid (oil, gases and produced waters) can flow (Rapor, 2015). This is when the sand production has filled up and accumulated in large quantities. While sand production can occurs slowly in blocking the reservoir waves, it can surprisingly fill up in huge quantities (Carlson et al, 1992).

2.2.2.1. Causes of Sand Production

Morita and Boyd (1991) provide an interesting analysis on sand formations. They argue that in totally unconsolidated formations, sand production may be triggered during the first flow of formation fluid due to drag from the fluid or gas turbulence (Morita and Boyd, 1991). This detaches sand grains and carries them into zones of some of the wells and hence this blocks the flow of the fluid. Down-hole wire line log measurements provide continuous profiles of sand data. However, no logging tool yields a direct measurement of rock strength or in-situ stress (Stein, 1998). This has given rise to interpretation techniques that combine direct measurements with sonic and density logs to derive the elastic properties of rock and predict from these the sanding potential (Santarelli et al, 1991).

Although no logging tool can accurately determine a direct measurement of the strength of the sand, potential sand prediction can be done. At its simplest, sand prediction involves observing the performance of nearby offset wells. In exploratory wells, a sand flow test is often used to assess the formation stability. Deruyck et al (1992) argues that a sand flow test involves sand production being detected and measured on surface during a drill stem test (Deruyck et al, 1992). While the quantitative information may be acquired by gradually increasing flow rate until sand is produced, the anticipated flow capacity of the completion is reached or the maximum draw-down is achieved. A correlation may then be established between sand production, well data, and field and operational parameters (Morita and Boyd, 1991). Deruyck et al, (1992) stresses:

> *Accurately predicting sand production potential requires detailed knowledge of the formation's mechanical strength, the in-situ earth stress and the way the rock will fail. Laboratory measurements on recovered cores may be used to gather rock strength data. Field techniques like micro-fracturing allow measurement of some far-field earth underneath formation (Deruyck et al, 1992).*

Sand production results to several damages and drawbacks such as surface and down hole equipment erosion, Wellbore damage, equipment failure and small maintenance free periods (Vijouyeh, et al, (2017). Obstruction of valves is a typical occurrence in the form of erosive damage for oil and gas explorers especially companies producing from unconsolidated formations. If the sand production issue is not handled promptly and effectively, sand particles in the wellbore will continue to accumulate, blocking the oil flow channels, resulting in a sharp decline in the production of oil and gas wells, and potentially even forcing the premature abandonment of the well (Xujiao, 2024).

2.2.3. Floods and Flooding

Floods and flooding are important cause of oil production decline. They are the most common and widespread natural severe weather events (Podoprigora, et al, 2024). Floods can look very different because flooding covers anything from a few inches of water to several feet. They can also occur quickly or build up gradually. Norton Wabala (2020) defines floods as parts of the earth's natural hydrological cycle (Wabala, 2020). Floods are occurrence that affected oilfields, reducing the oil production around the world. There are three types of flooding as follows:

- **Riverine flooding.** These are types of flooding that occur as part of overflowing of river. This mostly occurs due to the lack of dredging of the river or when the water levels increase spontaneously (Kaboka, 2019).
- **Coastal flooding.** These are types of flooding that occur when the coastal part of the country overflow with water. This type of flooding is difficulty to be noticed as it happens swiftly (Wabala, 2020).
- **Shallow flooding.** These are types of flooding that occur in small scale. They are shallow because they come with little water. Although they negatively affect the household, their effects are not quite devastating (Kaboka, 2019).

A study by the International Flood Initiative (2003) suggests that floods are the most taxing of water related natural disasters to humans, material assets as well as to cultural and ecological resources affecting people and their livelihoods and claiming thousands of lives annually worldwide (IFI, 2003). In the Eastern Africa region, floods have been usual occurrences. From 2015-2022, Eastern Africa countries that include Ethiopia, Eritrea, Sudan, Kenya, Uganda, Tanzania, Rwanda, Burundi, Djibouti and Somalia have experienced devastating floods. Although they have not occurred systematically for the last seven years, they have flip-poppidly occurred and the outcomes have been quite catastrophic (Mwape, 2009).

Floods have severely occurred in South Sudan with huge destruction. The peak of these floods was in February 2021until the time of writing this research. All the oilfields in South Sudan in the three blocks: 1,2 & 4, 5A and 3 & 7 were submerged with waters. While floods affected all these blocks, block 3 & 7 in Paloch area was more devastatingly affected. David Ngor (2021) emphatically argues that 240 oil wells were submerged in floodwaters in Paloch where block 3 & 7 is situated between 2020-2021 (Ngor, 2021). While 240 oil wells were flooded, 360 oil wells continued with production. From 2020 and 2021 floods, most of the Paloch area was submerged under water. Block 1,2 & 4 in Bentiu was flooded in February-April 2022 but currently the waters have receded. This is also similar to block 5A in Tharjah that was severely flooded with 13.1 meters raised water levels (Lado, 2022). Although the Tharjah floods receded, the damage on the oil facilities was surmountable. It is critical to argue that the oil production levels were between 130,000 to 135,000 bpd before the floods in block 3 & 7. However, due to the continuous flooding, about 100 oil wells have been shut down bringing the production levels to around 119,000 bpd (Ngor, 2021). Nonetheless, block 3 & 7 was shut down in February 2024 due to pipeline ruptured because of war in Sudan.

2.2.4. Poor and Obsolete Technologies

Poor technologies are responsible for oil production decline. Internationally, countries have resorted into horizontal drilling (directional) instead of vertical (non-directional) drilling (Johnson, 2003). Studies such as enhance oil recovery (EOR) and improve oil recovery (IOR) are critical for increasing oil production (Odili, 2024). In South Sudan, oil companies are using vertical (non-directional) drilling for oil production, which has not improved the production so far (Deng, 2019). Lual Achuek (2022) argues that South Sudanese government should replace the Chinese technologies as these are obsoletes in increasing production in block 3 & 7 (Achuek, 2022). He emphasizes:

> *Remove the inferior Chinese technology from our oilfields. I am sorry to say that. I am not longer a diplomat but a currently researcher. Yes, I am a former Minister of Petroleum in the defunct Sudan. I know what technology means. Bring American technology and we will increase the oil production immediately and make this oil production decline a story. With great technology, we will be able to produce 500,000 bpd or half a million barrels per day and let assume the oil prices will be $100 per barrel by the end of the second decade of our independence. We will be getting more than $50 million per day that translate to $18 billion per a year, clean oil money (Achuek, 2022).*

However, Lual Achuek forgot that the United States of America has sanctioned over fifteen oil and gas entities in South Sudan including Ministry of Petroleum and thus it is technically impossible for Americans to accept to bring their technologies to South Sudan, a country their government has sanctioned the industry for over six years now. Individual American technological companies cannot supply their products to South Sudan because the United States government has sanctioned the country. Unless, United States government lifts the sanction, Americans technologies will not be in South Sudanese oilfields. To be certain, enormous resources are required to be earmarked for technologies that increase oil production, particularly, in post conflicts countries such as South Sudan. Oil and gas production is going through rapid technological revolution now called Fourth Industrial Revolution (4thIR). This is shaping aspect of our lives from cloud, computing, mobile connectivity, artificial intelligence and big data analytics (Swine, 2021).

2.2.5. Conflicts and Wars in South Sudan

As if scientific decline is not enough, conflicts have continued to cause oil production decline. Conflicts breed insecurity and fears that lead to the displacement of the people, including oil contractors (Moro, 2008). When oil contractors left the oilfields in South Sudan, production automatically declined, as many wells were not operating.

The December 2013 and July 2016 civil wars between Sudan Peoples Liberation Movement/Army In Opposition (SPLM/A-IO) and Sudan Peoples' Liberation Movement/Army-In Government (SPLM/A-IG) led to the loss of lives and property (Riak, 2021). It is estimated that over 500,000 people were killed and dozens of property destroyed (Lama, 2018). The wars that begun as a democratic quarrel within the SPLM about the party elections led to President Salva Kiir stifling the freedom of the louder members of the party (Riak, 2021). This led to tension and on the 15th December 2013, serious guns shoots were heard from 9pm in Juba and the fighting spread to the whole country. The following morning, President Salva Kiir declared a foiled coup de tat against himself by Dr. Riek Machar who was relieved as the Vice President. Fightings engulfed the country until the signing of Agreement on the Resolution of the Conflict in the Republic of South Sudan (A-RCSS) on August 2015 mediated by Intergovernmental Authority on Development (IGAD). This agreement put Dr. Riek Machar as the 1st Vice President of the Republic of South Sudan. In less than a year, the A-RCSS collapsed due to lack of implementation of the chapter two of the agreement-the transitional security arrangement. To be exact, on the 8th July 2016, gun-violence erupted amongst the bodyguards of Dr. Riek Machar and President Salva Kiir and later spread across Juba leading to over 100 people dead (Riak, 2021). This second war was also halted by IGAD through a mediated deal known as Revitalized Agreement of the Resolution of the Conflict in the Republic of South Sudan (R-ARCSS) bringing Dr. Riek back as the 1st Vice President with other four Vice Presidents in charge of different clusters.

On the two wars, the oilfields were deserted as SPLM/A-IO soldiers were advancing to capture the oilfields. Block 5A and block 1,2 & 4 were captured by the SPLM/A-IO and destroyed. The remaining block 3 & 7, which is the mostly producing block, was highly protected with enough army to push back the rebels. As the rebels advanced, the SPLM/A-IG used all its military might and resources and the block was rescued from the advancing marauding white army militias

(Jiech Mabor). Although the rebels captured the barge that was carrying logistics for the SPLM/A and en-routed to capture Paloch (block 3 & 7) in thirty minutes time, the government repulsed, hotly pursued the rebels and destroyed their capabilities. While Paloch was maintained, the oil workers could not returned to increase the production. About 200 wells were shut down from March 2014-2017 due to insecurity and fears around block 3 & 7 (Marila, 2018). This drastically led to oil and gas production declined. With some spread violence between 2019 and 2020, several oil wells were shut down, particularly, disposal wells, which affected the storage of produced water. At the time of writing this scientific paper, production in block 3 & 7 has been shut down as the main crude oil pipeline that transport the crude oil from South Sudan via Khartoum to Marine Terminal at Port Sudan has been damaged by the Sudanese rebels, known as Rapid Support Forces (RSF) that are fighting the Sudanese Government. Hence, the collapsed of Sudan led to the decline and total shut down of the oil facilities in block 3 & 7 in South Sudan.

2.3. Solutions to the Oil Production Decline in Block 3 & 7 of South Sudan

2.3.1. Reducing High Water Cut/ Produced Water through Re-injection of Water

One of the ways of reducing high water cut/produced water during production is through the re-injection of the water to the reservoirs (Stephenson, 1992). This helps in lessening too much water that is, a mixture of oil and other waste materials (Ibid). Water is re-injected for reservoir pressure maintenance and for reduction of the produced water at the field processing facilities as well as at central processing facility (Chunyu, 2024). The other way is through studies of the reservoir characterization. This should be done through Enhance Oil Recovery (EOR) and Improve Oil Recovery (IOR). These two studies are quite pertinent in oil and gas industry as they are key in reducing high water cut/produced waters (Wu, 2024). Once the studies have demonstrated the problem of produced water is in the reservoirs then the solutions of checking the reservoirs beds became very important (Caudle, 2008). Besides, treating and discharging these waters is another important solution. This treatment and discharge can be done through bioremediation that assists in the separation of dirt, microorganisms and the clean water (Favret et al, 1999). Bioremediation is a holistic treatment of industrial waste materials/waters. Recycling of these waste materials/waters has been quite successful, particularly, in German and the Netherlands. China has joined in the successful control of high water cut/produced waters via bioremediation. While the clean water can be used for domestic purposes, the dirty water is treated in a pool area protected from people and animals due to pollution (Dine, 1998). Although bioremediation can be quite effective, the quality management process in bioremediation should not be compromised (Frankiewicz, 2001).

2.3.2. Cleaning of Reservoir from Sand Production

A number of approaches have been developed to predict or help to understand the sand production problem using physical model testing, analytical and empirical relationships including numerical models (Rapor, 2015). Routine laboratory tests can only predict the onset of sand production (Carlson et al, 1992). More sophisticated physical models could predict volumetric sand production. They are also time-consuming and expensive. In addition, because of the small sizes of the laboratory setup, boundary effects usually nuance the results (Vijonyeh et al, 2017). Analytical models are fast and easy to use but they are only suitable to predict the onset of sand production and they have limitations. Most of them are only valid for capturing a single mechanism of sanding and under implied geometrical and boundary conditions, which are not usually the case in complicated field-scale problems (Hossein et al, 2013). Numerical models are by far the most powerful tools for predicting sand production. They can be combined with analytical correlations to obtain the results more efficiently (Stein, 1988). Experimental results are also utilized to calibrate or validate a numerical model. Yet, numerical models have their own limitations and extensive efforts have been made to improve them (Santarelli et al, 1991). Modeling of sand production requires coupling of two mechanisms. The first mechanism is mechanical instability and degradation around the Wellbore and the second one is hydromechanical instability due to flow-induced pressure gradient on degraded material surrounding the cavity, for example, perforation and open hole (Morita and Boyd, 1991). In general, numerical methods in the mechanical modeling are categorized under continuum and discontinuum approaches.

2.3.3. Use of Dykes and River Dredging to Control Floods

Use of strong dykes is the most important solution to the floods in the world (Waweru, 2022). While dykes may come in different shapes and forms, strong concrete dykes are quite useful. But depending on the topography and gradient of the area, for example, the lower the area, the difficult in having successful dykes, as these dykes can be over flooded easily by the water. On the other hand, river dredging is critical for flood prevention as the dredging cleans out the wastes and debris in the rivers to allow faster flows of water (Nazir etal, 2024). Thus, avoiding restriction of water flows. While this is done worldwide, it is critical for South Sudan floods, particularly, the Nile River flooding. Dredging should begin from Kenya and Uganda side, which is a source of river Nile from the upstream section. Although it is being contested and it has not been agreed on where dredging should first begin, it is proper that it begins from Lake Victoria through river Nile in Entebbe and then to South Sudan (Lado, 2022). However, the independent firm that understands the merits and demerits of dredging of the Nile River should conduct scientific studies such as Environmental Social Impact Assessment (ESIA), geotechnical and hydrology studies.

The South Sudanese Government is already engaging United Nations World Food Programme (UN-WFP) to construct permanent dykes at the floods hotspots such as Jonglei and Upper Nile states. While at the Upper Nile, particularly, Paloch where block 3 & 7 is located, dykes constructions are critical along Sudd wetlands and a long river Nile banks to prevent the overflowing of water (Waweru, 2022). The Government of South Sudan is engaging the Arab Republic of Egypt to undertake River Nile dredging as soon as possible. Interestingly, the Egyptian government has already brought the dredging equipment to river Bahr el Naam in Bentiu and the government of Unity State had already proceeded with dredging. However, the public cried out about executing this enormous life and environmental impact project without feasibility studies and Environmental Social Impact Assessment (ESIA) has not been listened to by the Government of South Sudan. While the Government of South Sudan decided to dredge of river Bahr el Naam without international, regional and national experts' studies, the local communities in Unity state appreciate it as it has reduced water levels. Once feasibility studies of this project have been completed to cover the entire river Nile and its tributaries then the commencement of the actual work of dredging covering White Nile and its tributaries shall begin during the dry season (January-March 2025) and will continue for two years. Although dredging of river Nile has been prioritized by the Government, some citizens continue to feel that it will affect the Sudd wetlands that are vital for aquatic animals and cattle. New studies are being proposed by the citizens and water experts in seeing into it so that dredging project doesn't affect the Sudd wetlands (toic), which is a livelihood of the local population in the greater Upper Nile region (Elkhazin, 2022). Nonetheless, dredging has critical benefits that include lessening of flood risks, enabling people to return to original homes after their displacements and to resume their normal livelihood activities, promotion of navigation of the barges, and subsequent promotion of trade and movement of goods and services through the Nile river, including ferrying of petroleum products and other commodities from Unity state in South Sudan to the market in Sudan which is quite directly beneficial to South Sudanese people and the government (Tiitmamer, 2022).

2.3.4. New and Relevant Technologies

In providing solutions to the oil production decline, new and relevant technologies are critical as oil and gas industry is technologically driven. New and relevant big data analytics provide complex and real time insights about oil and gas. For example, data analytics is used to improve carbon dioxide sequestration, carryout data modeling for reservoir management and forecast production performance (Gochi, 2018). Besides, Industrial Internet of Things (IIOT) is an important technology that is useful in oil and gas industry. It is defined as a system of interrelated computing devices, machines and people, where data and equipment communicate. For example, in oil and gas industry, IIOT sensors can be used to gather data and provide instant insights and solutions during exploration, development, drilling and production (Derek, 2020). Finally, Augmented Reality/Virtual Reality (AR/UR) is a solution technology for oil and gas industry. Augmented Reality (AR) creates real-world settings, while Virtual Reality (UR) immerse the viewer in a virtual setting in showcasing the performance of geological rocks and reservoirs. Both technologies are used in oil and gas to train technicians to test complex geoscience and reservoir tasks before implementing them (Gochi, 2018). For the block 3 & 7 to experience oil increase, new explorations should be commissioned and the latest technologies should be applied. Indeed, sophisticated and relevant technologies can be used to evaluate the entire value-chain of oil and gas industry: downstream, midstream and upstream to ascertain the best technologically driven value-chain (Campbell, 1960).

2.3.5. Maintaining Genuine Peace Across the Country

It is quite evident that oil production improves when there is stability in the country in socio-economic and political spheres (Gamso, et al, 2024). In the context of South Sudan, there is need for absolute and genuine peace across the country. As it is argued earlier that violence begets violence and discourages the investments. A lot of efforts are required from the parties to the agreement to see into it the truce is systematically and timely implemented. These parties include SPLM-IG, SPLM-IO, FD, SSOA and OPP that have signed the August 2018 peace deal. In addition, and more importantly is the commitment of the parties' leaders of the peace accord. As it has been widely argued that South Sudanese leaders sign peace deals but don't implement their provisions. Hence, these leaders are viewed to be suffering from signing syndrome disease (Tekle, 2008). The implementation of revitalized peace deal known, as Revitalized Agreement on the Resolution of the Conflict in the Republic of South Sudan (R-ARCSS) is quite critical for shoring up oil and gas production and most importantly in encouraging the investors to invest in the nascent country (Doane, 2019). Before the conflict broke out on 15th December 2013, an International Conference for Investment was held in Juba, South Sudan on the 5th-8th December 2013 that attracted over 600 investors in critical sectors such as agriculture, infrastructure, energy (electricity) and petroleum amongst others. Majority of the companies from oil and gas industry immediately registered and established their satellite offices in Juba in order to invest in any of the division value-chain (downstream, midstream and upstream). While investors were interested in the entire value-chain of oil and gas sector, they heavily desired to invest in the upstream. Thus, 70% of the international oil investors showcased their interests in investing in the oil and gas industry in South Sudan (Mun, 2014). However, 'the hell broke loose' and the political conflict and violence engulfed the country, thus sending away the potential investors. While the hydrocarbon resources require any stability for their enhancement, investors' confident is embedded in sustainable peaceful environments (Riak, 2021).

3. Research methodology

3.1. Research Design

Research design encompasses qualitative, quantitative or mixed method in a study (Kombo and Tromp, 2006). Research design is a comprehensive plan of sequence operations that a researcher intends to carryout to achieve desired research objectives (Verma, etal, 2024). The study used both qualitative and quantitative research designs. Paloch Area of Melut County was a case study and ethnographic method was applied to detail the understanding of the depth of the oil production decline, factors that may have caused it and solutions to the decline. Qualitative design was used during surveys and quantitative design was used in form of frequent analysis in the presentation, discussion and analysis of the data.

3.2. Area of Study

The study was conducted at Paloch, Melut County of Upper Nile State. Paloch is situated at the northern part of South Sudan and it is the place where block 3 & 7 is located. This is where the oil production has experienced drastic decline from 2017-2022 and without studies to understand this decline. This is where a few surveys were carried out to understand the causes of oil production decline and the appropriate solutions to this decline. Besides, major surveys were carried out in Dar Petroleum Operating company (DPOC), focusing on: petroleum engineering, reservoir engineering and production departments' staffs and the Ministry of Petroleum senior staffs in Juba in comprehending the oil production decline.

3.3. Sources of Information

The study deployed both primary and secondary sources of data. Primary data was acquired through surveys and interviews. Secondary source of data was acquired through content analysis of empirical literatures, reports, periodicals and dataset from Dar Petroleum Operating Company (DPOC).

3.4. Population and Sampling Techniques

The study focused on the selected population in Juba and Paloch and drew a sample. Sampling is a finite part of a statistical population whose properties are studied to gain information about the people (Orodho and Kombo, 2002). Target population was 100 respondents.

3.4.1. Determination of Study Sample

Table 1: Target Population

Category	**Population**
Juba DPOC and MOP Senior Staff	60
Paloch (Block 3 & 7) DPOC Engineers	40
Total	**100**

3.4.2. Sampling Technique and Sample Types

The sample size of this scientific paper is derived using a formula designed by Taro Yamane (1967) with 95% level of confidence and when the size of the target population is known (Yamane, 1967). The size (n) is determined based on the below formula:

$$n = \frac{N}{1 + (e)^2}$$

Where N= population size, e=level of precision (0.05), n= sample size

$$n = \frac{100}{1 + 100(0.05^{2)}}$$

$$n = \frac{100}{1 + 100(0.0025)}$$

$$n = \frac{100}{1 + 0.25}$$

$$n = \frac{100}{1.25} = \underline{80}$$

The population of 100 respondents was targeted but was later determine as indicated above to 80 respondents. These respondents were selected in two research sites namely, Juba and Paloch. Juba respondents were purposely selected to represent strategic and policy makers in the oil and gas industry. In other words, Managers, Directors, Director General including the Minister of Petroleum fell in this category. Moreover, other respondents, particularly, technical engineers were purposively selected too in Paloch to explain oil production decline. Hence, the selection of the respondents was done with those with knowledge in the study.

Table 2: Sample Size and Selection of Respondents

Category	Population	Sample
Juba DPOC and MOP Senior Staff	60	50
Paloch (Block 3 & 7) Engineers	40	30
Total	**100**	**80**

Sampling types include purposive and cluster. Given that this is a specialized study with limited knowledge to the South Sudanese population, random or stratified samplings were not applied. Purposive sampling, depicting those with knowledge on oil production decline in block 3 & 7 in South Sudan combined with cluster sampling were applied in both Juba and Paloch oilfields. Thus, purposive and cluster sampling were thoroughly applied in this study.

3.5. Variables Definitions and Measurements

Various variables such as dependent variable: *Understanding the oil production* and independent variables such as *high water cut/produced water, sand production, floods & flooding, poor technologies and wars/conflicts in South Sudan* were defined and measured. Other variables such as intervening (moderating) and dichotomous were clearly defined and measured during the study. Indeed, the variables were nominally measured.

3.6. Procedure for Data Collection

A letter of permission to collect the data was obtained from Institute of Petroleum Studies, Kampala (IPSK) of Uganda Christian University (UCU). Another letter was obtained from the Ministry of Petroleum (MOP) to enable the researcher to access the oilfields of Paloch and interview the engineers in block 3 & 7 as well as acquire production data from 2017-2022. The researcher then liaised with the administration of Dar Petroleum Operating Company (DPOC) both in Juba and Paloch and engaged the staff and other people with knowledge in oil production decline.

3.7. Data Collection Instruments

The study deployed data collection instruments such as questionnaires and interview guides/schedules to collect the data on oil production decline in Juba and Paloch. Questionnaires and interview guides/schedules were first designed and piloted with experts in DPOC petroleum engineering department, reservoir engineering department and production department to ensure that information being sourced is as crystal clear as possible. Surveys via questionnaires and interview guides were conducted to deeply understand in detail the oil production decline in block 3 & 7 of South Sudan. The study acquired production data from DPOC from 2017-2022.

3.8. Piloting the study

Pilot study refers to small-scale study, which is conducted before the actual study (Malmqvist, et al, 2019). It is a trial run of the actual study.
The study was piloted to achieve the following:

- To understand the entire process of the research (research problem, research objectives, research questions, empirical literature, research design and the respondents). This shall help in clarifying issues before larger study;
- To understand the quality control of data collection tools. For instance, it was great checking questionnaires and interview guides if they were properly structured, clearly written and completed; and
- To help in proposing the data analytical tools such as Excel and SPSS.

Hence, this study was piloted by 10% of the sample size (80), which were 8 respondents in DPOC to clearly understand the entire research and make corrections before the larger study. This served time, money and energy. For instance, *questions 3, 14* and *16* in the questionnaire were timely modified to make clear sense to the respondents' base on the piloting done.

3.9. Quality/Error Control
The study ensured that quality is observed and errors during the collection of data were avoided. Reliability and validity mechanisms of data collection were deployed to ensure that the 80 respondents surveyed were reached on time and the information was recorded. The production data that was acquired from DPOC was double-checked to ensure that it has no errors but a complete data-set for 2017-2022.

3.9.1. Data Processing and Analysis
The study used simple and easy understandable data processing and analysis tools such as SPSS version 21 and Microsoft excel to interpret and present the data. SPSS and Microsoft excel were chosen because they are convenient to use and have great functions to analyze different variables appropriately. Cleaning up of the data was done first and later the analysis was presented in the context of research questions and literature review. Explanations were recorded.

3.9.2. Ethical Considerations
The study ensured that ethical considerations are observed. Ethical considerations include the issues of confidentiality, consent, assent, anonymity, integrity and benevolence during the research process. All respondents surveyed and interviewed were kept confidential. There were no any ethical challenges encountered during the entire research process.

3.9.3. Potential Limitations in the Data Collection Process
These limitations include delayed in the collection of data in Paloch. Many engineers had gone to the wells sites and were quite busy with the work-over on the rigs, fixing of down holes and other technical deficiencies in block 3 & 7. However, the researcher had to engage the management both in Juba and Paloch and the engineers finally returned to their base camps where the researcher completed the data collection.

4. Results and discussions
4.1. The Concept and Origin of Oil Production Decline

Table 3: The Origin of Oil Production Decline

Categories		Frequency	Percent
Valid	No	8	10.0
	Yes	72	90.0
	Total	**80**	**100.0**

Source: Fieldwork

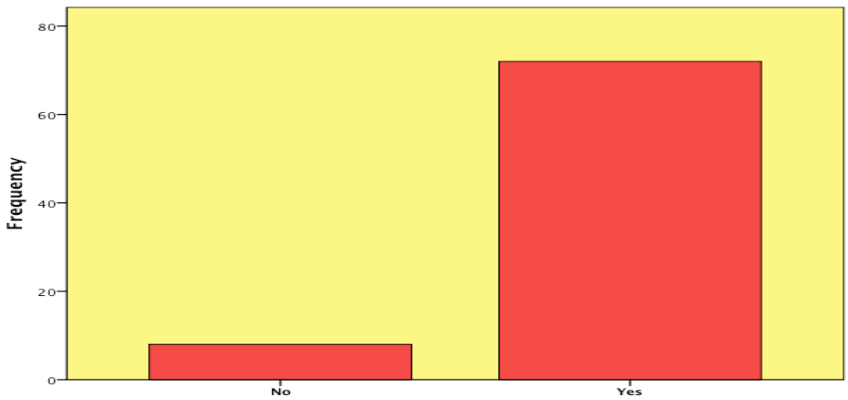

Figure 3: The Origin of Oil Production Decline
Source: *Author*

As shown in table 3 and bar chart in figure 3, when asked about the origin of oil production decline, 72 respondents, representing 90 percent noted with yes, the origin of oil production decline. This 90 percent respondents said that the concept originated in the USA around 1860s given that the discovery of oil in 1859 in the state of Pennsylvania. While some respondents associate the concept to China in 1850s, they also associate the concept with Scotland in 1840s. However, 8 respondents, representing 10 percent don't know the concept and origin of oil production decline as they left the spaces blanks.

Table 4: Meaning of Oil Production Decline

	Category	Frequency	Percent
Valid	Steady increasing of production rate of a given oilfield	1	1.3
	Steady reduction of production rate of a given oilfield	70	87.4
	Removing the rigs from the oil fields	1	1.3
	Production of waxy crude oil	8	10.0
	Total	**80**	**100.0**

Source: *Fieldwork*

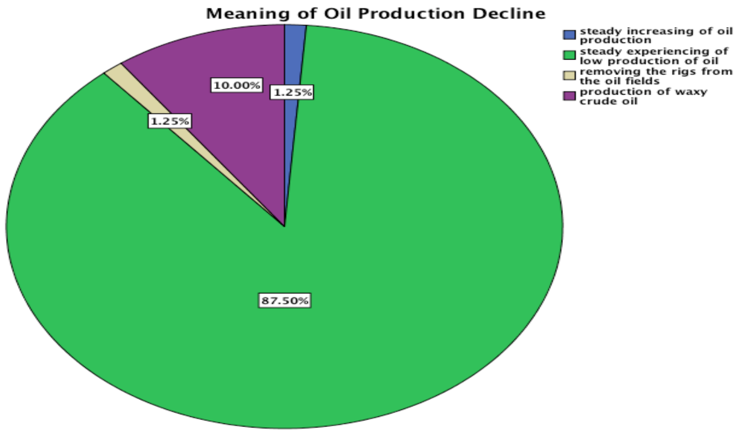

Figure 4: Meaning of Oil Production Decline
Source: *Author*

From table 4 and pie chart of figure 4 in understanding the meaning of oil production decline, 70 respondents, representing 88 percent define oil production decline as 'steady reduction of production rate of a given oilfield'. On the other hand, 8 respondents, representing 10 percent define oil production decline as 'production of waxy crude oil'. Besides, 1 respondent, representing 1 percent defines oil production decline as 'steady increasing of production rate of a given oilfield'. Finally, 1 respondent, representing 1 percent defines oil production decline as 'removing the rigs from the oilfield'. From the analysis and in tandem with literature review, oil production decline is defined as a steady reduction of production rate of a given oilfield.

Table 5: Country with the Highest Global Oil Production Decline Between 2017-2022

	Category	Frequency	Percent
Valid	United States	4	5.0
	Russia	6	7.5
	Iran	25	31.3
	Angola	9	11.3
	Nigeria	36	45.0
	Total	**80**	**100.0**

Source: *Fieldwork*

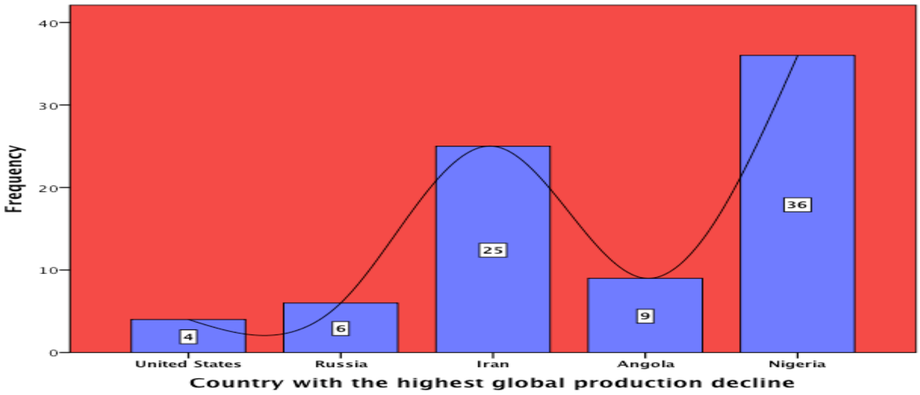

Figure 5: The Country with the Highest Global Oil Production Decline Between 2017-2022

Source: *Author*

Table 5 and bar chart in figure 5 present the respondents' views on a country that has the highest global decline from 2017-2022. When asked, 80 respondents responded differently. 36 respondents, representing 45 percent responded that Nigeria is the country with the highest global production decline from 2017-2022. They cited reasons such as the insecurity in Nigeria caused by Boko Haram and other insecurity incidences in Niger Delta caused by disruptions by the local people in Nigeria. These insecurity incidences installed fear to the contractors who are extracting oil in Nigeria. Other reasons cited include theft and diversion of crude oil by crooked Nigerians during piping. More reasons include the continuous use of poor technologies. On the other hand, 25 respondents, representing 31 percent argued Iran as the country with highest global oil production decline. They cited reasons such as sanctions that have been propelled on Iran by the USA coupled with poor technologies. Reasons such as the high sand production were cited including the poor quality of crude diet. Besides, 9 respondents, representing 11 percent cited Angola as the country with highest production decline from 2017-2022. The respondents cited high water production, high depletion of the oil fields and low pressure on the pumps to bring oil on the surface. More still, 6 respondents representing 8 percent cited Russia as the country with highest global production decline. The respondents cited aging of the fields (brown fields), lack of new explorations, high water cut and oil price volatility. These factors coupled with conflict with Ukraine have exacerbated the Russian global decline of oil production. Finally, 4 respondents, representing 5 percent cited United States as the country with the highest global production decline. The respondents cited the aging of the fields, high sand production, global price volatility and covid-19 pandemic as key factors that have contributed to the United States oil production decline.

Table 6: Continent with the Highest Oil Production Decline Between 2017-2022

Category		Frequency	Percent
Valid	Asia	2	2.5
	North America	1	1.3
	Europe	3	3.8
	South America	4	5.0
	Africa	70	87.5
	Total	**80**	**100.0**

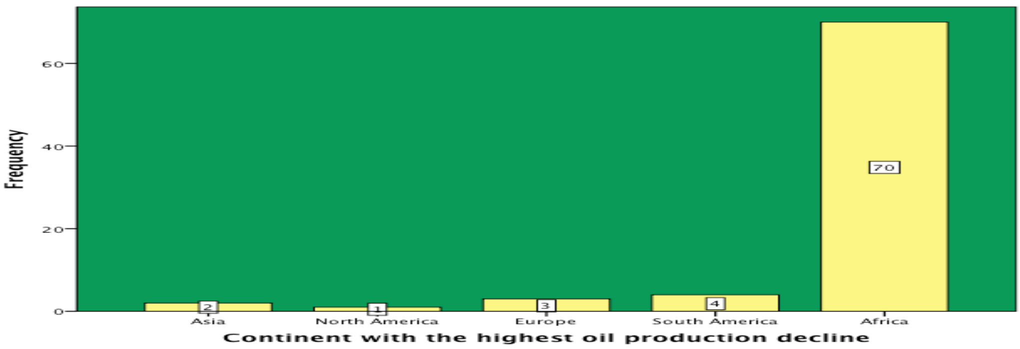

Figure 6: Continent with the Highest Oil Production Decline Between 2017-2022
Source: *Author*

Table 6 and bar chart of figure 6 presents respondents' view on continent that has the highest oil production decline between 2017-2022. Asked about a specific continent amongst the provided choices of the continent, 70 respondents, representing 87 percent cited Africa as the continent with the highest oil production decline. These respondents numerated various reasons such as high water cut, poor reservoir management, a lot of sand production, poor technologies, lack of machines work overs, floods and insecurity as the key factors that have made Africa the continent with highest oil production decline. In addition, 4 respondents, representing 5 percent cited South America as the continent with the highest oil production decline. These respondents cited aging of the fields, depletion of pressures in the reservoirs, lack of new explorations and lack of petrophysical studies as the key factors that have led to the production decline in South America. Besides, 3 respondents, representing 4 percent cited Europe as the continent with the highest oil production decline. The respondents noted factors such as matured (brown) fields, lack of new explorations and climate change have led to the oil production decline in Europe. Moreover, 2 respondents, representing 3 percent cited North America as the continent with the highest oil production decline. The respondents cited Covid-19 pandemic. Aging of the oilfields and swift transitioning of North America from fossil fuels to renewables as the factors that have contributed to the massive oil production decline. Finally, 1 respondent, representing 1 percent cited Asia as the continent with the highest oil production decline. They mentioned reasons such as depletion of pressures, poor reservoir management, high water cut, too much sand production and lack of enhance oil recovery (EOR) and improve oil recovery (IOR) as the factors for oil production decline making the Asia the least continent with the highest oil production decline according to the respondents.

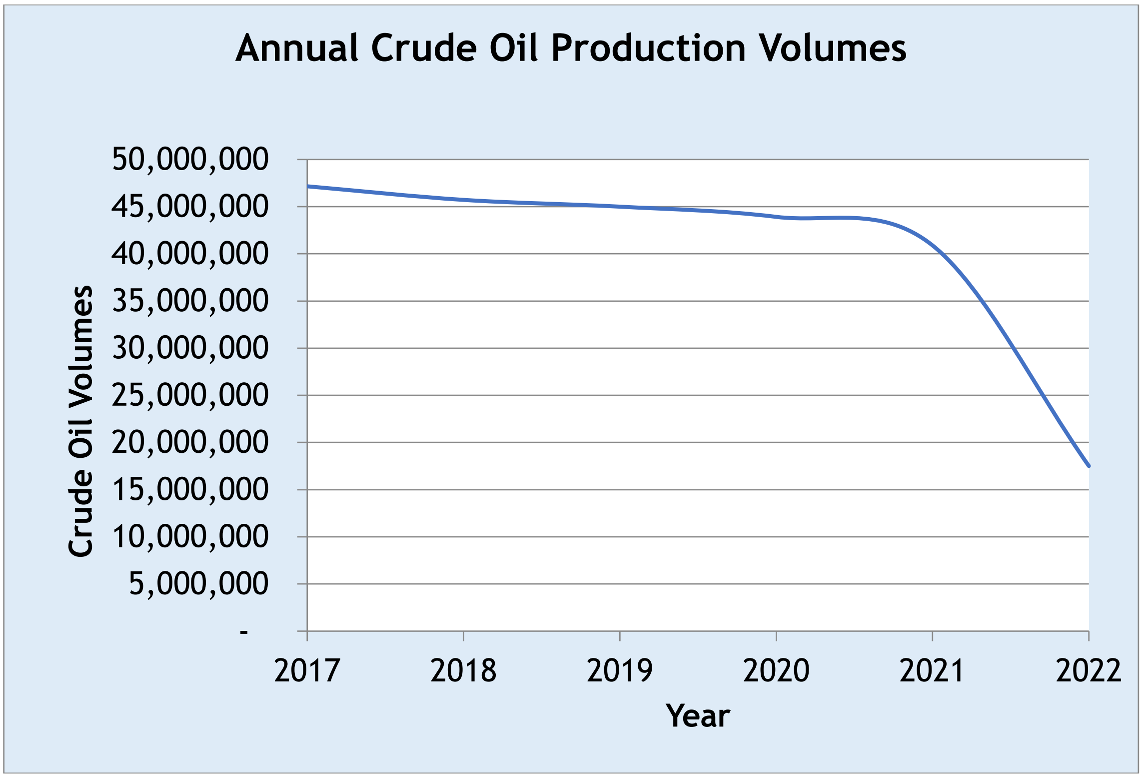

Figure 7. Decline Curve Analysis of Block 3 & 7 of South Sudan from 2017-2022
Source: *Author*

Figure 7 demonstrates the decline curve analysis of block 3 & 7 of Paloch from 2017 to June 2022. For 2017, the average daily production was 131,000 barrels per day that accumulated to 3,930,000 barrels per month then to 47,160,000 barrels for the year 2017. For 2018, the average daily production was 127,000 barrels per day that accumulated to 3,810,000 barrels per month and then to 45,720,000 barrels for the year 2018. For 2019, the average daily production was 125,000 barrels per day that accumulated to 3,750,000 barrels per month then to 45,000,000 barrels for the year 2019. For 2020, the average daily production was 122,000 barrels that accumulated to 3,660,000 barrels per month then 43,920,000 barrels for the year 2020. For 2021, the average daily production was 113,588 barrels that summed up to 3,407,640 barrels per month then to 40,892,000 barrels for the year 2021. For 2022, the year did not end during the time of this research. So the researcher took the volumes for 6 months (January-June). Hence, the average daily production was 97,267 barrels that accumulated to 2,918,010 barrels per month then to 17,508,000 barrels for 6 months for the year 2022. The above figure systematically demonstrates the decline curve analysis of the crude oil production for block 3 & 7 from 2017 to June 2022. It crystal clearly showcases the oil production decline in Paloch oilfield.

4.2. Factors Affecting the Oil Production Decline in Block 3 & 7 of South Sudan

4.2.1. South Sudan Experiencing Oil Production Decline in Block 3 & 7

Asked whether South Sudan is experiencing oil production decline in block 3 & 7 or not, all of the respondents noted with yes citing high water cut, pressure depletion, mature fields (brown fields), poor technologies, floods given that 40 percent of wells that were submerged in the waters in Paloch. The respondents also cited too much sand production that continues to block wellbore, lack of new explorations, poor reservoir management, formation dip, lack of petrophysical studies and wars and violence that was triggered by the 15th December 2013 political ignominy.

Table 7: Ranking of Factors that are Responsible for Oil Production Decline in Block 3 & 7 in Paloch

The highest factor responsible for oil production decline in block 3 & 7

Category		Frequency	Percent
Valid	High Water Cut	41	51.3
	Poor Technologies	25	31.3
	Too Much Sand Produced	5	6.3
	Floods and Flooding	6	7.5
	Wars and Violence	3	3.8
	Total	**80**	**100.0**

Source: *Fieldwork*

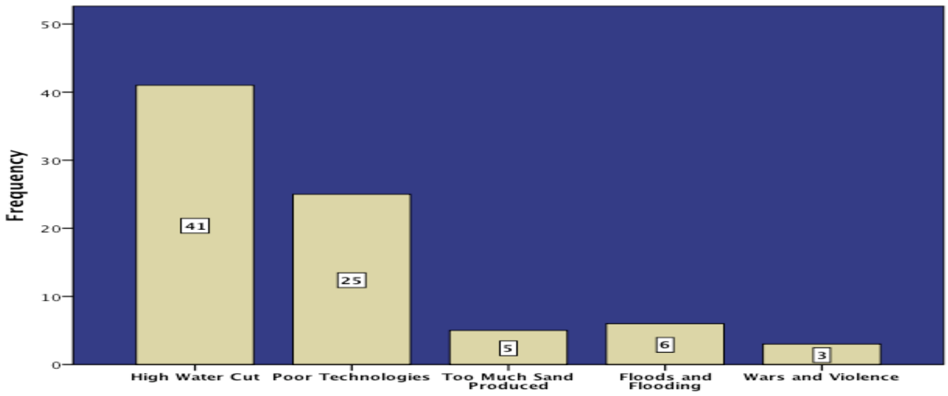

Figure 8: Factors that are Responsible for Oil Production Decline of Block 3 & 7 in PalochThe highest factor responsible for oil production decline of block 3 & 7

Source: *Author*

Table 7 and figure 8 above rank the key five factors that were previously mentioned by the respondents to be responsible for oil production decline in block 3 & 7. Asked to single out the most importance factor, 41 respondents, representing 51 percent cited high water cut as the most factor responsible for oil production decline. The respondents noted geological predicaments such as poor reservoir management and lack of petrophysical studies to address the high water cut (produced water) in block 3 & 7. Moreover, respondents noted that the soil in Paloch is continental, meaning that it is alluvial soil deep with less rocks hence it is geologically difficult to easily separate the water from the oil in the reservoir thus high water cut. *K.I.1* notes:

> *Automatic pumps are critical in the realization of production decline as well as production increase. These pumps in DPOC include ESP pumps for service such as maintenance and work over and PCP pumps for actual pumping of the oil underneath are not automatic and modern. If the PCP pumps are weak then the pumping will be low and this consequently leads to oil production decline (K.I.1).*

Respondents unanimously noted the high water cut levels in Paloch was between 70-90 percent, which is the highest in the world corresponding with the argument in literature review. Besides, 25 respondents, representing 31 percent cited poor technologies as the most disturbing factor that has led to the oil production decline in block 3 & 7. The factor, the respondents noted related to lack of exploration, drilling and production new technologies such as offshore exploration, vertical drilling and optimize automation production. The respondents acknowledged that for a very long time, DPOC has been using old technologies that have not promoted enhance oil recovery (EOR) and improve oil recovery (IOR) including industrial Internet of things (IIOT). These old technologies have been showcased on digging of vertical wells as well as disposal wells. In addition, 6 respondents, representing 8 percent cited floods and flooding as the major factor for oil production decline in Paloch. They argued that 40 percent of the 600 wells are submerged in waters and this has drastically reduced the oil production, particularly, at Paloch-FPF, Adar-FPT, Gumry-FPF and Moleeta-FPF. While the floods have affected the four FPFs, it has been worse for Paloch-FPF. What is more, 5 respondents, representing 6 percent cited too much sand produced as the main factor for oil production decline. The respondents argued sand production as detrimental because its blocks the reservoirs beds during geological extractions and more still block the wells during the pumping of oil to the FPF. These blockages impede the normal flow of oil and thus production decline. Finally, 3 respondents, representing 4 percent cited wars and violence as the most outstanding factor that has led to oil production decline in block 3 & 7 in Paloch. The respondents noted the 15th December 2013 political conflict that was later on followed by 8th July 2016 political violence in South Sudan affected the staff at block 3 & 7. Most of the staff working in the oil extractions and particularly those holding critical positions in the production in DPOC are Chinese, Malaysians, Indians and Egyptians who decided to abandon the field during the onslaught of the conflicts. This later led to few wells and FPFs being operated. Until at the time of writing this scientific paper, any slight insecurity provocations around the oilfields amongst the SPLM-IG soldiers, SPLM/A-IO, SSOA and OPP soldiers has continued to affect the production in block 3 and 7 in Paloch.

4.3. Consequences of oil production decline

4.3.1. On the Government of South Sudan

Asked about what consequence the oil production decline has on the Government of South Sudan, majority of the respondents noted that the consequence is the loss of oil revenues. The Government of South Sudan was receiving billion of United States dollars annually from 2011-2016 because the government was monthly getting its 600,000 crude oil cargo on time. However, between 2017-2022, the revenues drastically dropped as the government takes less than 600,000 crude oil cargo tankers per month. The government take has been swinging between 400,000 to 300,000 crude oil cargo tankers due to production decline in block 3 & 7. Moreover, the Government of Sudan has also given pressure to the Government of South Sudan to keep the production assurance flow rate to 120,000 bpd. The Government of South Sudan has not met this as the production went down to 98,000 bpd in March 2022 in block 3 & 7 and at average of 97,267 bpd for the 6 months (January-June) of 2022. Thus, the Government of Sudan has warned that failure to keep to the production flow rate assurance of above 120,000 bpd could lead to the shutting down of the pipeline. Moreover, the Sudanese government at the time of writing this paper has refused to bring down the tariffs for processing and transportation from 24.1 USD to 5 USD for a barrel as requested by the Government of South Sudan. In confounding the situation, the Sudanese rebels destroyed the pipeline and it was shutdown in February 2024.

4.3.2. International Oil Companies (DPOC Consortium)

Asked about what consequence the oil production decline has on international oil companies (IOCs) and in this case, DPOC consortium (CNPC, SINOPEC, PETRONAS, ONGC and Tri-Ocean), majority of the respondents cited loss of profits to these IOCs. As it is well known in the exploration production sharing agreement (EPSA), oil is contractually divided into two: cost and profit oil. In the case of block 3 & 7, cost oil takes 45 percent while profit oil takes 55 percent. This cost oil goes directly to the contractor and in this case it is DPOC and the 55 percent profit oil is shared between contractor consortium and the government. So, the contractor consortium takes 30 percent and shares it base on their individual company equities and the government takes 70 percent. Hence, since 2017-2022 DPOC has been losing substantive profit. The IOCs such as CNPC, SINOPEC, PETRONAS, ONGC and Tri-Ocean have reported through the respondents to have heavily lost substantial profits. This can delay cost recovery too.

4.3.3. South Sudanese Citizens

Asked about what consequence the oil production decline have on the citizens of South Sudan, many respondents cited loss of development such as constructions of roads, schools and hospitals. Moreover, respondents noted that South Sudanese citizens have lost energy related projects such as electricity power connectivity and renewable energies connectivity. Further still, the respondents noted compounded delay of salaries for the government workers and acute decline in the cost of living leading to object poverty and decline in life expectancy. Besides, the future of South Sudanese has been mortgaged through sovereignty guarantee related loans and this has resulted to untold anxiety to South Sudanese citizens. Finally, the South Sudanese citizens have lost jobs and the economy has turned to shambles due to lack of foreign currency.

4.4 Solutions to the Oil Production Decline for Block 3 & 7

Asked about what they think should be the possible solutions to oil production decline, majority of respondents argued that acquisition of relevant technology for EOR/IOR and horizontal drilling is a great solution to the production decline. Besides, some respondents said that embarking on the extensive exploration activities could help in increasing oil production in Paloch. In addition, some respondents noted that reservoir management need to be improved because this is what has led to high water cut and sand production that has further led to oil production decline. There is a great need to use suitable pumps to produce oil underneath. PCPS pumps are suitable and they can be used efficiently. However, according to *K.I. 2* during the interview:

> *Pumps can be overloaded and get stuck if there is too much sand production and hence they required diligent handling (K.1.2).*

Furthermore, some respondents note floods can be curbed through first doing prefeasibility studies and Environmental Social Impact Assessment (ESIA) then to be followed by feasibility studies and then building of strong dykes in Paloch and other FPFS. Finally, majority of respondents also noted that exploration and production of oil and gas take place when the block and the surrounding are secured. They said that proper security need to be put around block 3 & 7 so that workers don't fly away for fear of their lives. On top of this is genuine implementation of R-ARCSS so that all parties don't go back to war and all must observe a complete cessation of hostilities.

Table 8: Ranking of Solutions for Oil Production Decline of Block 3 & 7 in Paloch

The highest solution for oil production decline for block 3 & 7

	Category	Frequency	Percent
Valid	Re-injection of water to the reservoirs	24	30.0
	Use of laboratory to detect sand produced	10	12.5
	Dykes and river dredging to reduce floods	22	27.5
	Use of new and relevant technologies	15	18.8
	Genuine peace and security across South Sudan	9	11.3
	Total	**80**	**100.0**

Source: *Fieldwork*

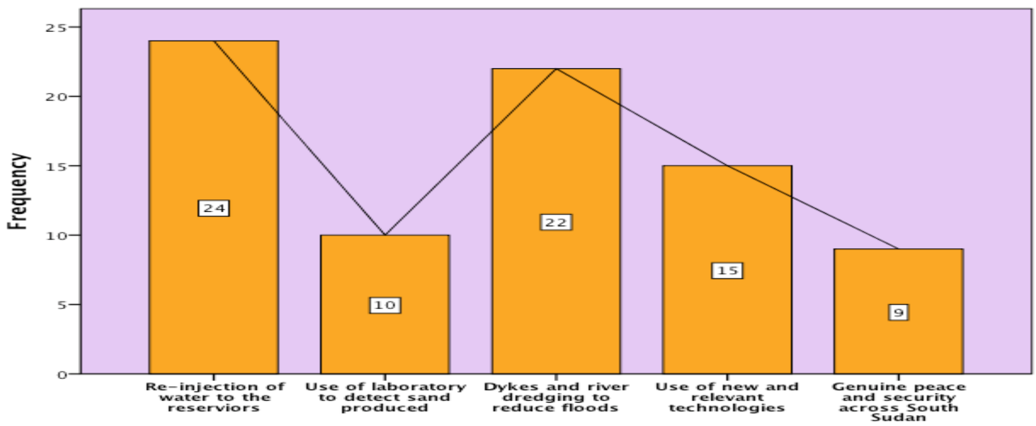

Figure 9: Ranking of Solutions for Oil Production Decline of Block 3 & 7 in Paloch
The highest solution for oil production decline in block 3 & 7
Source: *Author*

Table 8 and Figure 9 rank the key solutions for the oil production decline. Asked which of the solutions is the most importance, 24 respondents, representing 30 percent cited re-injection of water to the reservoir as the most importance solution. This, the respondents argue can help in the reduction of the water as well as part of reservoir management. Re-injection of water can help reduces the 70-90 percent high water cut. As water is re-injected, the re-injected water goes deep to the reservoir well bore depending on the pressure. If the pressure is so high then the water move quickly to the reservoir geological beds. However, if the pressure is low then the re-injected water doesn't move so fast. *K.I.2* during the interview notes:

> *Reservoir management is key for the increase of production. This reservoir management includes timely identification and separation of waters during logging and casing and during processing* (*K.I.2).*

As added by K.I. 3:

> *Petrophysical tools are critical during the reservoir management as petrophyscists help the reserviorists to prepare for either the best or the worst during production (K.1.3).*

K.I 4 during the interview noted in order to avoid high water cut during production, you require all the specialists in this area such as:

> *The production engineers, the reservoir engineers, petrophysicists, petroleum engineers and petroleum technologists are very essential in the realization of production increase (K.I.4).*

K.I. 1 confirmed and argued during the interview that production:

> *Is not about record keeping of the data but of forecast of what will happen in the foresable future (K.I.1).*

While production increase can occur any time*, KI 5* argued that during the interview:

> *That production increase should be annually planned and should be on the annual WPB because block 3 & 7 got only 35 percent explored, developed, drilled and produced. Hence, production decline is quite shameful and should be reversed with production increase (K.I.5).*

Besides, 10 respondents, representing 13 percent cited use of laboratory to test sand during production so that specific chemical solution is provided. The respondents also noted that sand keeps building up, as geologists or petrophysicists don't easily realize that it is being produced. Hence, a specialized laboratory for sand testing need to be built at Paloch so that it helps in testing of sand production at wells, FPFS and at the central processing facility (CPF). Moreover, 22 respondents, representing 27 percent cited dykes and dredging as the solution for floods at the center of block 3 & 7 at Paloch. These dykes should be built with the concrete wall and the excess water drained via river Nile dredging. While dredging of river Naam and Lake No of Bahr el Ghazal basin is a controversial matter for the Government of South Sudan, these respondents in the oil and gas industry believe that dredging can help open up the river which can assist in evacuating water from Paloch to allow submerged wells to be accessible again.

K.I.6 noted during the interview:

That prevention of floods by use of dykes, dams and river dredging is the work of the government not the DPOC (K.I.6).

What is more, 15 respondents, representing 19 percent cited use of new and relevant technologies as the most importance solution for oil production decline in block 3 & 7. The respondents noted the use of horizontal drilling, remote sensing of wells and reservoirs characterization coupled with new methods of work over for the rigs and pumps. These include the Industrial Internet of Things (IIOT). Other technologies such as enhance oil recovery and improve oil recovery (EOR/IOR) were cited as very importance for the increase of oil production in block 3 & 7. Finally, 9 respondents, representing 11 percent cited genuine peace and security across the country as a very importance solution to the oil production decline. These respondents also cited the importance of the implementation of R-ARCSS by all the parties. In the implementation of R-ARCSS, chapter two of security arrangement is key as it stipulates the permanent ceasefire and complete cessation of hostilities. The respondents added that partners like CNPC, PETRONAS, ONGC Videsh and Tri-Ocean would only increase the production in block 3 & 7 when they have seen a total return of peace to the country and when the guns are totally silent. This genuine peace and security boost IOCs confident to extract more oil and particularly, DPOC in doing new explorations, as many sub-fields have already been relinquished and new exploration required total and genuine peace and security across the country.

K. I.7 during the interview said t*hat DPOC has already identified 43 potentials sub-fields for explorations adjacent to block 3 & 7. These 43 fields once explore can aid in the increase of oil production in block 3 & 7 (K.I.7).*

4.5. The Stakeholder and Role in Providing Solutions to the Oil Production Decline in Block 3 & 7 of Paloch

Table 9: The stakeholder and role in providing solutions to the oil production decline in block 3 & 7 in Paloch

The stakeholder that should provide solutions to the oil production decline

	Category	Frequency	Percent
Valid	Government of South Sudan	51	63.7
	Dar Petroleum Operating Company	23	28.8
	Civil Society Organizations	4	5.0
	Both Government of South Sudan and Dar Petroleum Operating Company	2	2.5
	Total	**80**	**100.0**

Source: *Fieldwork*

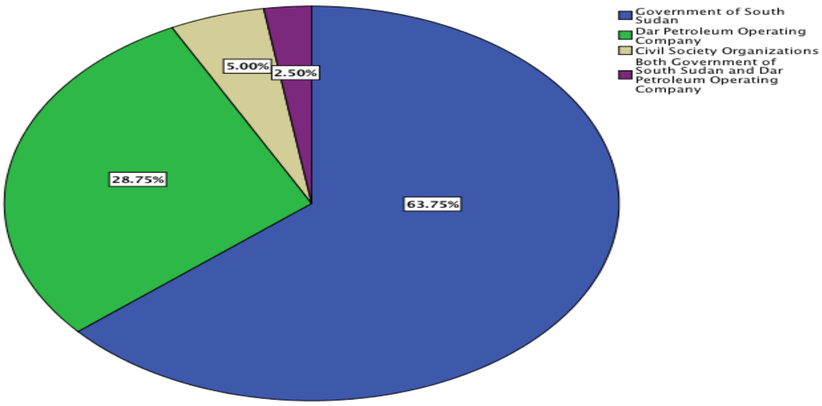

Figure 10: The stakeholder and role in providing solutions to the oil production decline
Source: *Author*

Table 9 and Figure 10 query the stakeholder and its role in providing already analyzed solutions to oil production decline in block 3 & 7 in Paloch. Asked which stakeholder should do this, 51 respondents, represented by 63.8 percent cited the Government of South Sudan through Ministry of Petroleum (MOP) as a responsible agency to provide solutions to the oil production decline. The respondents noted the constitutional role of the Government of South Sudan as the owner of natural resources including petroleum and which the Government regulate on behalf of the citizens of South Sudan. Having the ownership of these hydrocarbon resources, the Government through the Ministry of Petroleum should ensure that solutions to oil production decline such as re-injection of water to the reservoir, control of sand production, control of floods, provision of new and relevant technologies and provision of security to block 3 & 7 is its ultimate responsibility. The Government has a say over the contractors budgets and through the Ministry of Petroleum can pressurize Dar Petroleum Operating Company (DPOC) to put aside a budget for resolving oil production decline in tandem to production increase. Besides, 23 respondents, representing 28.8 percent cited Dar Petroleum Operating Company (DPOC) as the responsible agency for solutions to oil production decline. The respondents argue that DPOC is a company, operating block 3 & 7 and has a license responsibility of ensuring that production increase rather than decline. Every year, DPOC approves the Work Program and Budget (WPB) that ensures the performance of the company in the next financial year. In this WPB, DPOC can budget items that ensure that production is increased. This is the greatest leverage DPOC has over other institutions including the government because it manages cost oil funds and operation budget of the consortiums. In addition, 4 respondents, representing 5 percent cited civil society organizations as the responsible actor for the solutions of oil production decline. The respondents noted civil society as the voice of the citizens who can articulate the citizenry views on the matter of production decline. One of the ways on how civil society can excel is the advocacy on the environmental protection. For instance, the high water cut results to too much produced water, which if not treated can lead to environmental pollution that affect both plants, animals and human beings. Moreover, the civil society advocacy for ending of floods and insecurity in block 3 & 7 has been repetitively mentioned by the respondents as the surest way of increasing oil production and preventing the decline.

Finally, 2 respondents, representing 2.5 percent cited both the Government of South Sudan and Dar Petroleum Operating Company (DPOC) as the responsible agencies to solving the oil production decline. The respondents cited the power of the Government through the Ministry of Petroleum (MOP) as the approving authority of the WPB and this leverage can allow the Government to ensure that WPB prioritizes production increase. However, if it doesn't prioritize the increase of production then MOP can easily refuse to approve. What is more, respondents cited that DPOC has both the technical and financial capacity to ensure that oil production decline is a story, which cannot take place again in block 3 & 7. This capacity of both the Government and DPOC make them a combine actor responsible for oil production decline. When interview, the K.I.8 acknowledged that the MOP has power to reject the approval of the WPB until the DPOC adjust it accordingly (K.I.8). This is a leverage, which K.I.9 confirmed in an interview that the MOP has a powerful mandate that can make the JOCs, particularly, DPOC to increase production immediately. The conundrum according to the K.I.9 is that the MOP has not realized that it has such constitutional and regulatory power (K.I.9).

Table 10: Time for Providing Solutions to Oil Production Decline

Category		Frequency	Percent
Valid	Immediately	75	93.8
	After a year	2	2.5
	In five years time	1	1.3
	In ten years time	1	1.3
	Never at all	1	1.3
	Total	**80**	**100.0**

Source: *Fieldwork*

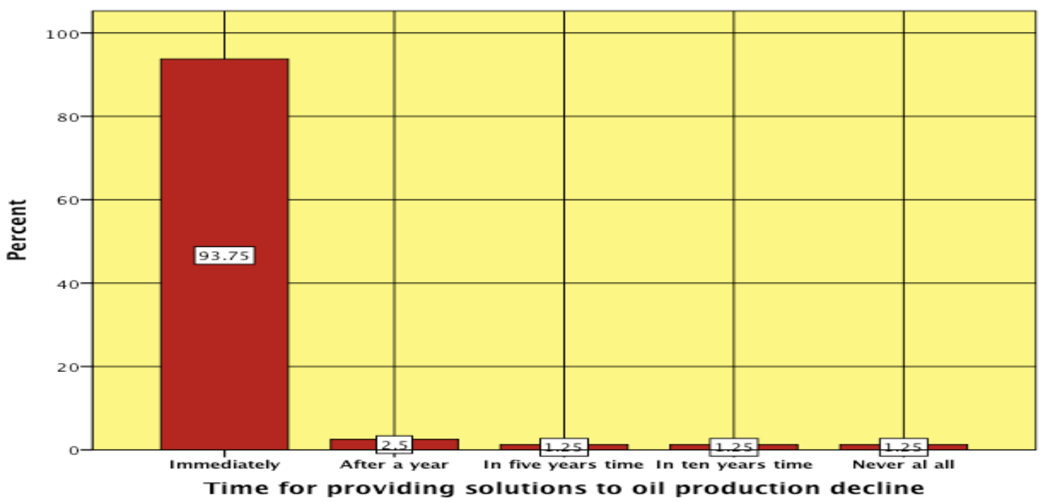

Figure 11: Time for Providing Solutions to Oil Production Decline

Source: *Author*

Table 10 together with figure 11 showcases the analysis of the time that is suitable for the implementation of solutions of the oil production decline. Ask about when to do that, 75 respondents, representing 93.8 percent cited immediately as the time for implementing the solutions of the oil production decline. These solutions as previously mentioned include re-injection of water to the reservoir, general reservoir management, and introduction of new technologies, use of laboratory to detect and control sand production, use of dykes and river dredging to control floods and maintenance of genuine and security peace across the country. These respondents noted that time is a great essence and increase of oil production is urgent and need to be done immediately. *K.I.10* noted during the interview t*hat production should be increased immediately as the situation is not favorable for the government* (*K.I.10).*

On the other hand, *K.I.11* also acknowledged during the interview t*he importance of using petrophysical tools on time so that production is increased and that decline should not be allowed to occur again* (*K.I.11).* On the other hand, *K.I. 5* notes that *DPOC has been ready to increase the production. However, insecurity and economic challenges have led partners, for instance, DPOC big* *partners (CNPC and PETRONAS to trade carefully) (K.I.5).* However, *K.I.12* laments t*he oil production decline has apportioned the blame on big partners of DPOC (CNPC and PETRONAS) who have been quite reluctant to increase the production budget together with petroleum engineering and petroleum technology departments (K.I.12).* In addition, 2 respondents, representing 2.5 percent argued that these solutions should be provided next year arguing that is not urgent. Besides, 1 respondent representing 1.3 percent argued that the solutions should be provided in five years time when the DPOC management has paid the cost recovery funds to the Government. What is more, 1 respondent, representing 1.3 noted that the solutions should be administered in ten years time as these respondents argue that there should be no hurry in Africa. Finally, 1 respondent, representing 1.3 percent cited never at all to provide solutions of oil production decline as this respondent has lost faith in the Government and South Sudan as a country. Overall, the solutions to oil production decline though practical, will take time as the country is going through challenges of protracted conflicts and economic collapse due to the wars in Sudan.

5. Comparison of study findings with existing literature

While the study findings are quite sound with empirical insights, they heavily reflect on the existing literature. For instance, the concept of oil production decline as indicated in table 3 and figure 3 reflect on the arguments of Hui-Ying, 2024; Hook et al., 2013 and Bradford, 1991 in the literature. Types of production decline as demonstrated in table 6 and figure 6 resonates with the arguments of Rapor, 2015 in the existing literature. All the five factors responsible for the oil production decline are discussed in table 7 and figure 7 but reflect on the various literature reviewed. For instance, high water cut finding resonates with Veil, 2004 argument, sand production reflects Rapor, 2015 and Hossein et al., 2013 arguments, floods and flooding resonates with Wabala, 2020 and Kaboka, 2019, Poor and Obsolete technologies reflect on the existing literature of Johnson, 2003 and Achuek, 2022 and finally conflicts and wars in South Sudan resonates with Lama, 2018 and Riak, 2021 arguments. On the solutions to the oil production decline, the findings are indicated in table 8, 9 and 10 as well as figure 8, 9,10 and 11. The solution to high water cut which is mostly re-injection of water into the reservoir resonates with Chungu (2024), Stephenson, 1992 literature, reduction on sand production using laboratory technologies reflect with Vijonych, 2017, avoiding of floods and flooding using dykes and early warning mechanisms reasonates with Waweru, 2022 literature, introduction of new cutting-edge technologies rhyme with the arguments of Gochi, 2018 and maintenance of genuine peace in South Sudan and beyond reflect on Muna, 2014 and Riak, 2021 existing literature.

6. Conclusion

The study has made a strong argument about understanding the oil production decline in South Sudan and particularly, investigating factors that have led to this historical decline. While the study appraised this oil production decline and problematized it on factors such as high water cut, too much sand production, floods and flooding, poor and obsolete technologies and wars and violence, it also interrogates these factors through the traditional decline analysis theory. Whereas the problem was further expanded into objectives and research questions, these research objectives and research questions were subjected to rigorous literature testing through literature review and further gaps were probed through field research in both Juba and Paloch. The successful distribution and filling of 50 questionnaires in Juba and 30 questionnaires in Paloch in addition to efficacious interviews of 12 senior Government and DPOC officials that were carried out in Juba have made this study quite ground breaking with original findings.

While the factors responsible for oil production decline as mentioned above were identified, solutions such as re-injection of water to reservoirs, laboratory test of sand, new and relevant technologies, use of dykes, dams & dredging of Nile river and maintenance of genuine peace and security across the country were identified as well and tested in both literature review and empirical field research. The implementation of these solutions have been largely mentioned by the respondents and interviewees to be done by the Ministry of Petroleum given that it is the regulator as well as the implementer of oil and gas policies in the Republic of South Sudan. While the Ministry of Petroleum has that role, it can also do this through Dar Petroleum Operating Company (DPOC), which is the operator of block 3 & 7. These solutions should be done immediately as indicated by the respondents. While this study was quite interesting and timely, it was quite technical given that oil production and decline is quite an area of geologists, geoscientists, geophysicists, petrophysicists, reservoir engineers and petroleum engineers. The study has confidently identified the factors and solutions to oil production decline in block 3 & 7 in the Republic of South Sudan. The solutions though practical, will take time as the country is going through challenges of protracted conflicts and economic collapse due to the wars in Sudan. The implication of this study on South Sudan oil and gas industry and, on its future development will rely on availability of technical and financial resources and more importantly, effective leadership to enhance more explorations, drilling, avail new technologies and restore sustainable peace in country.

7. Applications, Limitations and Future Research Directions

While the study has comprehensively and soundly analyzed the oil production decline in block 3 & 7 of South Sudan, the study is applicable to the political economy literature and more importantly to the body of knowledge of oil and gas industry. The study limitations are on the implementation of the conclusion and recommendations by the Government of South Sudan and lesson learned by other countries in ensuring that they don't allow their oil production to go to such drastic decline levels as it is in South Sudan. Given that this is a new area of scholarship, which I do not sufficiently claim to have exhausted it, future research is hereby recommended to other researchers or scholars in oil and gas industry in order to further investigate; either to confirm or refute each of my five factors and five solutions in explaining oil production decline in block 3 & 7 in Paloch, Melut County of Upper Nile State from 2017 to 2022.

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